Ground vibration measurements with special reference to pile driving

Uromeihy, Ali

Ground Vibration Measurements With Special Reference To Pile Driving

by

Ali Uromeihy BSc., MSc.

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Abstract

There has been increased concern in recent years over the level and nature of the ground vibrations. The importance of such vibration has increased rapidly due to developments in construction in urban areas, where the effects of ground borne vibration on both humans and structures are considerable.

Research has been undertaken to improve techniques used in the measurements, analyses and evaluation of ground vibrations caused by rail and road traffic, blasting and in particular those generated from pile driving activities. The amplitude of the vibration caused by the pile driving operation is a function of pile type, hammer type and the ground conditions. In order to investigate the effects of these three variables, a large number of visits were made to different sites which provided a range of different driving conditions.

The main requirements in the analysis of the vibrations measured include vibration amplitude and their relevant frequency. The vibration amplitude is usually expressed in term of peak particle acceleration, velocity or displacement. In this work, the ground vibration is measured in terms of peak particle velocity using velocity transducers (geophone). In order to evaluate the true peak particle resultant velocity, the three components of the ground vibration are measured simultaneously by three orthogonally positioned sets of geophone. Recording the vibration data is achieved by employing a portable digital recorder which digitizes the analogue signals recieved from the transducers and stores the captured data on standard floppy disks for further analysis.

The results are presented in tables and diagrams and detailed comments are given in the discussion of the recorded data. Some methods of analyses are reviewed and two new methods are proposed. These proposed methods include the application of the hemispherical projection technique in interpreting and displaying the three dimesional vibration information into a two dimensional plane. The other method analysed the attenuation of the ground vibration according to the arrival time of the generated waves from the pile toe and along the ground surface. It is suggested that when the arrival times of these two wave fronts coincide at one particular point, a highest vibration amplitude may be expected at that point.

The effect of ground vibration on building is investigated in large scale test in Flitwick where the dynamic strain of purpose built L-shape walls are recorded during driving steel sheet and H-pile at different stand-off from the walls using a winch-drop-hammer and a vibrodriver.

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Statement of Copyright

Declaration

No material from this thesis has previously been submitted for a degree at this or any other university.

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Where **ppv** : *peak particle velocity*

ppa : *peak particle acceleration*

ppd : *peak particle displacement*

dsgm : *dynamic strain gauge measures*

di. : *distance between the pile and the wall*

de. : *depth of pile-toe*

dr. : *drop height of the hammer*

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Notation

A	Cross-sectional area
A	Amplitude of vibration
B	Calibration factor of a geophone
C	Calibration constant of a geophone
D	Horizontal distance from vibration source
E	Young's modulus of elasticity
E	Input energy
F	Applied axial force
G	Shear modulus
I	Electrical current in resistivity investigation
I_p	Polar moment of inertia
L	Length of pile
L	Length of travelling wave
L	Length of strain gauge foil
P	Applied force to a pile head
P	P-wave
R	Angle of refraction of a wave at a boundary
R	Radial wave
R	Radius of projection sphere
R	Resistance force in a pile during the driving
R	Electric resistance in strain gauge
S	Horizontal distance from the pile
S_v	Shear wave propagation in the vertical direction
S_h	Shear wave propagation in the horizontal direction
T	Transverse wave
T	Period of one vibration cycle
T	Torque
V	Vertical wave of vibration components
V_r	Peak particle resultant velocity independent of time
V_{rt}	Peak particle resultant velocity with respect to time

V_{rt}	Resultant vector of radial and transverse waves
V_{res}	Resultant R_{rt} and vertical waves
W_o	Input energy from a vibration source
W_h	Weight of hammer head
W_p	Weight of pile
Z	Pile resistance, impedance
a	Acceleration
b	Building length
c	Wave velocity
c	Elastic movement of the pile, soil & cushion per blow
c_p	Body-wave velocity
c_r	Surface-wave velocity
c_s	Body-wave velocity in steel pile
d	Pile-toe depth
e	Distance of each eccentric mass from the shaft
e	Coefficient of hammer-pile restitution
f	Frequency
f_c	Centrifugal force in vibrodriver
f_h	Horizontal component of centrifugal force
f_v	Vertical component of centrifugal force
g	Gravity of the earth
h	Height of drop in impact hammers
i	Angle of incidence of a wave at a boundary
k	Constant expressing the regression intercept
l	Length of pile
m	Constant
m	Eccentric mass of a vibrodriver
n	Constant defining the gradient in regression analysis
r	Radius or radial distance
r	Correlation coefficient
s	Pile set per blow
t	Time

t_p	Arrival time of body-wave to geophone location
t_r	Arrival time of surface-wave to geophone location
t	Geophone positioned on top of the wall
u	Compression zone at the pile head after impact
u	Critical deflection below foundation
u_o	Maximum strain of the ground
v	Particle velocity
v	Velocity of the hammer head ($v = \sqrt{2gh}$)
x	Horizontal distance of geophone from source
z	depth
BH	Bore hole log or position
A/D	Analog to digital converter
FFT	Fast fourier transform
PDR	Portable digital recorder
Ch.n	Channel number
LCD	Liquid cristal display
SGA	Strain gauge amplifier
Sg.n	Strain gauge number
dpc	damp proof course
ppv	Peak particle velocity
ppa	Peak particle acceleration
ppd	Peak particle displacement
α	Constant
α	Angle between R and T
β	Constant
δ	Relative strain in the wall
γ	Shear strain
γ	Damping ratio
ϵ	Normal strain
θ	Angular distance, angle of torsion
θ	Angle between V_{rt} and V_{res}
λ	Wave length of transmitted vibration

ν	Poisson's ratio
η	Hammer efficiency
π	3.1416
ρ	Density
ρ	Material resistivity of strain gauge
σ	Normal stress
τ	Shear stress
ϕ	Friction angle
ω	Angular frequency
ω	Vibration frequency
ω_n	Natural frequency

Volume One

Chapter One
An Introduction to Ground Vibration

1.1 Introduction

Vibration is a form of energy transmission which disturbs the equilibrium condition of a medium. A simple form of vibration may be characterized as sinusoidal motion of the soil particle, but in most cases the nature of vibration is more complicated and may be identified as periodic, transient or random motion. The type of vibration is directly controlled by the source which produces them.

The source of vibration can be *natural* or *artificial*. Natural sources, such as earthquake, landslide, wind or waves may generate high levels of energy over a period of time of several seconds while the energies induced from artificial sources, such as pile driving, rail and road traffic, quarry blasting or demolition, by comparison, generally are of smaller magnitude, and are often of short duration.

Recently, vibrations caused by civil engineering construction operations have become the subject of concern. The effect of vibration, above the perception level, may cause disturbance to human comfort and even damage to existing structures. According to British Standard BS 5228, part(4) (1986), vibration can be the cause of serious disturbance and inconvenience to anyone exposed to it. The Control of Pollution Act (1974) defines noise, including vibration, as nuisance and gives a local authority the power to minimize its effect and put a limit to its cause. The act did not define any vibration limit, so research work in this field is required to identify approximate limits of vibration. The level of vibration is usually expressed in terms of peak particle acceleration, velocity or displacement and also by its frequency characteristics. The magnitude of ground vibration can be evaluated by means of transducers which can detect vibrations at ground surface and generate voltage signals proportional to either acceleration, velocity or displacement. Details of suitable measurement systems can be obtained from several sources, for example, Attewell(1985, 1986), Skipp (1984), Steffens (1974).

1.2 The Importance of Vibration Study

One important aspect of vibration study is to consider the environmental effects on both humans and buildings. The effect of vibration caused by civil engineering activities has been the interest of many researchers since the start of this century. As the speed of civil engineering construction (for example; buildings, roads and tunnels) is increased, and often in urban areas, more attention must be paid to reduction of the effects of the induced vibration and also to definition of limits for an acceptable vibration. In the following sections some of the literature considering the effects of vibration on humans and on structures is reviewed.

1.2.1 Human Responses to Vibration

The effect of vibrations on humans is dependent on many variables. According to British Standard BS 6841(1987) and Griffin(1982), these variables include *intrinsic* and *extrinsic* factors. The intrinsic variables are related to the reaction of an individual person to the imposed vibration and are influenced by the character of that person, for example, age, sex, fitness, experience, motivation, financial involvement and body posture. The extrinsic variables are related to factors which control the exposed vibration such as vibration magnitude, frequency, axis, direction and duration.

The British Standard BS 6472 (1984) gives detailed guidance for the evaluation of vibration exposure of humans in the frequency range of 1-80Hz. The document suggests that the vibration measurement should be in terms of particle acceleration and should be taken along the three orthogonal directions with reference to human axes. The coordinates of vibration directions with respect to human axes is shown in figure (1.1).

Richart and Woods (1987) considered the effect of vibrations on humans. They concluded that the vibration effect is influenced by the amplitude, the frequency and the duration of vibration. They denoted vibration of 0.25mm/s as *barely noticeable to persons* and 2.5mm/s as *troublesome to persons.* The human response to vibration with respect to displacement amplitude and frequency, derived by Richart *et al* (1970), is displayed in figure (1.2).

Beverstock (1980) defined the vibration thresholds of human exposure to be *perception* at 0.3-1.0mm/s, *noticed* at 1.0-3.0mm/s and *concerned* above 3.0mm/s. Similar limits were suggested by Massarsch (1983) within a frequency range of 2-50Hz.

Attewell (1986) described the human perception, although a most sensitive detector of vibration, as a poor measuring device, He added, *'natural response tends to exaggerate vibration magnitude and its possible effect. A person at home, for example, fears for the safety of his or her property when vibration is high enough to be felt but too low to cause any superficial damage'.*

Steffens (1974) stated that human sensitivity tends to over-estimate the magnitudes of vibrations. He explaned that *'at certain frequencies of vibration likely to be experienced in buildings, amplitude as small as about one micron (0.001mm) and acceleration of about 0.001g can be detected by the human body'.*

The author has also observed the concern and fears of the local people in different sites about the induced vibration to their properties from pile driving operations, (for example, at Keighley, Blaydon & St.Annes) and from blasting (for example, at Newton Aycliffe and Blaydon). Despite the people's concern about the imposed vibration, it was of negligible magnitude. The phenomenon of high human sensitivity to low amplitude vibration was also discussed in many reports, for example, Jeffrey (1980), Steffens (1974), Skipp (1984).

1.2.2 Structural Response to Vibration

The problem of structural damage to buildings caused by vibration has been the subject of research in recent years. Because of the frequent construction of high rise buildings on piled foundations, especially in the urban areas, much work has been concentrated on the study of vibrations from civil engineering, and particularly pile driving, activities. The magnitude of vibration caused by pile driving in terms of peak particle velocity, is typically in the range of 2-80mm/s and in a frequency range of 15-80Hz. The levels of vibration caused by road and rail traffic are in the range of 1-4mm/s and a frequency of 12-35Hz. Their effects are generally less than those caused by pile driving.

The risk of damage to a particular structure depends on its condition and the type of ground on which it is founded. The building may be previously stressed from differential settlement or uneven loading, so that small additional dynamic strain may be sufficient to trigger damage (Selby (1988)). With respect to the ground conditions, pile driving in loose granular soils, or fill may cause settlement, while driving into very dense soils may cause heave of a temporary or permanent nature.

Although there is no British Standard defining a safe vibration threshold in buildings, several authors have proposed acceptable levels of vibration to avoid risk of damage to buildings. For example, Attewell *et al* (1988) suggested that the vibration level should be limited to 4mm/s for ancient and historic buildings. Beverstock (1980) commented that a vibration level of 5mm/s can cause minor damage such as cracking of plaster, and breakage of windows. The vibration level was required to be limited to 0.25g and at a frequency not lower than 7Hz in a site in docklands, London during the driving of 400 bottom driven cast-in-place piles adjacing to a sensitive computer house building (Grose (1986)). The effect of vibration on a building tends to decrease as the frequency of the applied vibration increases.

A large number of references was reviewed by Skipp (1984) and some acceptable levels of vibration given by international standards were compared. The vibration thresholds suggested by these standards are shown in table (T1-1). The frequencies for most of the values given in the table, were considered to be in the range of 0-60Hz. Also, a comparison of some acceptable levels of vibration for domestic building is displayed in figure (1.3).

1.3 Scope of the Research

This thesis forms part of a continuous research programme at Durham University, active since early 1970's, concerning the environmental effects of vibration associated with the construction industry, and, in particular, the evaluation of the vibration levels caused by pile-driving operations.

1.3.1 Objectives

The fundamental objectives of the project are summarised below:

- to develop and modify the recording techniques including transducers, data recorders and data processing.
- to investigate acceptable levels of vibration adjacent to a construction site.
- to provide a means of estimating the level of vibration likely to be induced in the ground by different sources (mainly pile driving operations) at different distances from the source.
- to give guidance in controlling and reducing the level of vibration.

1.3.2 Procedure

The procedure followed in the project comprised the factors below:

- recording the ground vibration from different sources (road and rail traffic, quarry blasting and pile driving), primarily piling.
- monitoring the vibration caused by pile driving with respect to the site conditions, the type of hammers, and the type of piles.
- Studying the main parameters of piling vibration and employing appropriate methods for analysing these parameters.
- measuring vibration under controlled conditions and identifying its effects on buildings.

1.3.3 Structure

The measurement of vibration, identification of its characteristics and analysing of its transmission has formed a central part of the work described in this thesis.

Any source of vibration transfers its dynamic energy into the ground by one of several means. The transmitted energy propagates as both body-waves and surface-waves. Body-waves may comprise two components known as *compression-waves* (P-wave) and *shear-waves* (S-waves). The vibratory movement of a constitutive particle in the body is in the direction of the wave propagation for the P-wave, while it is normal to the direction of wave propagation in the case of a slower moving body wave as in S-waves. The particle motion of a surface-wave is broadly similar to that of a Rayleigh wave form. The mechanisms of wave propagation are explained in Chapter two.

In order to assess and evaluate possible controls on vibration levels induced into the ground by some artificial sources such as quarry blasting, road and rail traffic and pile driving activities, more than 100 site visits were made between September 1986 and March 1989 where the majority of the visits were in connection with pile driving operations. The effects of different sources on the ground vibrations are explained in Chapter three.

The ground vibrations from the various sources were measured at the ground surface by sets of velocity transducers (geophones). Each set comprised three orthogonally located geophones to record radial, transverse and vertical components of partical velocity. The vibration data were recorded simultaneously at five different stations at locations of 2m to 25m from the source.

The geophones were connected to a recorder ((PDR1) or (PDR2) units). The recorders, PDR1 and PDR2, were designed and assembled in 1985 and 1987 respectively, at *Microprocessor Centre*, Durham University, and functioned as analog-digital converters with facilities of recording, storing and processing the data. The details of the equipment used in this project are given in Chapter four.

Descriptions of the sites visited are reviewed in Chapter five, where the information of each site, together with the results obtained are represented in tables, plots, graphs and diagrams. The nature of the results is discussed and some recommendations are given for minimizing the effects of vibration.

Different methods of analysis are discussed in Chapter six. The results are compared to some previous work and suggestions on predicting the vibration level are given. The use of a hemispherical projection method to present the vibration records is explained. The method visualizes the resultant vibration vector with respect to the sense and magnitude of each individual direction of the propagation axes. The effects of vibrations on buildings are discussed. The use of a data-base program is also mentioned.

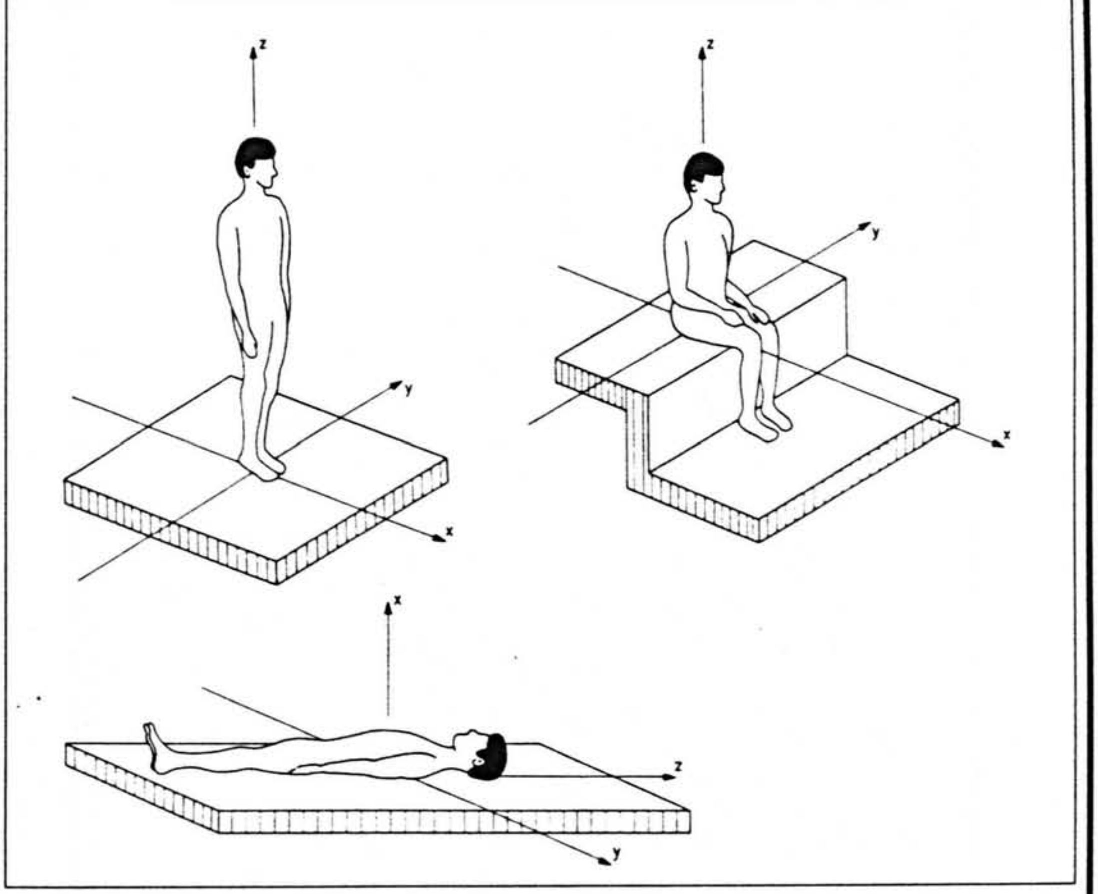
The effects of vibration on brickwork walls were examined by dedicated large scale tests. The tests were carried out in Flitwick, Bedfordshire on four L-shape brick walls. The walls were instrumented with electrical resistance strain gauges, demec-gauges, and glass telltales in addition to the measurements of the ground surface vibration by the sets of geophones. Piles were driven at different stand-off distances from the walls and the effects of the vibrations were recorded. These tests are described in Chapter seven.

Finally conclusions are drawn from the results and some suggestions for future work are given in Chapter eight.

Table (T1-1)

Comparison of some International Standards

		German, 1975 *DIN 4150*	Swiss, 1978 *SAS*	Australian, 1967 *ASC A23*
class	type of buildings	peak particle velocity resultant (R_{vt}) mm/s		
I	Historic and sensitive structures	4	3-5	15
II	Residential structures	8	8-12	25
III	Commercial structures and factories	30	30-40	50



x–axis = back to chest y–axis = right side to left side z–axis = foot to head

Figure (1.1) The coordinates of vibration directions with respect to human axes

after BS 6472–1984

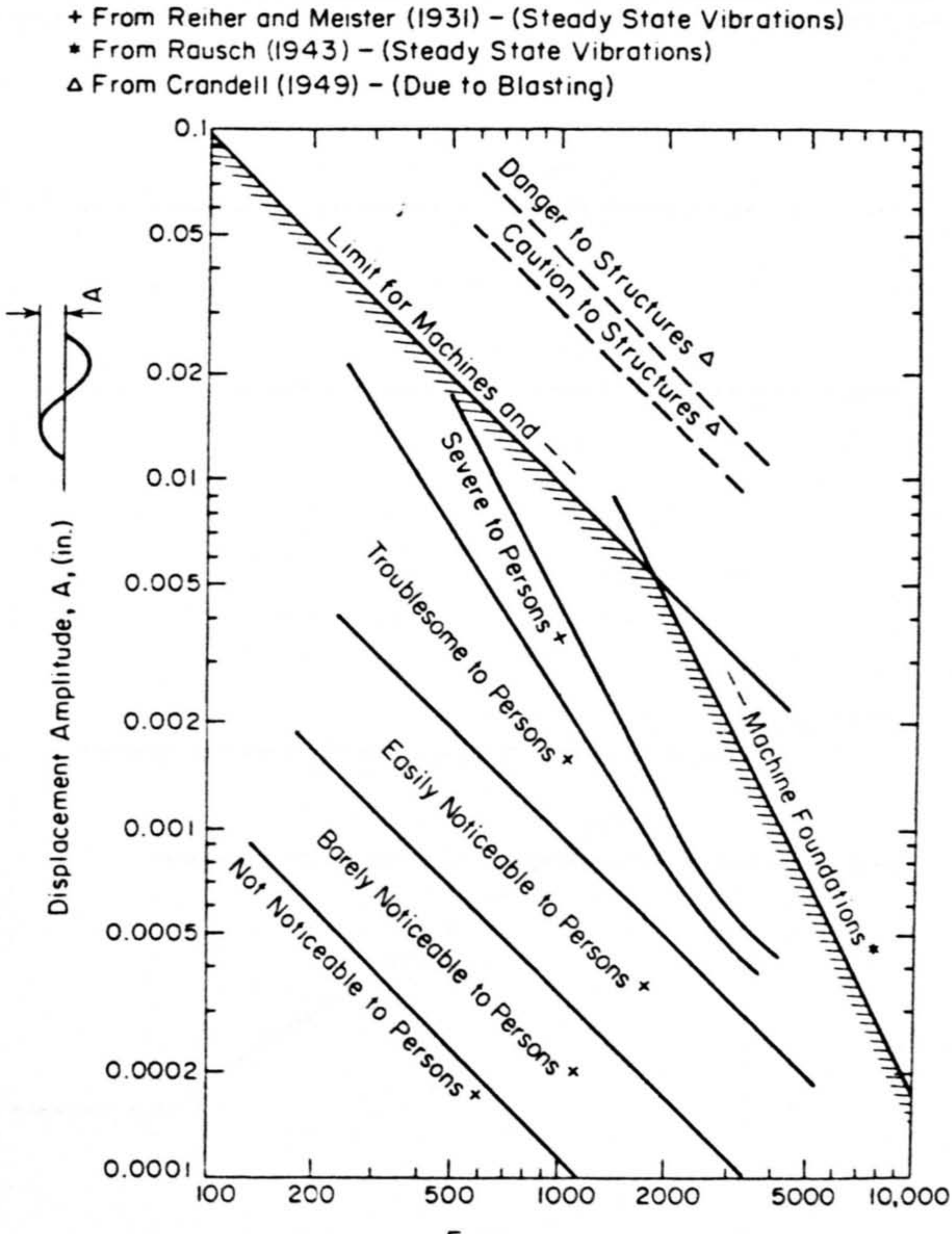


Figure (1.2) Acceptable level of vibration interm of displacement amplitude and frequency

after Rechart et al (1970)

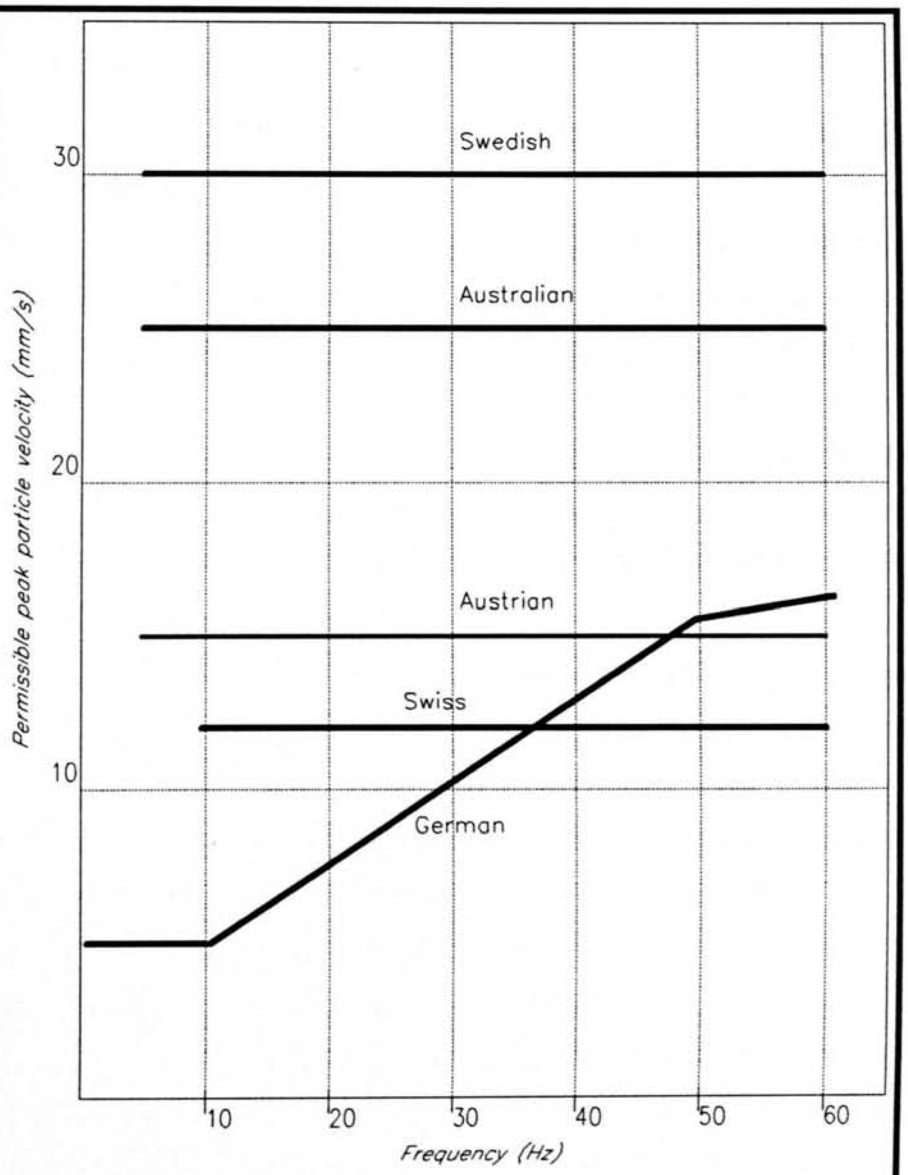


Figure (1.3) Permissible peak particle velocity for domestic buildings *(after Selby 1990)*

Chapter Two

Basics of Wave Mechanics and Vibration

2.1 Introduction

A wave can be defined as a disturbance travelling from one point to another transferring energy but not particles.

Vibration can be defined as a particle disturbance about its equilibrium position in a repetitive fashion.

A wave can be distinguished from particle vibration through the following example. Consider the movement generated in water when a small piece of stone is thrown into the centre of a pond. A single disturbance moves at a constant speed away from the source of the disturbance towards the edges of the pond. The movement of the disturbance is described as `wave motion` and it has a *wave velocity*, (c). If a piece of wood lay on the water surface, the up and down movement of the wood as the water wave passed its location may be described as `vibration motion` also described by its *particle velocity*, (v).

In engineering practice, attention is focussed on studying ground motion which is defined as particle velocity v, while less attention is given to wave velocity c. The measurement of the vibration at the ground surface is usually expressed in terms of particle velocity where its form and amplitude is a function of the source, the ground conditions and the radial distance from the source.

Much of the contents of this chapter is covered in several specialist soil dynamics textbooks, for example Prakash (1981) and Das (1983). However, the chapter is intended to provide in simple form some basic information on waves and vibration. The phenomena and characteristics of waves are presented in sections (2.2) and (2.3). The mechanics of wave propagation, discussions on the types of waves, and a brief review of their mathematical background, are discussed in section (2.4), the phenomena of reflection and refraction of body waves are reviewed in section (2.5), and finally the transmission and attenuation of vibration generated from different sources are explained in section (2.6). In addition, some experimental data and discussion are given in this section.

2.2 Wave Characteristics

For a better understanding of the nature of waves and vibration, some of the fundamental definitions are described below with respect to a simple harmonic (sinusoidal) vibration as shown in figure (2.1).

- *Amplitude* (A): is the maximum displacement of an object from its equilibrium position (or the zero line). This is referred to as *single amplitude.* The peak-to-peak displacement amplitude(2A), is usually called *double amplitude.* The amplitude expression is also used to define the magnitude of particle velocity and acceleration.
- *Period (T)* is the time required for one object to complete one vibration (or cycle).
- *Wavelength* (λ) is the distance between any two identical parts of adjacent vibration cycles. The wavelength is proportional to the wave velocity and inversely proportional to the frequency.

$$\lambda = c/f$$

- *Frequency* (f) is the number of vibrations (or cycles) that occur in a given period of time. The common frequency unit is the **Hertz (Hz)**.

$$f = \frac{1}{T} \quad or \quad 1\text{Hz} = 1\frac{\text{vibration}}{\text{second}} \quad \text{or} \quad = \frac{\text{number of cycles}}{\text{relevant time}}$$

- *Angular Velocity* (ω): is the ratio of the change in angular position $\Delta\theta$ to the change in time Δt (see figure(2.2).

$$\omega = \frac{\Delta\theta}{\Delta t} \quad (radians/sec)$$

- *Wave Velocity* (c): is the ratio of the change in distance position Δx to the time change Δt.

$$c = \frac{\Delta x}{\Delta t}$$

- *Particle Velocity* (v): is the rate of change in vibration displacement with respect to time.
- *Free Vibration*: is the vibration of a system under the action of its internal forces. Free vibration can also be expressed as the *natural frequency* of the system.
- *Forced Vibration*: is the vibration of a system generated under the action of external forces.
- *Resonance*: resonance occurs when the applied frequency to the system coincides with its natural frequency, so resulting in a large level of vibration. Usually the failure of major building structures and bridges happens at resonance, in which the forced amplitude of the motion may reach its maximum.
- *Degree of freedom*: is the number of independent coordinates required to describe the motion of a vibrating system. Any free particle may have three degrees of freedom in three orthogonal positions (*longitudinal, transverse & vertical*), and any rigid block may have six degrees of freedom; three describe its displacements along x, y & z axes which are known as *lateral, longitudinal & vertical*, and three describes the rotations of the block about x, y & z axes (*pitching, rocking (rolling) & yawing*) (see figure (2.4)).

2.3 Vibration Motion

Any vibration has a form of motion which can be generated from different sources. This motion can be measured and expressed as acceleration, velocity or displacement of that vibration. Some negative forces (damping) can act in opposition to the direction of the motion and cause a faster return of the system to its equilibrium position.

2.3.1 Types of Vibration

Depending on the source of the vibration forces, their time dependence and the medium in which they act, vibration motions can be classified into the following categories:

1. *Transient vibration* is characterized by the sudden occurrence of an impulsive force which, by definition, acts for a short time. The response dies rapidly with time. Such vibration can be generated by blasting, impact hammers and dynamic compaction.

2. *Periodic vibration* has a repetitive character in which the same form of motion re-occurs repeatedly. Vibration generated by a vibratory hammer is an example of periodic motion. Harmonic motion is the simplest form of periodic motion which is also called *sinusoidal vibration*.

3. *Random Vibration* means that the occurrence of the events are not predictable and no instantaneous value can be expected for any future time. Seismic activity and the movement of heavy compaction plant are examples of random vibration sources.

2.3.2 Measures of Vibration

Vibration amplitude may be expressed in term of particle displacement, velocity or acceleration. For a sinusoidal vibration, these quantities may simply be related to each other. Referring to figure (2.1) in which the motion of a point around a circle is projected on to a straight line, the vertical position of the point represents the particle displacement and its amplitude is:

$$x = Asin\omega t \qquad 2.1$$

Particle velocity can be obtained by differentiating Eq(2.1) with respect to time:

$$v = \omega Acos\omega t \qquad 2.2$$

$$or \qquad v = \omega Asin(\omega t + \pi/2)$$

Also, differentiation of Eq(2.2) with respect to time gives the particle acceleration:

$$a = -\omega^2 Asin\omega t \qquad 2.3$$

$$or \qquad a = \omega^2 Asin(\omega t + \pi)$$

The phase relationships between displacement, velocity and acceleration are illustrated in figure (2.2).

For a harmonic (sinusoidal) vibration, if the amplitude of one of the above quantities together with its relevant frequency is known, all other quantities could be obtained by the use of a *vibration nomograph* or *tripartite paper*, as shown in figure (2.3). For example, by plotting a particle velocity of 25mm/s (or 1 in/s) and frequency of 30Hz, the amplitude of particle displacement of 0.0055in and particle acceleration of 0.47in/s^2 can be derived. The method is very useful for a quick interpretion of simple data.

2.3.3 Damping

In the preceding section, the motion of free vibration is discussed without considering the effect of friction on the vibrating system. However, in practice, the presence of friction causes the vibration to be *damped*. Under the effect of damping, the amplitude of vibration decreases with time (temporal attenuation coefficient) and with distance (spatial attenuation coefficient). The degree of damping depends on the presence of friction forces. The friction force is directly proportional to the velocity of a medium having lower wave velocity such as granular soil, and proportional to square of the velocity of a medium with higher wave velocity such as dense soils and rocks.

The vibrating system is said to be *weakly damped* where there is little effect of the friction forces, *overdamped* where the effect of friction is greater and *critically damped* where the system returns to its equilibrium position in the shortest possible time. Damping has a great influence in limiting the amplitude of vibration at resonance.

2.4 Wave Propagation

The propagation of waves depends mainly on the type of wave, ground condition (its stiffness, density and water content), and the boundaries between different layers, especially at the ground surface. In the following sections, the type of waves will be reviewed first with respect to the properties and character of the waves. Later, the mathematical solution of the wave equation will be briefly discussed.

2.4.1 Types of Waves

According to the medium of propagation, elastic waves can be classified as *Body-waves* and *Surface-waves.*

2.4.1.1 Body Waves

A body wave is a type of wave which moves through a medium such as soil or rock. They can be classified according to the direction of the propagation as *compressional waves* or *shear waves.*

a. Compressional Waves, (P-waves)

Also known as Longitudinal, Dilational, Irrotational and Primary waves

A compressional wave causes the particles to vibrate parallel to the direction of the wave propagation. Considering figure(2.5a), the particles in the medium vibrate back and forth in the same direction that the wave travels and cause a change in the volume of the elements during compression and expansion of the medium. A sound wave is an example of a longitudinal wave. The `P-wave`, velocity c_p, in a rod (one dimensional medium) and in an infinite medium (three dimensional medium) can be represented as

$$\text{in a rod} \quad c_p = \sqrt{\frac{E}{\rho}}$$

$$\text{in an infinite medium} \quad c_p = \sqrt{\frac{E(1-\nu)}{\rho(1-2\nu)(1+\nu)}}$$

where E : is the elastic modulus of the medium

ρ : is the density of the medium

ν : is Poisson's ratio

This means that the `P-wave` velocity of propagation is faster in an infinite medium where there is constrained lateral displacement than in the rod where lateral displacement is free.

The degree of saturation in the soil has a direct effect on the **P-wave** propagation velocity. Since water is relatively incompressible as compared to the soil structure, the measurement of **P-wave** velocity in saturated soil does not represent the velocity in the soil alone. Das(1983) has suggested that a **P-wave** propagates in saturated soil with two components, a *fluid wave* and a *frame wave*, through pore water and the soil structure, respectively.

b. Shear Waves, (S-waves)

Also known as Transverse, Distortional, Equivoluminal and Secondary waves

A shear wave causes the particles to vibrate perpendicularly to the direction of the wave propagation. Light waves and radio waves are some examples of transverse waves. Transverse waves may be polarized into a single plane, for example a vertical plane ($\mathbf{S}_v$**-wave**), see figure (2.5b), or a horizontal plane ($\mathbf{S}_h$**-wave**), see figure (2.5c) . The transverse wave causes a change in the shape of an element in the medium but no change in volume as the wave passes through. The **S-wave** velocity c_s in a rod and in an infinite medium can be expressed as

$$c_s = \sqrt{\frac{G}{\rho}}$$

where G is the shear modulus of the medium.

The propagation of an **S-wave** depends on the degree of saturation of the medium. Since the pore water has no shear strength, the velocity of an **S-wave** in saturated soil represents the wave velocity in the soil elements only if the soil elements remain in contact within one another. Theoretically, if not always practically, the passage of shear waves and their amplitudes, assessed also in the context of **P-waves** in the same medium, provide information on the pressure of groundwater if the assessment is performed in the context of the effective stress conditions in the soil.

2.4.1.2 Surface waves

Surface waves exist only at the surface or in the vicinity of bounded media having different acoustic impedances. Different types of surface wave have been recognized. The most important types are discussed in the following sections.

a. Rayleigh Waves (R-Waves)

Rayleigh (1885) investigated the propagation of elastic waves along a free surface and along the boundary of two different (acoustic impedance, ρc) layers. A Rayleigh wave is defined as a combination of P and S_v waves with no horizontal S_h component. These waves exist in a radial-vertical plane as particle retrograde ellipses where the major axis is perpendicular to the boundary surface and the minor axis is parallel to it. The particle motion is opposite to the propagation direction at the top of the ellipse (see figure (2.6a)). The motion of an `R-wave` is confined to a zone near to the boundary of two continuous media and the amplitude of the waves decreases exponentially with increasing distance beneath the surface. They have a velocity slightly lower than that of shear waves.

The equation for the evaluation of the velocity of these waves is;

$$c_r = f\lambda$$

where f is frequency and λ is the wave length

In homogeneous solid media, an `R-wave` propagates with a velocity proportional to the S-wave velocity as the following equation;

$$c_r = kc_s$$

Jaeger and Cook (1979), suggested that the factor k has a maximum value of $k = 0.9553$ when $\nu = 0.5$ and a value of $k = 0.9194$ when $\nu = 0.25$.

`R-waves` are phenomena observed within seismic wavetrains. At the close-in distances associated with civil engineering vibration, it is unlikely that the individual waves will have separated out sufficiently to permit discrete `R-waves` to be identified.

b. Love Waves (Q-waves)

A Love wave is the transmisson of a horizontally polarized shear wave S_h through a surface layer (interstrata). This wave, which was defined by the French scientist Love in 1911, has the particle motion parallel to the free surface and perpendicular to the direction of wave propagation, see figure (2.6b). These waves have no vertical component and need at least one stratified solid layer for their propagation. The last comment with respect to Rayleigh waves applies also to Love-waves.

2.4.2 Wave Equations

The propagation of an elastic wave is a function of the elastic properties of the medium. The body wave equations can be solved in one and three dimension to represent wave propagation in an elastic rod and in an elastic infinite medium, respectively. The surface wave equation can be solved in a plane at the surface of an elastic half space. A brief discussion and derivation of the body-wave equations are included in Appendix (A1.1). The detailed information on the derivation of the equations can be found in several text books; for example, Das (1983), Jaeger & Cook (1979), Prakash (1981), and Timoshenko & Goodier (1984).

2.5 Wave Transmission

When a wave reaches the boundary between two different media, the wave separates, part being reflected and part being refracted. The degree of reflection and refraction of the wave is dependent on the elasticity and density of the medium and the angle of incidence. The phenomena of wave reflection and refraction are detailed in several textbooks; for example, see Dowding (1985), and Heurelen (1986). A condensed outline is given in Appendix (A1.2).

2.6 Geometric Attenuation of Ground Vibrations

If input wave energy is created in the ground by means of pile driving, blasting or any other dynamic sources, the vibration will propagate into the ground in the form of body waves and on the ground surface as surface waves. In the following sections, the wave transmission into the ground caused by some civil engineering sources of vibration will be examined.

2.6.1 Attenuation of Blast Vibration

Creation of a blast generates energy at or near ground surface. If the ground is assumed to be an elastic homogeneous medium, the body wave will propagate into the medium with a sensibly hemispherical wavefront. Figure (2.7)† which was suggested by Woods(1968)⊙, illustrates the form of the wave propagation from the source of vibration. The body waves propagate radially outwards from the source along a hemispherical wave front and the surface-wave propagates radially outwards along a shallow cylindrical wave front. The energy of the spherically-propagating body waves distributes over an area that increases with the square of the radius, so it can be deduced that the energy disturbance over the wavefront decreases with the square of the radius of propagation.

$$W_o \propto 1/r^2$$

where W_o is the energy per unit area and r is the radial distance from the source. The amplitude of the disturbance is proportional to the square root of the energy per unit area ($Amplitude \propto \sqrt{W_o}$).

The amplitude of the body waves is inversely proportional to the distance as in the following relation

$$\text{amplitude of body-waves} \propto 1/r$$

Along the surface of the half space `only`, the above relation will be as

$$\text{amplitude of body-waves} \propto 1/r^2$$

while the amplitude of the surface-wave decreases with distance as

$$\text{amplitude of surface-waves} \propto 1/\sqrt{r}$$

† The distance from the source of waves to each wave front was drawn in proportion to the velocity of each wave for a medium with $v = 0.25$.

⊙ See Richart and Woods (1987).

Since the **P-waves** are the fastest, they will arrive first followed by **S-waves** and then by surface waves (**R-wave**).

Miller and Pursey (1955)[⊕] determined that the distribution of total input energy of the three elastic waves at the ground surface due to point surface excitation as

P-wave	S-wave	R-wave
7%	26%	67%

This suggests that for a near surface source the Rayleigh wave dominates the particle movements near or at the ground surface and causes the major disturbance to the structural foundations.

The amplitude of vibrations caused by blasting is mainly controlled by the charge weight and the distance from the source of blast. The above relation can be expressed as

$$v \propto \left(\frac{\sqrt{W_o}}{r}\right)^n$$

Where v : the amplitude of particle velocity

W_o : weight of the explosive

r : distance from the source

n : constant

Other factors such as type of explosive, type of the ground, depth of the holes and spacing, and sequence of detonation, also exert a significant effect on the amplitude of the transmitted vibration.

2.6.2 Attenuation of Traffic Vibration

The form of attenuation of the vibrations caused by road or rail traffic is similar to that of blast vibration. However the magnitude of the input energy is relatively small, and hence the induced vibration has a small local effect. The source of the vibration is at the contact points of the wheels and the ground surface or rail. The amplitude of vibration is affected by the weight, type and speed of the vehicle or train, the roughness of the road or track and the radial distance from the source.

⊕ See Richart, Hall & Woods (1970)

2.6.3 Attenuation of Pile Driving Vibration

When compressional energy is transferred to a pile-head by means of an impact hammer, rather complicated wave fields will be generated within the driven pile and the surrounding area. Figure (2.8) (after Attewell and Farmer (1973)) illustrates the vibration attenuation from a typical pile driving operation where there is a uniform distribution of the body waves around the pile toe. It could be argued that because the input energy by the hammer has a downwards direction, it is expected to have non-uniform distribution of the transmitted energy around the pile-toe, as shown in figure (2.9) where the maximum concentration of the transmitted energy is in the location below the pile toe while the minimum energy content is vertically above the position of the pile-toe.

After each impact, the generation of three types of elastic waves, *compressive-wave, shear-wave* and *surface-wave* can be recognized. The transmission of these waves and their attenuation in the ground is explained in the following sections. It is assumed that both pile and soil are behaving as elastic medium.

1. *Compressive-wave*†:

Most of the transferred energy from the hammer into the pile travels through the pile as a **P-wave** at a constant speed of $c \approx 5200m/s^{\oplus}$. At the pile-toe, and at the soil-pile interface, some of the energy will be reflected back up the pile and some will be transmitted into the surrounding soil. The amplitudes of the reflected and transmitted waves are dependent on density and wave velocity in the two media. Attewell and Farmer (1973), suggested that the ratio between the transmitted and the reflected waves is approximately 2 to 1.

The **P-wave** transmitted to the ground medium will propagate radially outwards from the toe of the pile along a spherical wavefront. When the **P-wave** reaches the ground surface there will be reflected **P** and **S_v-waves** and a surface wave (see Appendix (A1.2)). Because of the great difference in density between the ground

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† The phrase **P-wave** is used instead of *compressive-wave* in this section.

⊕ This is the sonic wave velocity in steel.

and the air, most of the transmitted P-wave will be reflected.

2. *Shear waves*

The passage of the compression wave down the pile causes the generation of shear waves at the friction surface of the pile-soil interface (see figure (2.9)). Because of the earlier transmission of the wave at the pile-top compared with that at the pile-toe, an inverse conical wavefront will be formed around the pile as shown in figure (2.9). The cone will have a narrow angle to the vertical as the following calculations show.

Let the wave velocity in the steel pile $c = 5200m/s$ and wave velocity in the soil $v = 300m/s$. If the pile depth $d = 10m$, then the wave will reach the pile-toe at time $t = d/c = 0.0019sec$. At the same time the wave transmitted to the soil at first pile-soil contact will travel distance $x = vt = 300 \times 0.0019 = 0.577m$. Then

$$tan \quad \alpha = \frac{x}{d} = \frac{0.577}{10.0} \qquad and \qquad \alpha = 3.3^{o}$$

The amplitude of the shear-wave generated by frictional contact along the surface of the pile-shaft-soil interface is a function of the pile length, pile cross-section (boundary of the pile-soil interface), the method of pile driving (vibrodriver or impact-hammer) and the ground conditions. It can be expected that a greater shear-wave component from this source may be generated during the driving of a number of interlocked sheet piles where a larger section of the pile is in contact with the soil than when driving an H-pile. Similar deductions may be made for the driving of large tubular piles and concrete piles. The use of a low frequency vibrodriver may also generate grater frictional shear wave vibration than will an impact hammer when driving in a similar granular soil. Finally, soil properties such as density, degree of saturation and degree of cohesion have a direct effect on the generation of vertical shear waves around the pile-shaft. It seems that more energy will be transmitted into a clay soil than into sands in this way.

3. *Surface wave:*

This wave is transmitted close to the ground surface and propagates radially outwards. This wave might be generated from the pile shaft near the surface either by friction or by whip. Surface waves can also be generated from the refraction of body waves at the ground surface. It will be shown that close to a driven pile, there is a zone in which surface waves are dominant over body waves from the toe. When the pile toe is near the surface, the waves measured at the ground surface are predominantly **"surface waves"**. When the toe is deep, there will be a zone close to the pile in which **"surface waves"** predominate, but at greater distances the **body waves** from the toe become dominant. The terms **"surface wave"** is used in preference to **"Rayleigh-wave"**, since the form of measured waves is not of the pure, classical, retrograde ellipsoid.

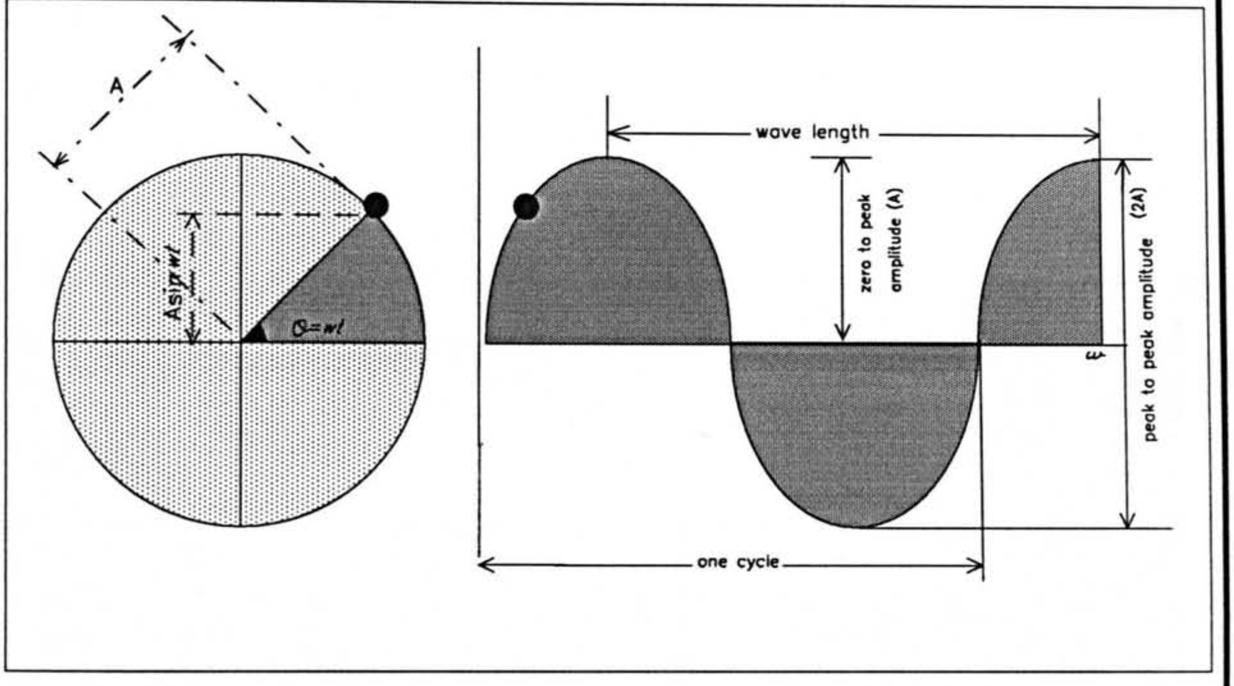


Figure (2.1) Characters of a simple sinusoidal vibration

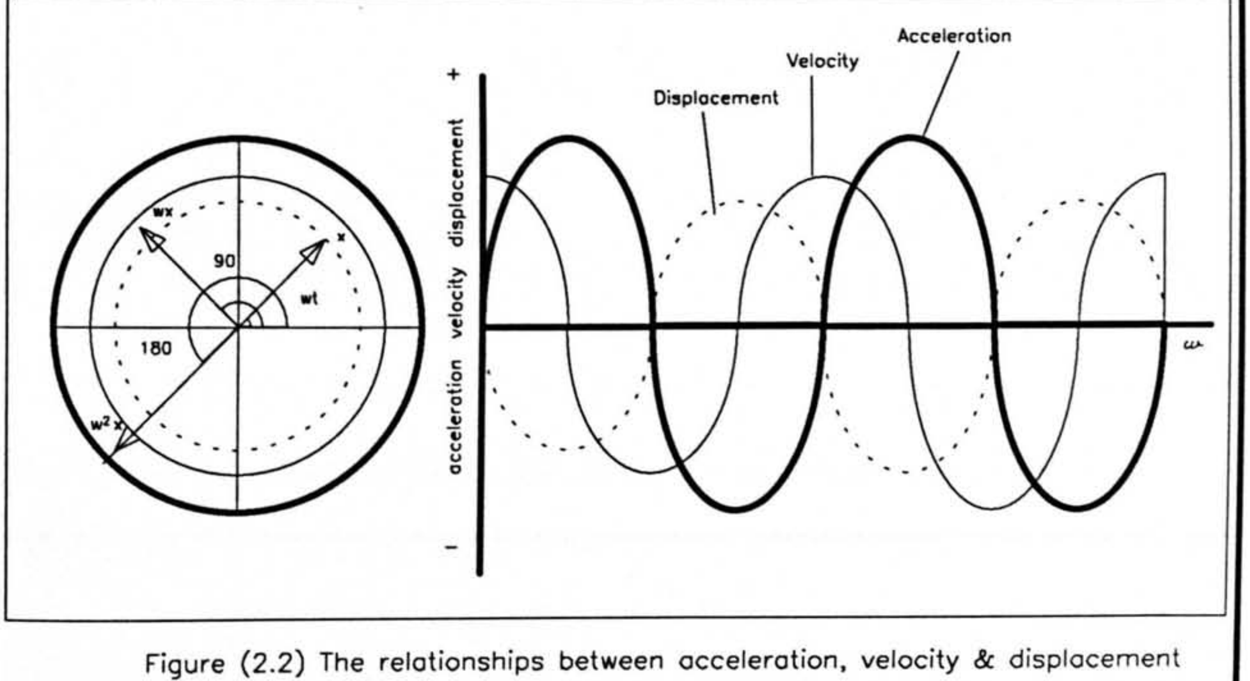


Figure (2.2) The relationships between acceleration, velocity & displacement

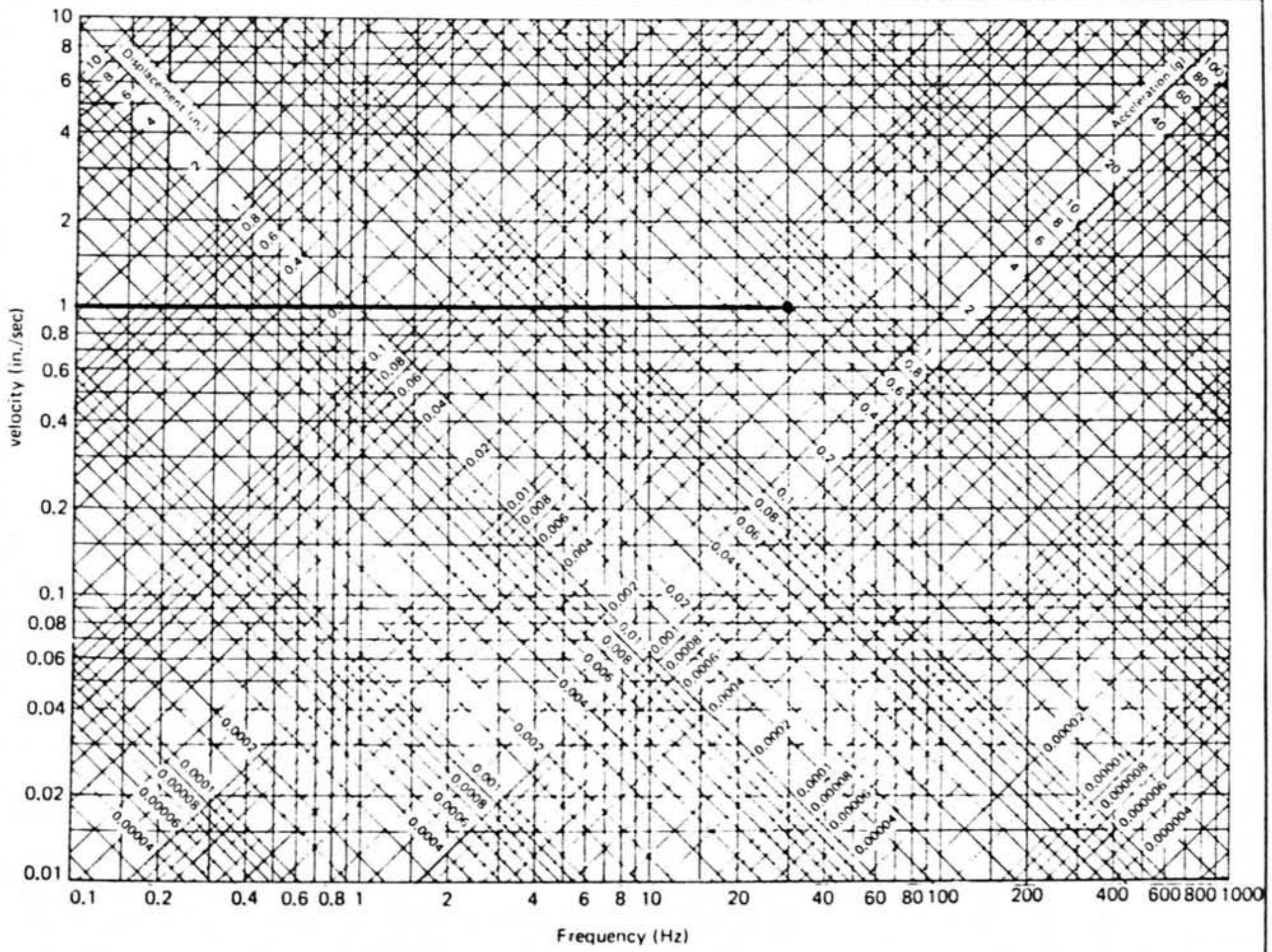
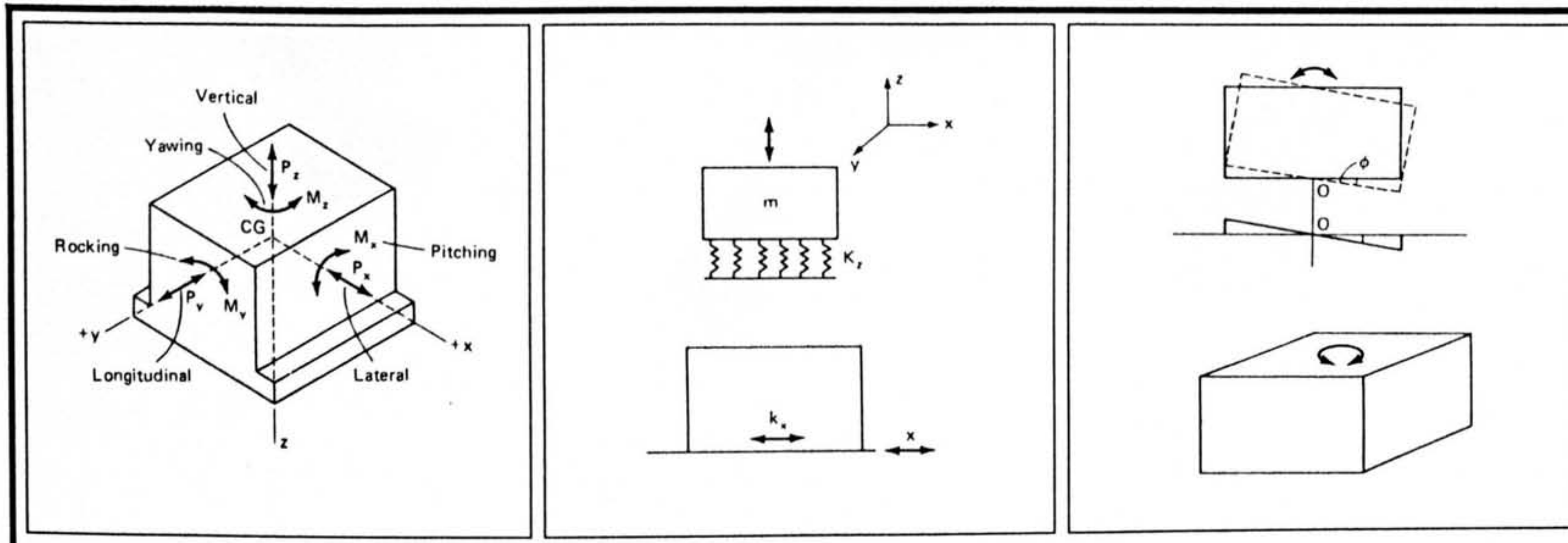


Figure (2.3) The use of a vibration nomograph for determining relevant quantities



Directional axes of block vibration

Translation of a block along x, y & z axes

Orientation of a block along x, y & z axes

Figure (2.4) Degrees of freedom of a rigid block

after Prakash 1981

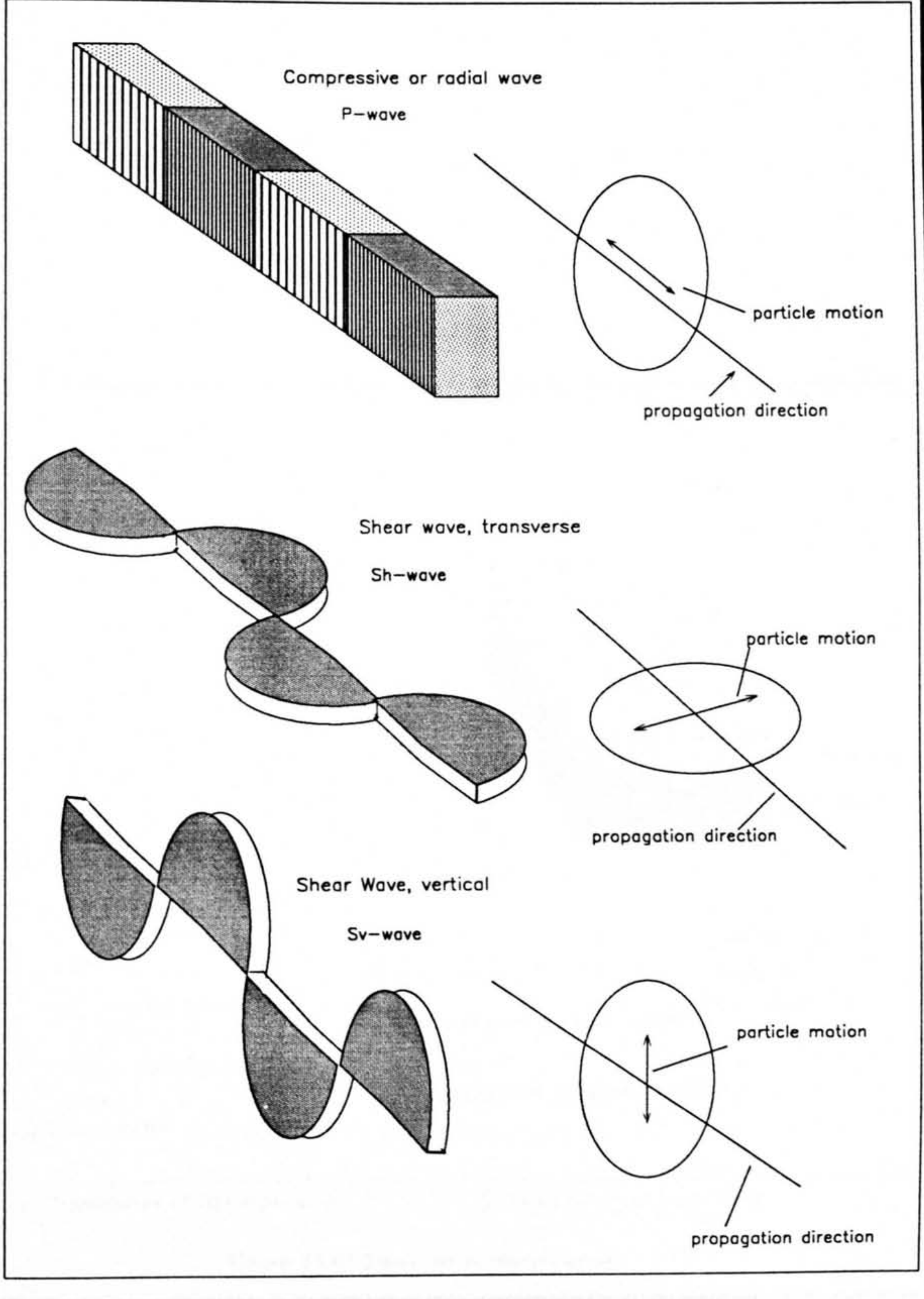
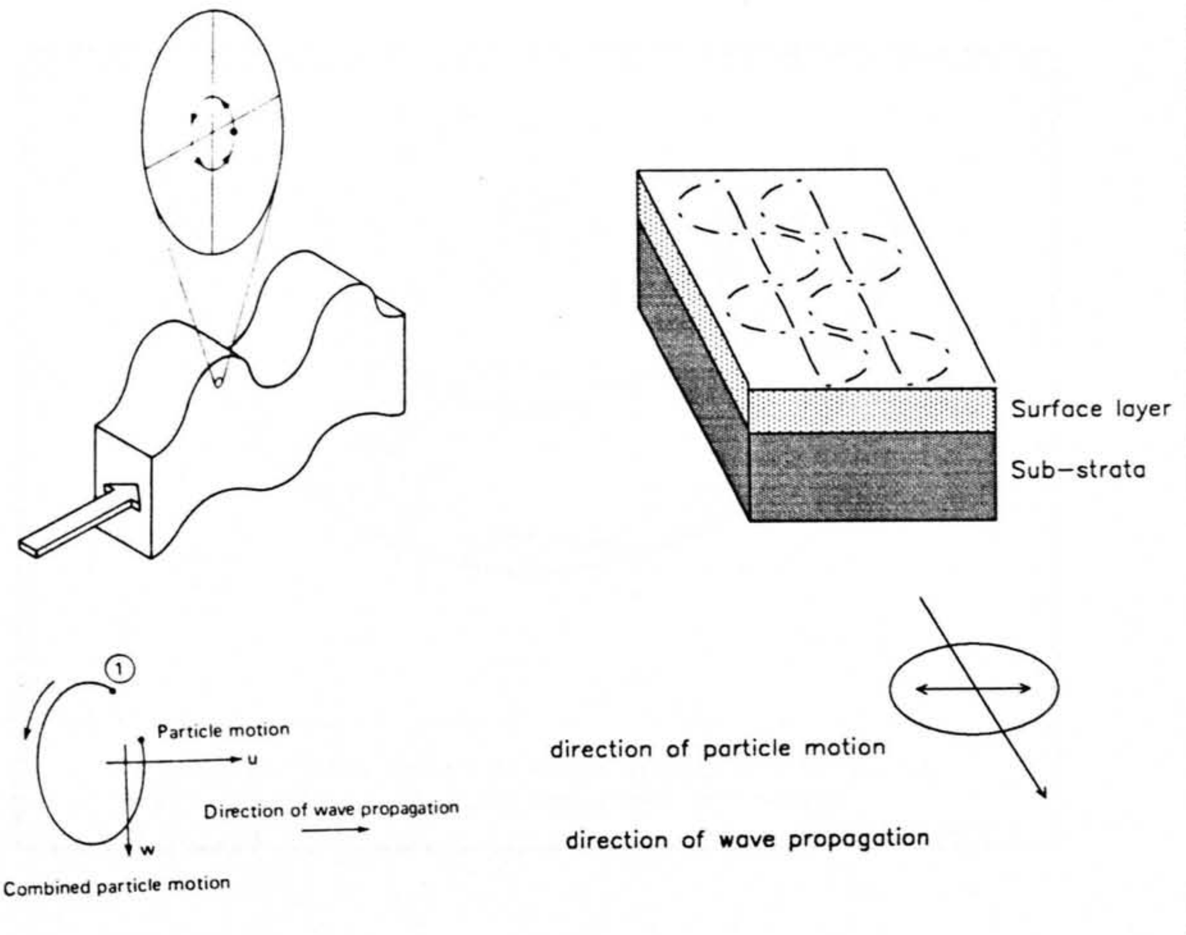


Figure (2.5) Display of different types of body-waves



a. Propagation of Rayleigh-wave b. Propagation of Love-wave

Figure (2.6) Types of surface-wave

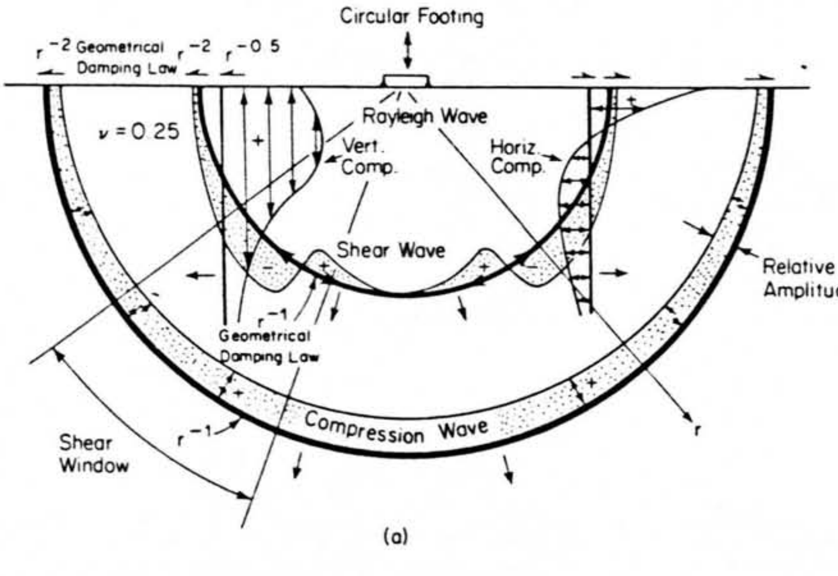


Figure (2.7) Attenuation of waves from a circular footing on homogeneous, isotropic and elastic half–space

after Woods 1968

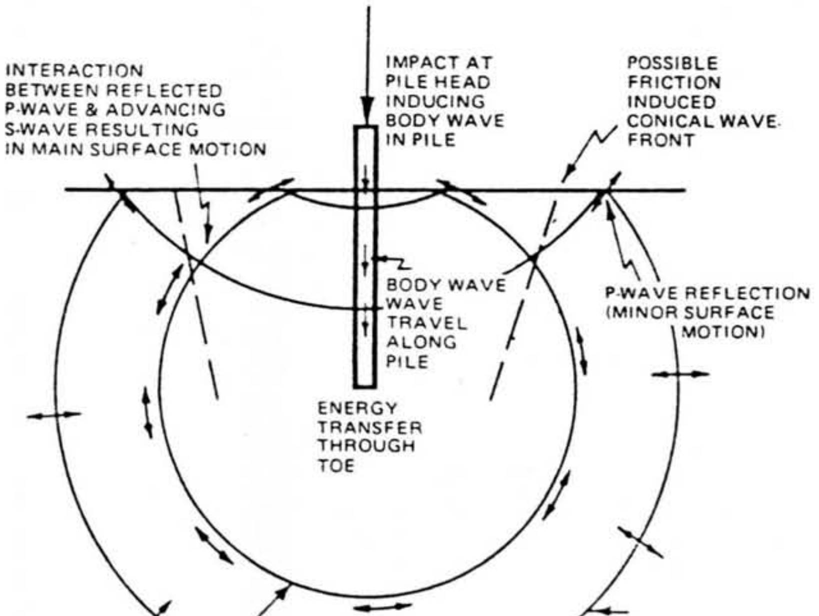


Figure (2.8) attenuation of waves from a pile driving operation

after Attewell & Farmer 1973

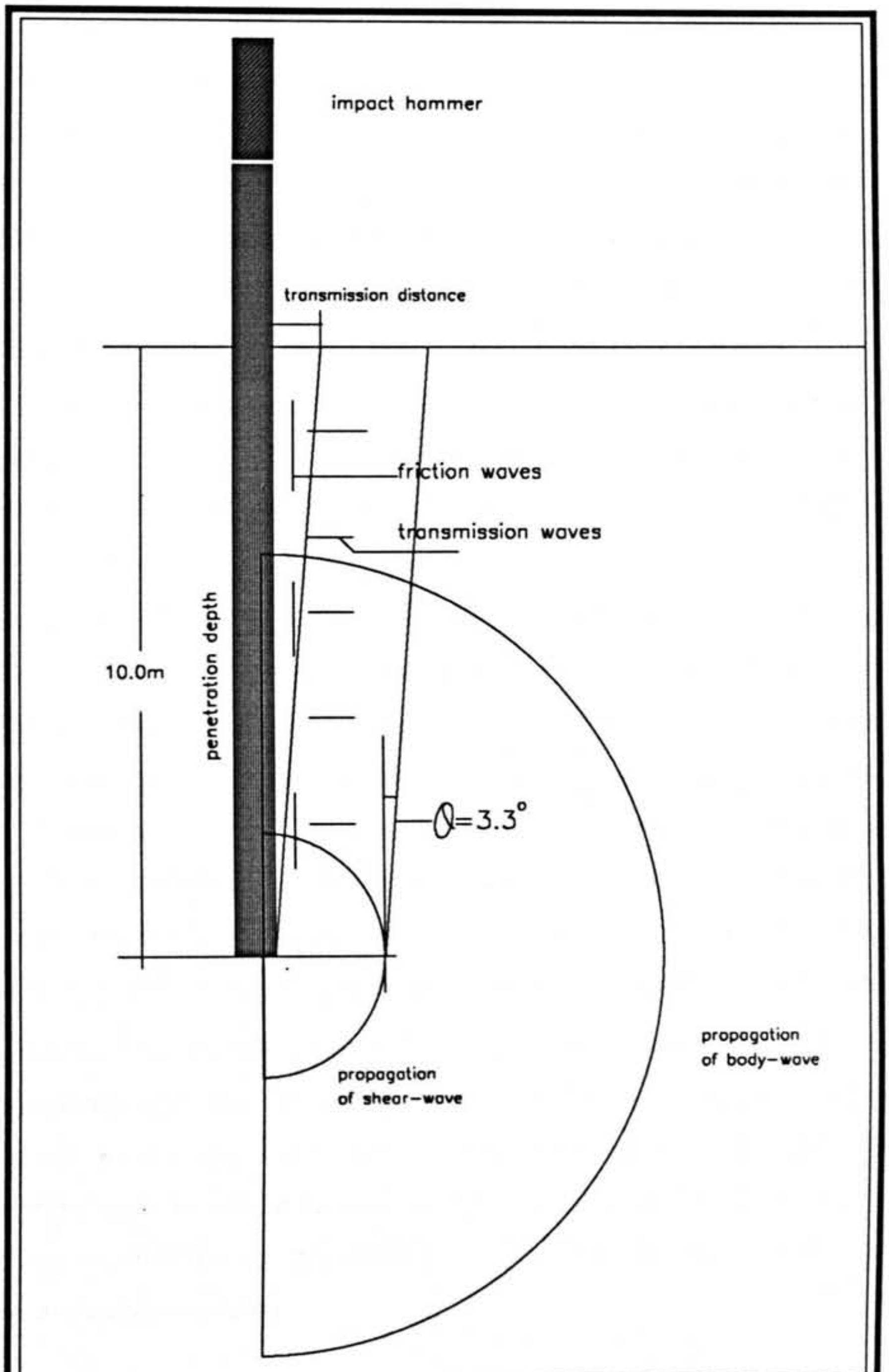


Figure (2.9) Wave transmission from a pile driven by an impact-hammer

Chapter Three

3. Sources of Ground Vibration

3.1 Introduction

Ground vibrations can be generated from a number of different sources. These sources can be either *natural*, for example earthquakes, liquefaction, slope-instability, ground settlement and wind, or *artificial*, such as civil engineering activities, mine and quarry blasting, traffic vibration(road, rail, aeroplane) and military activities.

Natural vibrations normally occur when a large magnitude of energy is released in a very short period of time, and severe damage may be caused to buildings and structural foundations. On the other hand, artificial vibrations (except those associated with military activities) occur frequently while their effects are less damaging and potentially controllable.

The maximum energy released from an artificial source (excluding a nuclear blast) is up to 10^9 joules†, while a medium sized earthquake can release energy of 10^{12} joules (Skipp (1984)). The energy released by an earthquake may cause two types of displacement on the ground surface: *permanent* and *transient* (Ambraseys *et al* (1984)). Faults are typical examples of permanent displacement which are caused by the lateral movement of the crustal surface. Some of the faults are active and their activities should be considered for any construction design. The transient displacements are caused by the propagation of seismic waves through the ground.

The frequencies of vibrations induced by natural sources are usually much lower than those caused by artificial vibration. For example, the dominant frequencies of earthquakes are in the order of 1-10Hz and those of wind 0.005-0.5Hz (Waller (1969)), while recent studies of the vibrations recorded from artificial sources showed a frequency range of 10-50Hz for rail traffic, 15-50Hz from quarry blasting and 16-85Hz from pile driving operations.

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† Impact energy of explosion used to demolish a cooling tower of 6000 tonnes weight

The important aspects of any study of ground vibration include considerations of their effects on buildings and other structures coupled to the ground. The first step in any vibration problem is to study the source of vibration, its magnitude and its method of propagation.

The aim of this chapter is to describe the generation of vibration from some specific artificial sources including pile-driving, quarry blasting and traffic. Attention is focussed particularly on vibrations associated with pile driving activities, where the effects of pile type, hammer type and ground conditions on the generation of vibrations are considered and a full description of these variables is given. Finally a brief review is made of the vibrations caused by blasting and by road and rail traffic.

3.2 Vibration from Pile Driving

Pile driving works frequently form one of the main sources of ground vibration, particularly in urban areas, where the recent developments towards medium and high rise buildings has led to increasing use of piled foundations. The piled foundation (or deep foundation) is a method used to carry the structural loads by a number of piles to lower levels of ground which are capable of sustaining the applied load. The piles are usually driven into the ground by means of driving hammers. The designs of many types of hammers have been developed in recent years to enhance the driving performance and to minimize the induced ground vibration during their operations.

During pile driving, a falling hammer transfers energy into the pile-head at impact and advances the pile into the ground. The transferred energy then travels down through the pile and some of the energy transmits to the surrounding soil through the pile-toe and some through the pile-shaft. The transmitted energy propagates throught the soil as body waves and the measurements of the vibration at the ground surface may help to evaluate their magnitudes. The magnitude of the vibration caused by pile driving operation is controlled primarily by three factors: *pile type, hammer type & ground conditions.*

Records of ground vibrations were taken during driving different types, size, weight and length of pile by a wide range of driving hammers in different types of ground conditions. Typical levels of ground vibration recorded within 10m from the location of piling activities were in the range of 5-25mm/s at frequencies between 15-60Hz.

A brief description of classifications, dimensions, properties and functions of different types of piles, hammers and ground conditions, is given in the following sections.

3.2.1 Types of Pile

Piles are structural members that are made of either steel, concrete, or timber. They may be used to construct piled foundations, which carry the superstructure load to deeper and stronger strata. The purpose of the use of piles is to increase the bearing capacity and to reduce the settlements of a foundation in weak compressible soil. They may also be employed for the construction of land reclamation and sea defence works. Plate (3-1) shows the use of steel sheet-pile as a permanent retaining wall along a river bank in Workington and plate (3-2) shows a steel H-pile under static load test which was to be used as an end bearing pile for bridge foundation in Blaydon.

Different types of pile have been developed to suit the construction conditions such as the type of the load to be carried, the subsoil condition, and the ground water level.

Generally, piles may be classified with respect to the way in which the load is transferred to the soil either as *friction piles* or *end bearing piles.* In friction piles, the applied load is transferred to the surrounding soil mainly through skin friction on the shaft of the pile, although a part of the load is carried by the pile toe. For end bearing piles, the pile is driven down to a layer having a high bearing capacity and therefore the applied load is transferred from the pile to the surrounding soil mainly through the pile toe.

According to British Standard BS 5228:part:4,(1986), piles are classified with respect to their functions either as *load bearing piles* or *retaining piles.* The load bearing piles include *jacked, driven & bored* piles, while the retaining piles include *sheet-piles, diaphragm-walls & secant piles.* Figure (3.1) illustrates the **British Standard** classification of different types of pile.

Piles may also be classified as *displacement piles, small-displacement piles* or *non-displacement piles.* The soil around a displacement pile is disturbed and displaced laterally during the pile driving, (for example, precast concrete, timber, and close ended steel piles). The properties of the surrounding soil change, showing local compaction in cohesionless soil and reduction of the shear strength in cohesive soil. Small displacement piles, such as H-section and sheet steel piles, cause small changes in the strength and properties of the surrounding soil provided that these do not plug. In the case of non-displacement piles, the volume of excavated soil corresponds to the volume of the pile, as in augered or bored piles and drilled casings.

Piles may also be classified with respect to the installation method as *driven piles, jacked-down piles, cast-in-place piles* and *screw piles.* Driven piles are installed using one of a range of types of hammer (see section 3.2.2). Hydraulic jacks are used for the installation of jack-down piles. For cast-in-place piles, the soil is first excavated for the pile and the resulting hole is filled with concrete. It is also possible to screw piles into the ground, but this method is more commonly used for augered ground and grouted piles.

According to their material, piles may be divided into the following categories: *Steel piles, Concrete piles, Wooden (timber) piles,* and *Composite piles.* The details of this classification are included in Appendix (A2).

3.2.2 Types of Hammer

Driven piles are installed into the ground by means of a hammer. The hammer is a device used to input sufficient energy to the pile in order to drive it into the ground. There are many types of hammers available to suit driving different types of piles in different ground conditions. The selection of the most effective type of hammer for a given task involves a consideration of the length and weight of the pile, and the condition of the ground. Redhead (1986), suggested that the selection of a successful driving hammer depends on the following factors:

- dimensions, size, type and length of pile.
- soil conditions.
- site conditions.
- working load and factor of safety.
- whether piles are vertical or raking.
- any special requirements.

Figure (3.2) shows a pile driving assembly using drop hammer, in which, a *Leader* has the function of holding and guiding the pile and hammer at its correct alignment from the stage of first pitching in position to its final penetration. A *Cap (helmet)* which is made of cast steel, is attached to the top of the pile to protect the pile-head from possible damage caused by the hammer during the driving. A *Cushion or Dolly* may be used between the pile-head (ram) and the cap to reduce damage from the hammer impulses. Both cushion and dolly are made of wood or plastic. The *Ram* is the rising and falling part of the hammer which delivers the blow.

The principles of the different types of hammer are described below. For more information about the dimensions and performance of each hammer, a reference should be made to the manufacturers handbooks and the available textbooks, for example, Fleming *et al* (1985), Harris (1983) and Tomlinson (1977). In the following section, the hammers are classified into two main types: *impact hammer* and *vibratory hammer.*

3.2.2.1 Impact Hammers

Impact hammers give the traditional method of pile driving, in which a hammer weight causes an impact by falling through a certain height on to the pile head or mandrel. The simplest type is the winch operated drop hammer but other methods of driving hammers have been developed using different sources of power such as diesel, steam, air and hydraulics to speed up the number of strikes per minute and to enhance the efficiency of the blow.

The notional input energy of most impact hammers can be calculated by multiplying the drop weight by the falling height which may be expressed as:

$$\texttt{ram mass} \times \texttt{g} \times \texttt{drop height} = \text{kg} \times 9.81\text{m.s}^{-2} \times \text{m} = \text{N.m} = \text{J}$$

For effective pile driving, the weight of the hammer should normally be between 0.5 to 2 times the weight of the pile (see section 3.2.2.3). The overall efficiency of the hammer may be affected by the presence of friction between the hammer and the guide, hammer-pile mis-alignment and some other weakness of the hammer performance. The method and performance of the most frequently used types of hammer are explained below.

a. Drop Hammer

The drop hammer is the traditional and the simplest method of driving which has been widely used for driving piles since ancient times. Today drop hammers are successfully used to drive all type of piles including steel piles, concrete piles and timber piles, in all types of ground conditions. Basically, the drop hammer consists of a solid mass usually made of cast steel, ranging in weight between 0.5 tonne to 5.0 tonne. The mass is suspended by a rope or cable running over a pulley to a winch which can be operated by a diesel-engine or using the motor drive supplied by the crane. The hammer is raised to a certain height above the pile head, either in a guide or suspended from the lifting rope of a crane, and is then released to fall free and strike the pile head. The height of the drop is usually between 0.2-2.0m depending on the condition of the ground, and can be adjusted through the driving machine. Different parts of a typical drop-hammer are shown in figure (3.2).

Drop-hammers are relatively slow in operation and can achieve a maximum of only 12-18 blows per minute. The striking rate decreases with the increase of drop height and hammer ram weight. When driving in stiff ground, the hammer may cause damage to the pile head. Also, the heavy blows of the hammer may have some effect on the driving equipment, such as leaders, driving caps, cranes and winches, mainly through wear to winches and clutches. The notional energy of some drop-hammers is listed in table (T3-1).

Measurement of ground vibration was taken during the operation of this type of hammer in the driving of concrete piles in Whalley and Selby, and steel H-piles in Newark.

b. Steam & Air Hammers

Steam and air hammers are another type of impact hammer which employ compressed air or steam for operation. The steam/air hammer consisits of a ram, and a piston which can move up and down inside an enclosed cylinder. The compressed-air or steam is used to actuate the piston which moves the ram to a certain height in the cylinder and then falls under the action of gravity forces. This is the case of the single acting steam/air hammer. But for the double acting hammer, the downward force on the ram is a combination of the weight of the ram in free fall, and the input energy from the release of compressed air or steam in the upper part of the cylinder. By switching the air supply to the lower part of the cylinder, the piston is raised upwards and the air/steam in the upper cylinder is compressed, so the driving is continued. Figure (3.3) shows the components and the operation of a double acting air hammer. The movement of the ram inside the cylinder may be affected by the presence of friction, which reduces the hammer efficiency.

Single acting air hammers are usually available in a wide range of ram mass and striking rate of 40 blows per minute. Double acting hammers use a relatively light ram weight of 0.9 to 1.5 tonnes but they achieve a high strike rate of up to 300 blows per minute. The input energies and other relevant specification of some air hammers are displayed in table (T3.2).

Air hammers usually are used for driving all types of pile, especially steel bearing and sheet piles, in granular and gravelly soils. The heavier types of the hammer are also used in driving long H-piles deep into the ground. Ground vibrations were measured during the operation of these hammers on several different sites. The results showed relatively small levels of vibration in comparison to other types of impact hammers. The most serious drawback of the hammer is the very high noise level generated during its operation; this may cause some disturbance to people when the hammer is used in residential areas.

c. Diesel Hammer

The diesel hammer is a form of impact hammer which uses air and atomized diesel fuel to provide the energy to drive the pile. The hammer is a self contained unit that includes both a fuel tank and driving ram, so that no additional power pack is needed, and it can easily be mobilized. There are many models of diesel hammer in the market but all are based on same technique. The operation technique of a **Delmag** hammer is demonstrated in figure (3.4). The different stages of the hammer operation are described below (see **Delmag**(1988)).

1. *Starting*: the ram (piston) is raised by means of a top rope to a given height and then released.
2. *Fuel injection*: the piston falls, actuating the pump lever and a quantity of diesel fuel is injected on top of the impact block. The piston then starts to compress the air in the cylinder chamber.
3. *Explosion*: diesel fuel inside the cylinder atomizes by compression of the piston on the impact block. The atomized fuel ignites in the highly compressed air. The resulting explosive energy pushes the pile further down which is already moving downwards under the blow of the ram, and also accelerates the piston upwards.
4. *Exhaust*: while moving upwards, the exhaust ports open and exhaust gases then escape, equalizing the pressure in the cylinder.
5. *Repeating*: as the piston moves upwards, clean air is drawn in through the inlet ports, while releasing the pump lever. The pump lever returns to its starting position, and the operation continues.

As described above, the single acting diesel type allows free fall of the ram, while in a double-acting diesel hammer, the downward movement of the ram is accelerated by the compressed air pressure in the upper part of the chamber. The upper part is enclosed so that air is compressed as the piston moves upwards. When the piston reaches its highest position in the chamber, the compressed air drives it down again. By this means a more rapid rate of strokes per minute can be achieved. The striking rate of a single acting diesel hammer is normally in the range of 40-50 blows per minute while the double acting diesel hammer can achieve a maximum of 80-100 blows per minute. The striking rate and energy increase as soil resistance to pile driving increases.

Research carried out by **Delmag** (1988), identified three forms of energy during the impact of a diesel-hammer. These energies together with their functions are listed below:

- *compression energy:* this holds the helmet tight on to the pile head.
- *impact energy:* a portion of this energy is transferred to the pile head and forces the pile into the ground.
- *driving energy:* this is caused by explosion of the expanding gases in the chamber, and drives the pile downwards into the ground and rebounds the ram upwards into the chamber.

Diesel hammers are suitable for use in stiff cohesive soils. In loose granular cohesionless soils the input energy absorbed by the soft ground may allow insufficient impact for fuel ignition in the chamber, so no hammer rebound occurs and the driving must be restarted. The hammer can be used on all types of piles particularly steel-piles. The input energy by the diesel hammer is proportional to the pile resistance and hence to the stiffness of the ground material. A summary of the notional input energy ranges of different models of diesel hammer is given table (T3-3).

Diesel hammers with relatively lighter rams may be less efficient than a drop hammer, but the loss of efficiency can be compensated by the faster strike of the hammer. Also the use of the hammer with a heavier striking ram may cause some deformation and damage to the pile head. The level of noise produced during the operation of this hammer is much higher than that produced by drop-hammer.

d. Hydraulic Hammer

The hydraulic hammer is becoming one of the most widely used impact hammers in the construction of piled foundations in Britain. Different models of hydraulic hammer are available, but the hammer in most common use is the BSP-357 which is designed and supplied by *British Standard Piling.* The hammer provides a choice of three drop weights; 3, 5 & 7 tonnes.

The hydraulic hammer consists of a *hydraulic actuator, ram weight, support cage, power source* and *control panel.* The piston in the hydraulic actuator is connected to the ram weight and lifts the ram upwards hydraulically to a selected height which then drops under free fall condition, see figure (3.5). The hammer cage supports the actuator and guides the ram weight on to the pile head. The standard ram weight is 3 tonnes mass which can be extended to 5 and 7 tonnes by adding additional segmental weights of 2 tonnes.

The hammer system is remotely controlled by an electro-hydraulic system which allows for both manual single blow operation and fully automatic mode. The drop height of the ram can be varied from 0.2-1.2m and the height can be adjusted even during cyclic driving. When an automatic sequence is chosen, the hammer blow rate will normally be in the region of 40 blows per minute at maximum stroke height. The hammer is powered from a separate diesel hydraulic power pack. The input energy per blow varies between some 10kJ upto 82kJ depending on the weight of the ram and height of the fall. A list of the notional energy of some hydraulic-hammers is given in table (T3-4).

This type of hammer is suitable for driving long and heavy piles for deep penetration, and has been operated successfully on many sites. However some minor difficulties in operating the hammer have been observed on some sites, involving the hydraulic pressure hose to the hammer which occasionally fails. The hammer can be operated on a piling lead, a piling frame, or freely suspended from a crane. Special equipment can be added to the hammer to make it suitable for under water work. Also a sound damping case can be built around the striking area to reduce the noise level.

3.2.2.2 Vibratory Hammer

The vibratory hammer, or vibrodriver, is a type of hammer which introduces continuous sinusoidal vibration into the pile and the ground during its operation. This method is used to reduce the pile soil interface friction and toe resistance in the procedure of driving. The hammer is suitable for driving most types of pile in granular and cohesionless soil deposits.

History

The vibrodriver was originally employed and developed in Russia in the 1930's. A high speed vibrodriver running at 3000 rpm was developed in 1948 and mainly was used to drive large tube piles. The method was later adopted in Germany and then France and different prototypes of the hammer were built and developed which were then introduced to the market. Now a wide range of different models is available with various ranges of input energy and frequency. Recently, the vibrodriver has become a popular choice among pile driving contractors, especially when piling is to be undertaken in residential areas where low noise and vibration levels are demanded by the local authorities.

Advantages

The main features of a vibratory hammer are listed below:

1. Can be used both for driving and extraction.
2. Produces low piling vibrations.
3. The driving noise is low.
4. It achieves rapid driving in granular conditions.
5. There is low risk of damage to pile head.
6. Light weight in comparison to impact hammers.

However, in loose soil it may cause compaction and settlement. Also severe vibrations may occur during run-up and run-down, and if an obstruction is encountered.

Classification

Weisflog (1967) has classified the vibrodriver into two groups as follow:

- **Sub-sonic Vibrodrivers** which operate at frequencies of between 6-50 cycles per second.
- **Sonic Vibrodrivers** which work at frequencies up to 140-150 cycles per second.

According to **PTC Vibrofonceur** (1986), the vibrodrivers are also classified regarding their driving frequencies as *standard* and *high frequency or City* vibrodrivers.

The vibrodrivers may also be classified with respect to their components either as *multi-unit* or *single-unit* vibrodrivers. In the following sections the vibrodrivers are classified according to their driving power as *standard vibrodriver* and *hydraulic-vibrodriver.*

a. Standard Vibrodriver

These vibrodrivers comprise three separate units: a vibro-hammer, a power pack and pressure cables. The vibro-hammer consists of several pairs of eccentric masses rotating at the same angular velocity in opposite directions. Each eccentric mass produces a centrifugal force f_c, in which the horizontal components f_h of the centrifugal forces cancel each other out while the vertical components f_v are additive giving a vertical resultant F_c, and causing reciprocating force of the hammer. The mechanism of the hammer operation and the components of a vibrodriver are illustrated in figure (3.6). The vertical forces are at their greatest when the eccentrics reach the top or bottom position. If each eccentric mass is expressed as $m/2$ and their position from the centre of the mounting shaft is e, then f_v at top and bottom position is;

$$f_v = \frac{1}{2} m e w^2$$

$$\text{and} \quad F_c = f_v + f_v = m e w^2$$

where w is angular velocity of the eccentric masses

When the eccentrics are at some angle described as ωt from the vertical, then f_v is given by

$$f_v = mew^2 sin(wt) = f_c sin(wt)$$

Figure (3.6) also shows the relationship between the applied force and the amplitude of the wave generated during the operation of the hammer.

A pair of hydraulically adjustable clamping jaws allows the hammer to fit onto different sizes and profiles of pile head. Spring or shock absorbers are used to prevent transmision of the vibration from the hammer to the crane carrier. The whole unit is housed in a steel case and suspended from the lifting rope of the crane. The operation of the hammer and control of the running frequency, and the action of the clamping device can be done through a hand held remote control device. The rotating masses are driven either by electric motor or more commonly by hydraulic action.

The basic principle behind this type of hammer is to reduce the friction forces between two moving elements (pile and soil) by applying vibration to the pile through the hammer. The applied vibration causes a temporary state of instability or liquefaction in the surrounding soil which causes reduction of friction at the pile-soil interface. The pile is then driven down under the combined weights of the pile and hammer assembly.

Vibrodrivers are suitable for use in cohesionless soils, and as the soil cohesion increases the driving becomes less effective. They may also be used in saturated silty cohesive soils. Some vibrodrivers may be operated under water. These hammers can drive sheet piles or H-piles up to 20m in length.

A summary of hammer specifications is given in table (T3-5).

b. Hydraulic-vibrodriver

The principle of operation of this vibrodriver is similar to that described in the previous section, but here there is an additional force supplied by a hydraulic power pack acting in the vertical direction which is used to enforce the vertical movement of the hammer and consequently the pile during the driving and extracting procedure. The hammer can be used in drilling when it is fitted with special devices. The driving frequency of the hammer is in the range of 50Hz, and so produces a lower level of ground vibration and noise.

The only model available in the UK is the ABI Mobilram System. The input driving energy at 50Hz varies between 1.0-2.4kJ/cycle for the range of sizes and weights, see table (T3-5).

These vibrodrivers are relatively small and light weight. The whole driving system including the hammer, hoses, power pack and the tracked carrier unit are integral. All the site activities can be controlled from the driver's seat. They are suitable for driving sheet piles up to depth of 14m in granular soils and they are particularly suitable for pile driving in residential areas.

3.2.2.3 Pile-driving Formulae

The principle of any pile-driving formula is based on the calculation of an energy balance between the effective energy used to drive the pile down, and the wasted energy. The loss of the energy depends primarily upon the elastic compression of the pile, with secondary losses dependent upon soil type, pile type, hammer type and the hammer-pile alignment.

The hammer-pile alignment is essential for delivering the impact energy to the axial line of the pile, and in this case the driving will be most efficient; otherwise the applied energy will be lost in the contact of hammer-pile which may cause some damage to the pile head.

The applied driving energy from the hammer to the pile can be assessed using different driving formulae methods. In practice, one of the simplest methods is the calculation of pile set (pile penetration) per blow. If an increase of resistance occurs during the early stages of driving, this may be attributable to a boulder, rubble, roots, etc. If the driving resistance is increased during deep pile penetration, this could be due to driving in hard stratum or rocks. In both cases the driving should be immediately stopped otherwise the input energy may cause some damage to either pile-head or pile-toe.

There are many driving-formulae in use and most of them are reviewed by Chellis

(1961), Whitaker (1976) and Fleming *et al* (1985). In the following sections, some driving formulae are discussed.

a. Static Analysis

A schematic diagram of the pile driving process is shown in figure (3.7a). After each hammer blow, the impact energy transferred by the hammer head to the pile causes the pile to penetrate into the ground. There will be some elastic resistance from the soil to the pile displacement which increases as the pile is driven deeper and remains constant for further displacement and then falls to zero as the pile rebounds. The sequence of the above events is shown in figure (3.7b), where the line OABC represents the resistance-displacement diagram. The area OABD represents the total energy supplied by the hammer to displace the pile to the maximum penetration OD, the area BDC represents the elastic energy used to rebound the pile and the input hammer energy just before the start of penetration can be represented by area OAE. The effective energy employed to achieve the final displacement OC, is represented by area OABC. Then the total work done(OABD) is

$$\mathrm{OABD} = \mathrm{OABC} + \mathrm{BDC}$$

$$W_h h = R(s + c/2)$$

or

$$R = \frac{W_h h}{(s + c/2)} \qquad 3.1$$

Eq(3.1) was published by Wellington in 1888† and is known as *the Engineering News Formula.* Hiley (1925)† modified the above formula and assumed that there are losses of energy in the driving system during the impact due to elastic compression of the pile c_p, elastic compression of the cushion c_c and elastic compression of the ground or quake c_q. Then the driving resistance will have the following form:

$$R = \frac{\eta W_h h}{(s + c/2)} \qquad 3.2$$

† See Whitaker (1976)

Eq(3.2) is known as Hiley's formula, where

R : is the pile resistance

η : is the hammer efficiency

W_h : is the hammer weight

h : is the drop height

s : is the pile set per blow

c : is the elastic movement of the pile, soil & cushion per blow

or $c = (c_p + c_c + c_q)$

In America, various empirical values are given for c and η. For example, for a drop-hammer $c = 1.0\mathtt{in}$ (25.4mm), and for single acting steam-hammer $c = 0.1\mathtt{in}$ (2.54mm), and the value of hammer efficiency η is adopted from the hammer rated energy supplied by the manufacturer's reports (see Chellis (1961)).

In Europe, both c and η are chosen with regard to the type of hammer, the material used as a cushion, and the pile properties. The value of η can be estimated from the following equations:

$$\eta = \frac{k(W_h + e^2 W_p)}{(W_h + W_p)} \qquad 3.3$$

where W_p : is the pile weight

k : is the output efficiency of the hammer

(ratio of energy delivered at the cushion, to rated energy)

e : is the coefficient of the hammer-pile restitution

The value of η can also be derived using the principle of conservation of momentum. According to that theory, the sum of momentum before impact is equal to the sum of the momentum after impact.

$$(M_h v_h + M_p v_p) = (M_h + M_p)v \qquad 3.4$$

The above equation is known as the *Momentum formula*, where

M_h : mass of the hammer

M_p : mass of the pile

v_h : velocity of the hammer before impact($v_h = \sqrt{2gh}$).

v_p : velocity of the pile before impact($v_p = 0$).

v : velocity of the hammer and the pile after impact.

Eq(3.2) can be expressed as;

$$v = \frac{(M_h \times \sqrt{2gh})}{(M_h + M_p)}$$

Now, if

$$\eta = \frac{E_k}{E_p} = \frac{\textit{transmitted energy}}{\textit{input enrgy}}$$

and

$$E_p = 1/2 M_h v_h^2$$

$$E_k = 1/2 (M_h + M_p) v^2$$

Then

$$\eta = \frac{M_h}{(M_h + M_p)} = \frac{W_h}{(W_h + W_p)} \qquad 3.5$$

where $W = m \times g$

So, when the weight of the hammer is equal to the weight of the pile, the hammer efficiency η is only 50%. A heavier hammer mass with lower velocity is more suitable to produce a higher efficiency than a lighter hammer with higher velocity. This estimate of efficiency is not exact, because the pile does not behave as a rigid body, moving at velocity v after impact. Instead a compression wave is induced into the pile, implying a higher efficiency. The relation between the hammer effeciency and the pile-hammer weight is displayed in figure (3.8).

b. Dynamic Analysis

The driving resistance to pile penetration can be predicted by the measurement of the applied dynamic forces and pile head velocity during the impact. The dynamic analysis of the forces is based on the one dimensional solution of wave propagation in an elastic medium(see section 2.4.2). Consider figure (3.9); the pile is shown as a thin uniform rod with constant cross section and elastic modulus. The impact of the hammer generates a compressional wave at the pile head which propagates through the pile with constant speed $c = \sqrt{E/\rho}$, where E is the elastic modulus of the pile and ρ is the density. Due to the effect of compression, the pile-head undergoes some form of deformation and its magnitude is a function of the hammer mass, height of drop and the pile properties and can be expressed as

$$u = \frac{mv}{Z} \quad (mm) \tag{3.6}$$

where u : compression of the pile-head

m : hammer mass (kg)

v : velocity of the hammer head ($v = \sqrt{2gh}$), (m/s)

Z : pile resistance (also known as *Impedance*)

The magnitude of the impedance can be calculated from the following equation

$$Z = \frac{EA}{c} \quad (kN.sec/m) \tag{3.7}$$

where A is the cross section area of the pile.

It can be noted that the impedance Z is directly proportion to the elastic modulus and the cross sectional area of the pile, and inversely proportional to the wave propagation velocity of the pile.

In practice, the velocity of the pile-head cannot be recorded with sufficient accuracy. The most practical and generally adopted method is to measure the acceleration and to establish the velocity by integration. The force at the pile-head is recorded by the aid of strain gauges. The applied force P, can also be calculated from Eq(3.6) as:

$$P = Zc \tag{3.8}$$

Then the resistance to the pile penetration can be determined with the variation of the acceleration and strain signals with respect to a given time (see figure (3.10)). A shock wave applied to the pile-head during the impact experiences soil resistance from the shaft of the pile on its way to the pile tip. At time $t = x/c$ (where x is the pile length), the wave reflects at the pile tip and moves upward and reaches the pile head at time $t = 2x/c$. The upward and downward resistance to the pile penetration can be estimated by the following equations:

$$R_{(down)} = (P + Zc)/2 \tag{3.9}$$

$$R_{(up)} = (P - Zc)/2 \qquad 3.10$$

This method of analysis was originally introduced by Smith (1960)[⊕]. Then practical ways of pile head measurement were developed at *Case Institute of Technology, USA*. Later a computer programme **CAPWAP** (*Case Pile Wave Analysis Programme*) was completed by Goble in 1979[♣]. In this program, the pile is divided into a number of mass elements interconnected by springs. The soil is modelled to provide only the shaft and base resistance. Today, the method is widely used by a number of consultant companies for a wide range of inquiries. Examples include calculation of pile-set per hammer blow, estimation of the applied energy to the pile head, identification of hammer performance and a selection of the best type of driving equipment can be made for the given pile/soil information. An assembly of hammer, pile and soil is presented in figure (3.11) as *spring-mass* system used by Fugro Ltd. (1986) for their analysis.

3.2.3 Ground Conditions

The ground conditions have a very important role in foundation design. The site investigation team uses standard methods to classify and define the types of soil in the ground. Relevant information is presented of the boreholes on which the water level and the types of soil at different depths are shown. The strength of the ground can be found from the cone penetration tests or SPT and laboratory soil mechanics tests can be used to measure the cohesion, the angle of friction and the compaction characteristics. From this information, the type of foundation can be designed. Then, according to the ground conditions suitable types of pile and hammer can be selected. In many sites, the condition of the ground varies with depth, in which case it may be neccesary to use different hammers to drive the pile to the required penetration.

The behaviour of the soil around the driven pile depends on whether the soil is *cohesionless* or *cohesive*. In cohesionless soil, a driven H-pile will displace adjacent

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⊕ Also see Rausche & Goble (1979) and Gravare *et al* (1980).

♣ See Goble and Rausche (1979).

soil radially outwards and possibly also downwards. Local compaction may occur due to the introduction of the pile volume into the soil. The magnitude of compaction depends on soil density, the degree of saturation, the type of the driven pile and the input energy from the hammer. A primary factor is the relative density of the soil. The induced vibration in the soil may compact a loose soil but a dense soil in hard ground may be loosened and weakened under its effects. Plugging may occur when an open ended tubular pile is driven, which introduces high lateral stresses acting on the internal surface of the tube.

In cohesive soil, depending on its density and pore pressure, the driven pile may cause the soil (clay) to be displaced, remoulded, sheared or distorted and a high pore water pressure may develop around the driven pile. In stiff clay, because the soil cannot be compacted and the volume of the soil remains sensibly constant, the soil may respond to the intruding volume with some upward movement in the ground. The upward movement may produce an extensive cracking system in the soil around the radial direction of the driven pile. The crack system may dissipate the increase of pore water pressure which reduces the high ultimate resistance of the soil.

According to British Standard BS 8004,(1986), cohesionless soils are classified by the standard penetration test with respect to their density into three groups as shown in table (T3-6a), and the cohesive soils are classified with respect to their stiffness into five groups as indicated in table (T3-6b).

The instantaneous increase in pore pressure in loose and saturated cohesionless soil (sand) causes a reduction in the shear strength of the soil which leads to *liquefaction.* The loss of strength occurs due to a transfer of intergranular stress from grains to pore water. The application of sudden stresses during the pile driving from the driving equipment to the soil may increase the pore water pressure of the soil which consequently increases the possiblity of a local liquefaction around the driven pile. The risk of liquefaction is higher when a vibrodriver is used than any other types of impact hammer because the vibrodriver introduces a continuous vibration into the ground which lasts for a longer period. Since the pressure wave introduced by an impact hammer is rapid, its effect is less. The occurrence of liquefaction develops the process of consolidation and settlement in the soil. Prakash and Gupta (1970)‡ concluded that horizontal vibrations in dry and saturated sands lead to larger settlements than does vertical vibration.

The installation of bored piles has different effects on the surrounding soil. In cohesive soil the drilling causes a relief of lateral pressure on the walls of the drilled hole which results in swelling of the clay and the possibility of immigration of pore water towards the exposed hole. In cohesionless soil, the surrounding soil may be drawn or slumped towards the hole either during the drilling or after the drill machine is pulled out. After replacing concrete into the bored hole, the water will immigrate from the unset concrete into the soil, causing softness in the surrounded soil. Usually bentonite is used to support the sides of the bored holes and to increase the soil friction on the shaft of the pile.

When a pile is driven into a strong stratum, towards bedrock, the pile may shatter, disrupt and break the weathered and weak rock. The resistance will be at its maximum at the pile base and the driving should stop as soon as the pile reaches the bedrock otherwise some damage may occur at the pile toe, and reduces its bearing capacity.

3.3 Blasting

Explosion or blasting works often produce substantial vibrations lasting a very short period of time and create a disturbance in the ground which may affect nearby buildings and local residents. Dowding (1985), defined explosives as chemical mixtures that decompose rapidly by burning and in turn release a large amount of heat and gas. Examples of common type of explosive are `ANFO`†, `Gelex`♡ and `black-powder`. The use of explosives has many different applications in civil engineering works, for example, tunnelling, demolition, excavation, and in pile driving using the

‡ Also see Prakash 1981.

† Mixture of ammonium nitrate and fuel oil.

♡ A mixture of nitroglycerin and fuel.

Rosenstock Shock Blasting technique[⊙].

3.3.1 The mechanism of the explosion process

Dowding (1985) stated that each blast generates two types of impulse pressures which are described as *detonation or shock pressure* and *explosion pressure.* Depending on the type of the ground, the shock pressure has a peak magnitude of 10-140kbar and wave velocity of 2700-8400m/s while the explosion pressure has a longer duration and causes most of the deformation in the surrounding media.

Three physical zones can be identified around the blast source (see figure (3.12). The diameter of each zone is dependent on the weight and type of the explosive. The three zones can be identified as follows:

1.*Crushed Zone*: this zone is located immediately adjacent to the blast hole and the detonation pressure causes the surrounding area to melt, flow, crush and fracture. The expanding stress waves are dominantly compressional in a radial sense from the source. The tensile strength of the medium is typically small.

2.*Fractured Zone*: this zone is mostly dominated by the effect of explosion pressure which has tensile character and causes the formation of radial cracks in the surrounding media.

3.*Seismic Zone*: there is no clear pattern of waves due to the explosion in this zone either because the zone is too remote from the source of blast, or the ground condition of the medium absorbs the applied vibrations. The explosion pressure propagates through this zone as elastic waves and the medium has an elastic reaction.

3.3.2 Blast control

The magnitude of the ground vibration caused by blasting can be controlled through the following factors:

⊙ RSB is a blasting technique used to change impenetrable hard ground into drivable granular soil for driving steel sheet piles. The method uses very low power explosives in which according to BSC 1988, the width of the granulated rock zone would be 500-700mm and to the exact depth of the required pile penetration and the rock immediately adjacent to this zone remains totally intact.

- Explosive type and weight.
- Ground type and conditons.
- Detonation sequence and delay.
- Hole depth and spacing.

The measurements of such ground vibrations were taken from different sources of explosion used for different purposes. The maximum level of vibration measured at 15m from the source, was in the range of 40-50mm/s.

3.4 Traffic Vibration

The vibration caused by road and rail traffic is usually small in comparison to the other sources of vibration. Both road and rail traffic vibrations have a complicated character and their form is a mixture of impact and continuous type of vibration, Steffens (1974) and Skipp (1984). Generally, the vibrations caused by traffic attenuate rapidly with the increase of distance from the source. They may sometimes be a source of annoyance and discomfort but they rarely involve structural damage or personal injury.

3.4.1 Road Traffic

The vibration generated by road traffic is mainly caused by the variation in contact forces between the wheels of a vehicle and the road surface, Watkins (1980). If the road surface has a smooth finish, the induced vibration is unlikely to be a matter of concern. When there are some discontinuities on the road surface, this causes the vehicle to bounce and subsequently give a rise in the level of vibration. The magnitude of the induced traffic vibration is a function of condition, type, weight and speed of the vehicle. The depth of the irregularities on the road surface also controls the produced vibration. The measured vibrations from road traffic were in the range of 0.5-2.5mm/s.

3.4.2 Rail Traffic

The ground vibrations induced by rail traffic may cause cause permanent damage to buildings around the railway line and can sometimes be the source of nuis~~e~~nce a in residential areas. The levels of vibration recorded by rail traffic are relatively small and their magnitudes are dependent on the condition, type, speed, length and weight of the train. The heavy and long cargo or passenger trains may be more stable on the rail line than the local passenger trains which may cause some lateral movements during their passage and subsequently raising the level of the induced vibrations.

Many measurements of ground vibration due to rail traffic have been taken since the early 1900's when the passage of trains in town and cities was the subject of concern. Most of these studies are reviewed by Steffens (1974). The vibrations caused by rail traffic were measured in different sites during this project. The levels of vibration measured at 3-18m from a local rail line were in the range of 6.5-0.3mm/s and with frequencies of 35-50Hz.

Table (T3-1)

Rate of the input energy of some **Drop-hammers**

Winch Operated Drop-hammer			
Weight kg	Drop m	Energy kJ	Rate blows/min
2000	0.5	9.81	14
3000	1.0	29.43	12
5000	1.2	58.86	10

Motor Operated Drop-hammer				
Model	Weight kg	Drop m	Energy kJ	Rate blows/min
Banut	3000	0.5	14.7	18
	4000	0.5	19.6	16
	5000	0.5	24.5	14

Table (T3-2)

Rate of the input energy of some **Air-hammers**

Double Acting Air-hammer				
Hammer	Model	Ram W. kg	Max.Energy kJ	Blow rate bl/min
BSP	500N	91	1.6	330
	600N	227	4.1	250
	700N	385	6.4	225
	900N	726	11.9	145
Menck	SB80	270	3.9	205
	SB180	600	9.3	150
	SB400	1300	21.8	115

Single Acting Air-hammer				
Hammer	Model	Ram W. kg	Max.Energy kJ	Blow rate bl/min
BSP		3000	49.3	50
		5000	79.3	50
		8000	122.0	50
		12000	183	50
		25000	418	40
Menck	MRB500	5000	61.3	50
	MRB1000	10000	122.6	50
	MRBS1500	15000	183.9	42
	MRBS7000	70000	858.4	42

Table (T3-3)

Rate of the input energy of some **Diesel-hammers**

Diesel-hammer				
Hammer	Model	Ram W. kg	Max.Energy kJ	Blow rate bl/min
Delmag	D8-22	800	24	38-52
	D16-32	1600	54	36-52
	D22-23	2200	67	38-52
	D30-23	3000	91	38-52
	D36-23	3600	115	37-53
	D46-23	4600	146	37-53
	D62-22	6200	219	35-50
	D80-23	8000	267	36-45
	D100-13	10000	334	36-45
BSP	B15 (d)	1500	37.2	80-100
	B25 (d)	2500	61.9	80-100
	B35 (d)	3500	86.8	80-100
	DE30c (s)	1360	36.6	47
	DE50c (s)	2260	61.0	47
IHC	180	.800	17.4	35-55
	422	1700	42.5	40-50
	520	2500	60.7	40-50
	640	3000	76.5	40-50
	1070	5400	133.0	38-48
Hera	3500	3500	110	37-50
	5000	5000	160	37-50
	7500	7500	235	37-50
Kobe	K25	2500	73.6	39-60
	K35	3500	103	39-60
	K45	4500	132	39-60

Table (T3-4)

Rate of the input energy of some **Hydraulic-hammers**

Hydraulic Hammer					
Hammer	Model	Ram W. kg	Drop m	Max.Energy kJ	Blow rate bl/min
BSP (357)	HH3	3000	1.2	35.3	46
	HH5	5000	1.2	58.9	40
	HH7	7000	1.2	82.4	36
IHC	S70	3500	2.0	70.0	50
	S90	4500	2.0	90.0	50
	S200	10000	2.0	200.0	45
	S400	20000	2.0	400.0	45
	S800	40000	2.0	800.0	45
	S1600	80000	2.0	1600.0	40
	S3000	150000	2.0	3000.0	35

Table (T3-5)

Rate of the input energy of some Vibrodrivers

Standard Vibrodrivers				
Hammer	Model	Static W. kg	M. Frequency Hz	Energy kJ/cycle
PTC	6H2	650	29	1.4
	13H1	1220	28	2.9
	25H2	2100	27.5	6.9
	50H3	4650	27.5	10.7
	60H1	5550	27.5	14.0
	119H2	7250	22.5	19.0
	7HF1	800	38.3	2.0
	13HF1	1200	38.3	3.4
	23HF1	2100	40.0	5.6
Delmag	PE2001		32-40	0.8
	PE3001		32-40	2.3
	PE5001		32-40	3.3
	PE7001		32-40	4.1

Hydraulic-vibrodriver				
Hammer	Model	Weight kg	Frequency Hz	Energy kJ/cycle
ABI	VRZ 200GL	600	50	1.0
	VRZ 300GL	800	50	1.6
	VRZ 400GL	1000	50	2.0
	VRZ 500GL	1200	50	2.4

Table (T3-6a)

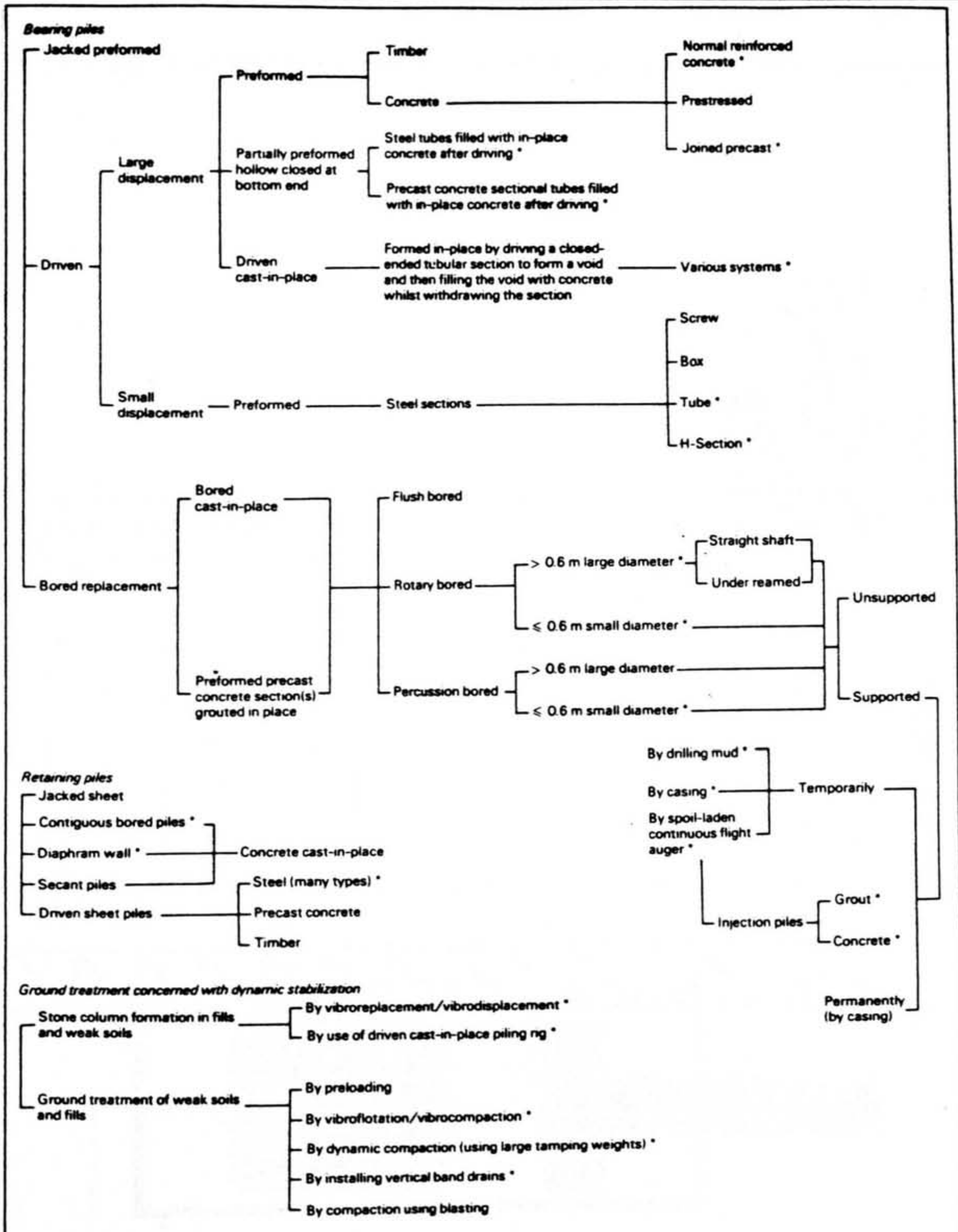
Classification of Cohesionless Soils (BS:8004 1986)

Sand & Gravel Classification by standard penetration test	
Relative density of packing	Number of blows for 0.3m penetrations
Loose	Less than 10
Medium dense	10 to 30
Dense (or compact)	More than 30

Table (T3-6b)

Classification of Cohesive Soils (BS 8004:1986)

Clay Classification by undrained shear strength test			
Consistency			Undrained shear strength
As BS 5930	Widely used	Field indications	$kN.m^{-2}$
very stiff	hard	brittle or very tough	greater than 150
stiff	stiff	can not be moulded in the fingers	100 to 150
	firm to stiff		75 to 100
firm	firm	can be moulded in the fingers by strong pressure	50 to 75
	soft to firm		40 to 50
soft	soft	easily moulded in the fingers	20 to 40
very soft	very soft	exudes between the fingers when squeezed in the fist	less tan 20



NOTE 1. It should always be remembered that the type of pile to be used on any site is normally governed by such criteria as loads to be carried, strata to be penetrated and the economics of the system.

NOTE 2. Where necessary, allowance should be made for the extraction of piles in addition to their installation.

NOTE 3. Sound level data for systems marked thus * are included in table 1. Other data may be found in table 8 of BS 5228 : Part 1 : 1984.

Figure (3.1) Classification of piles according to British Standard BS 5228–4 1986

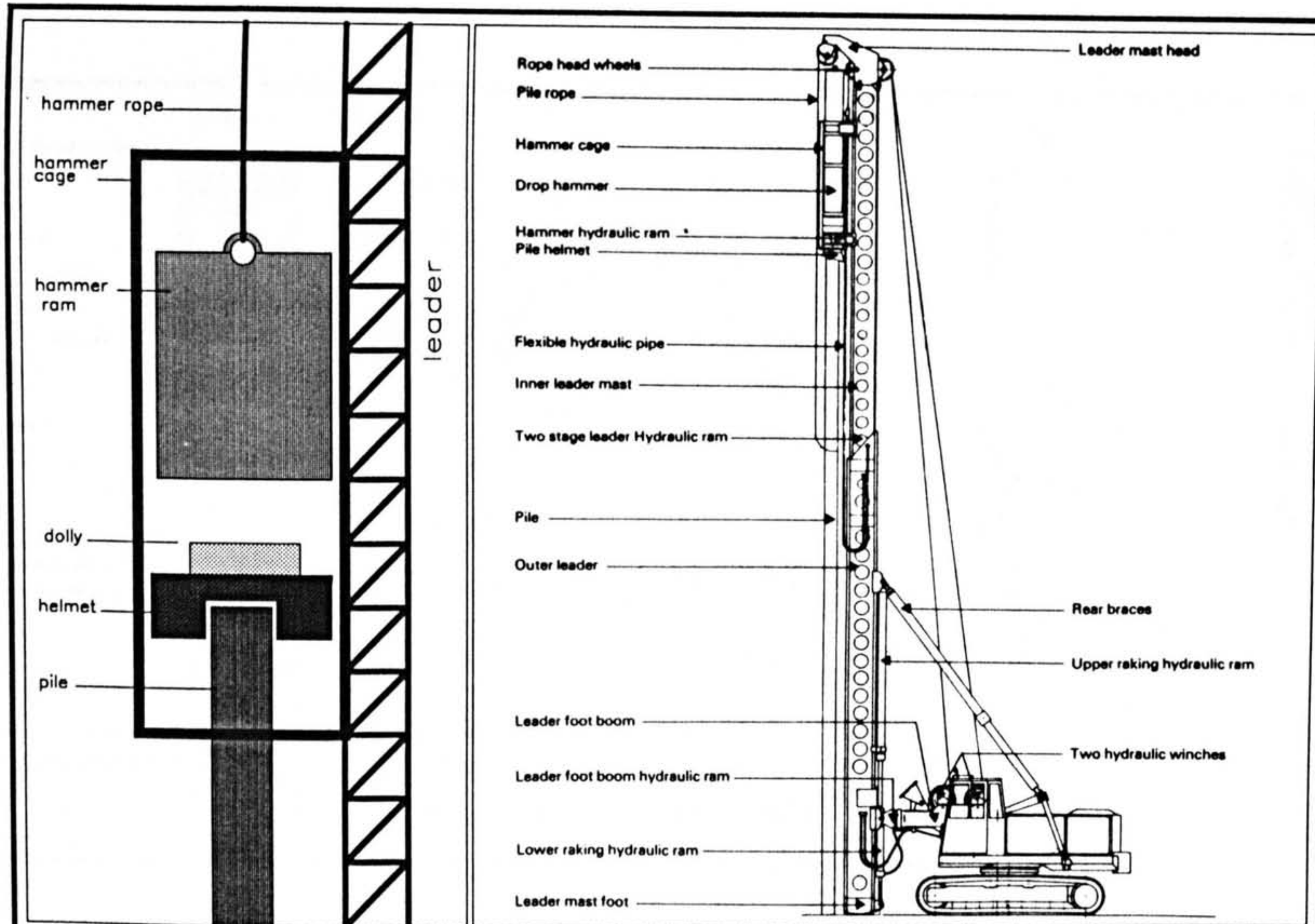
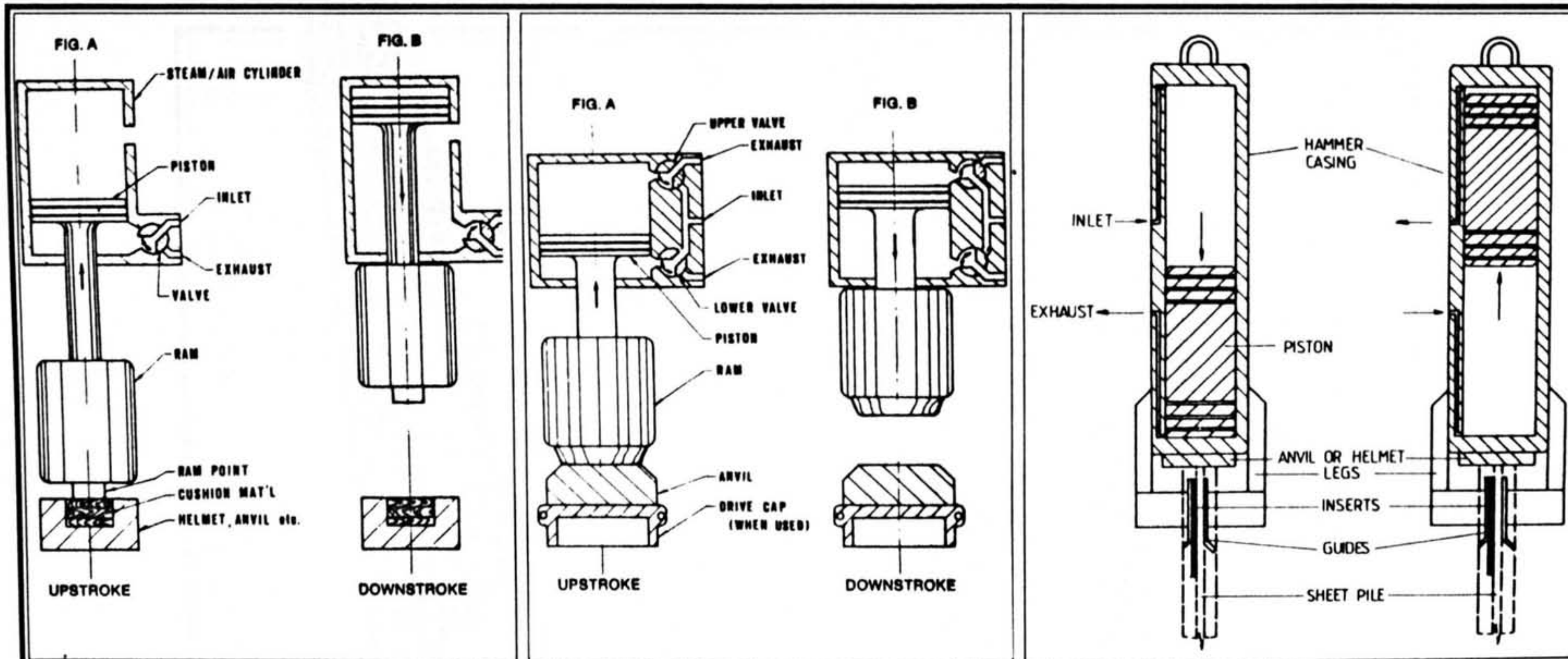


Figure (3.2) Assembly of different parts of a drop-hammer



Single–acting steam/air hammer

Double–acting steam/air hammer

A double–acting air–hammer inside a case

Figure (3.3) Components and operation of steam/air hammers

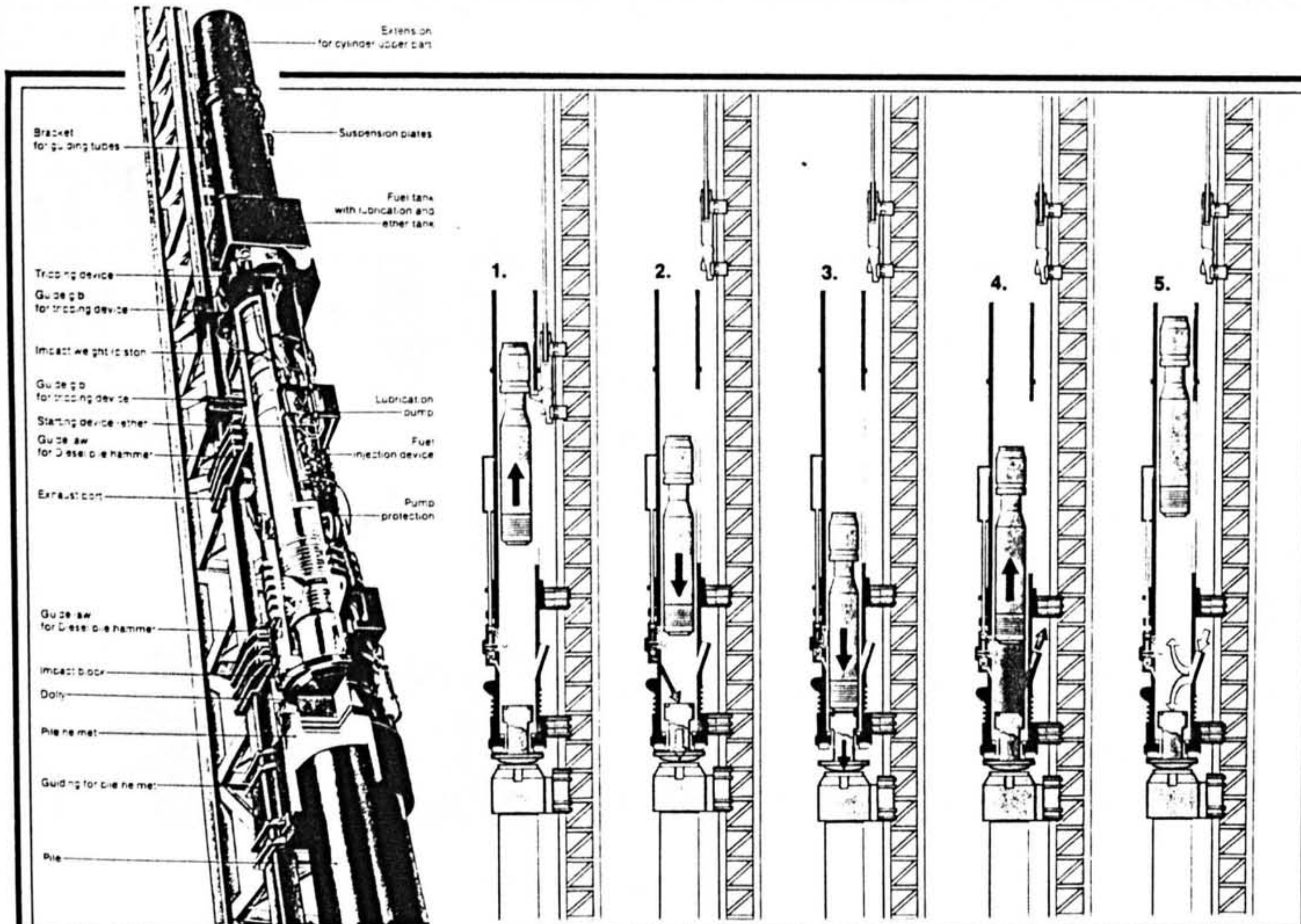


Figure (3.4) Components and operation of a diesel–hammer *(after Delmag 1988)*

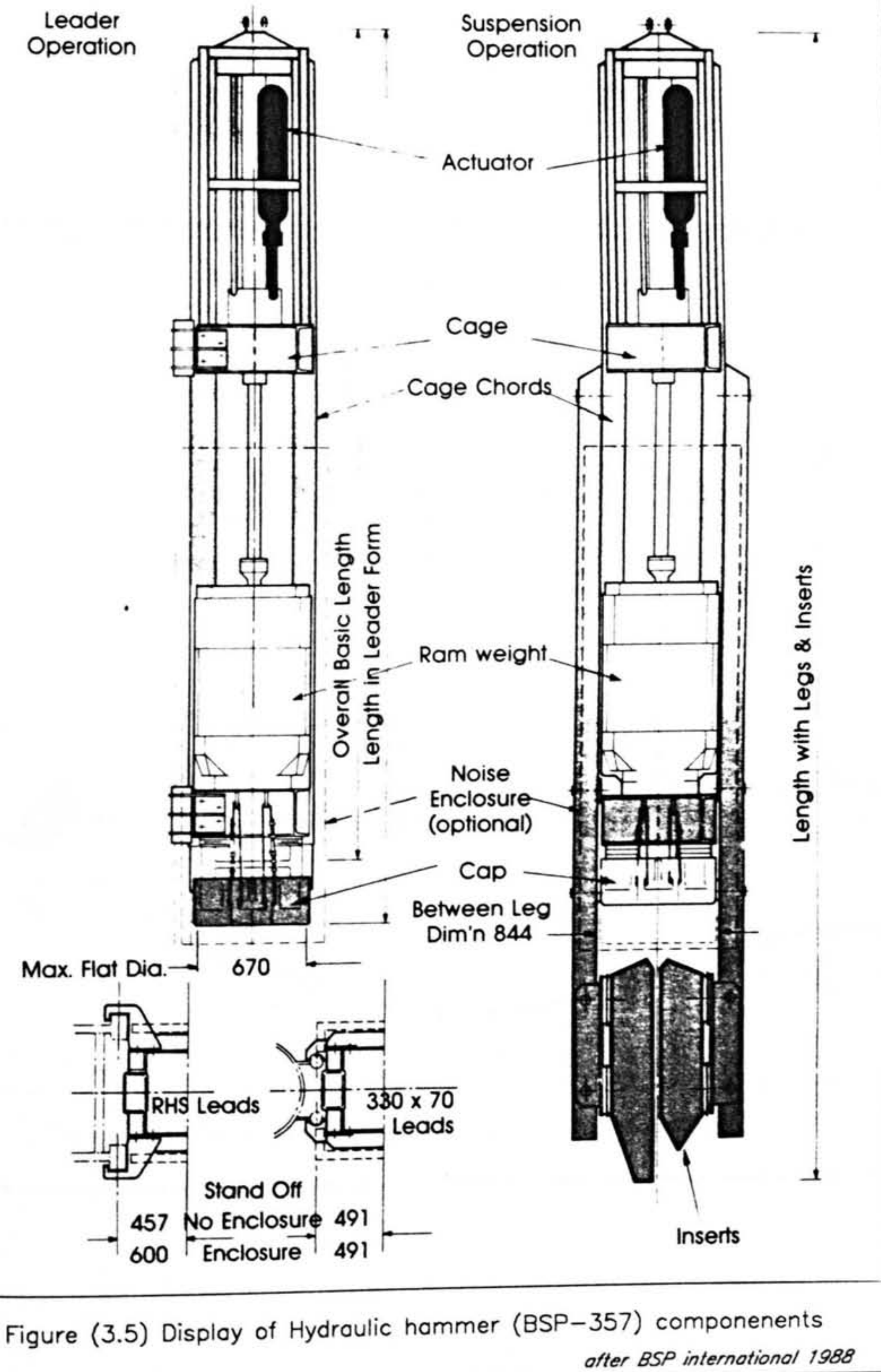
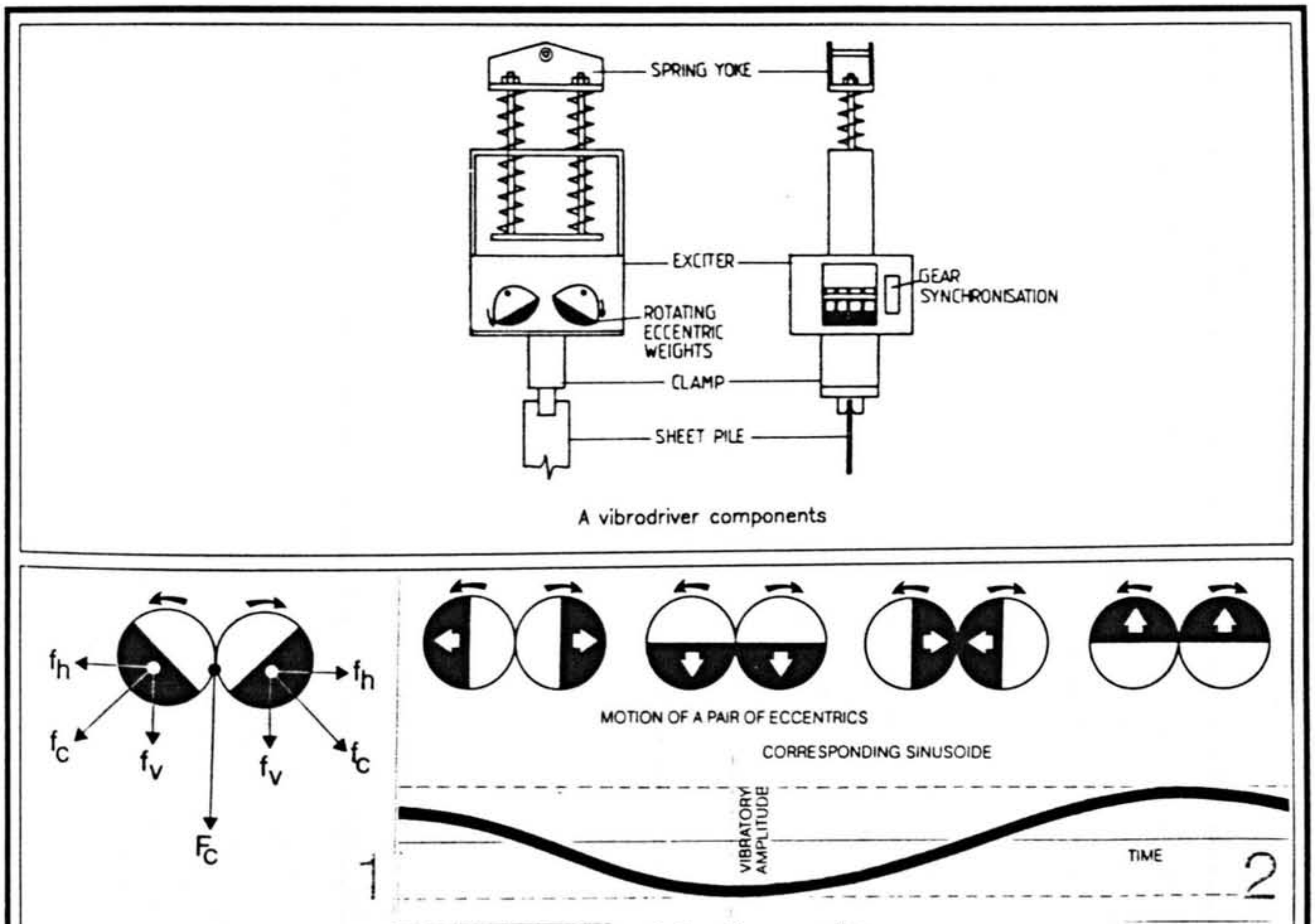
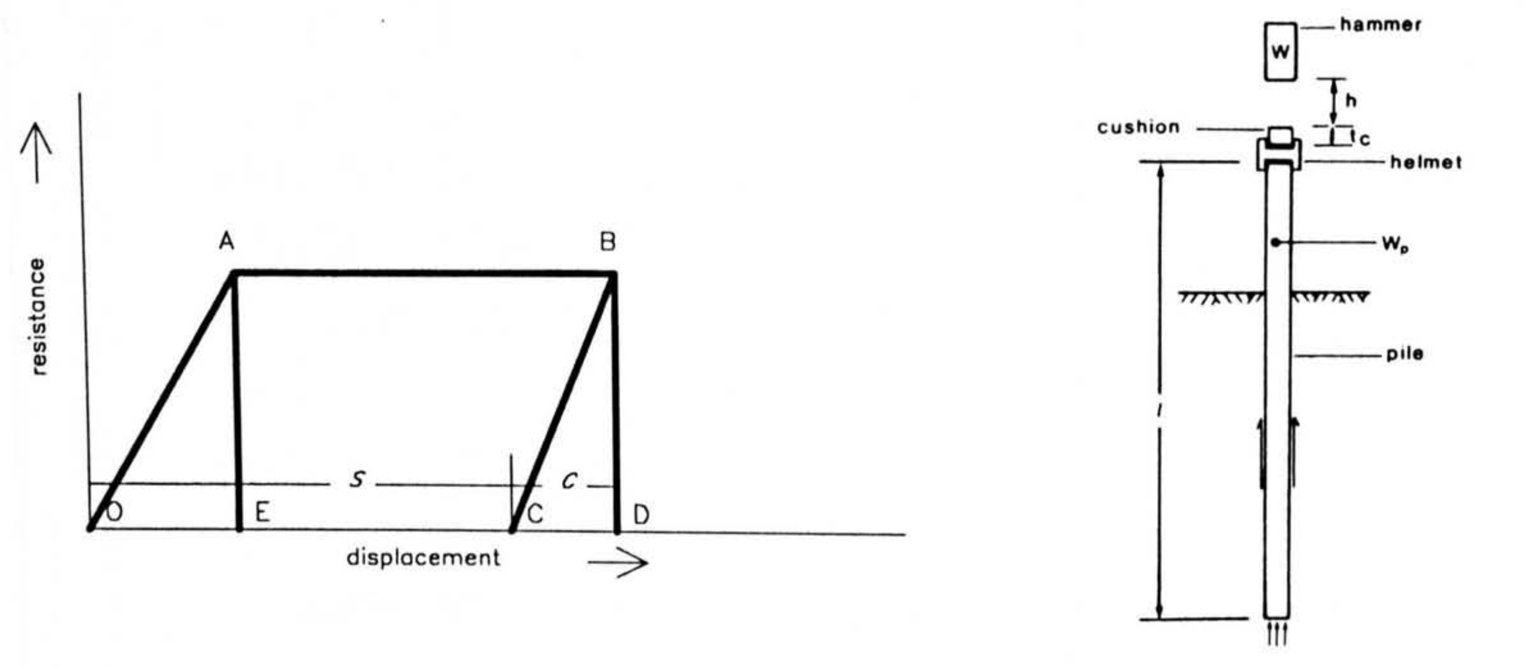


Figure (3.5) Display of Hydraulic hammer (BSP-357) componenents

after BSP international 1988



Figure(3.6) The components and principle of a vibrodriver



b. Variation of pile resistance with displacement

a. Process of pile driving

Figure (3.7) Simplified diagram of pile driving procedure

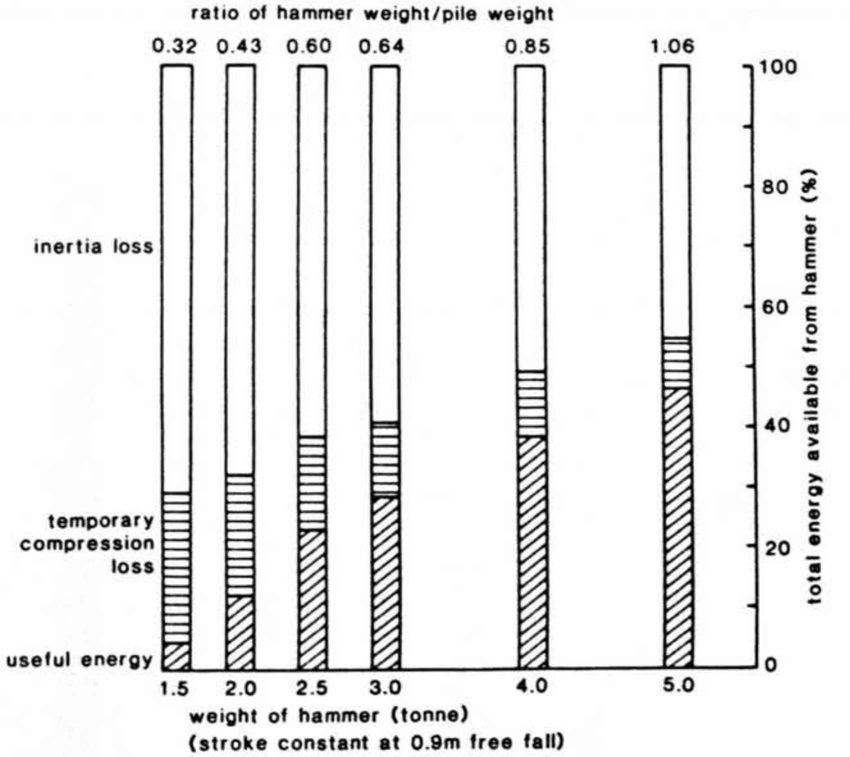


Figure (3.8) Display of the relation between driving efficiency and pile–hammer weight

after Fleming et al 1985

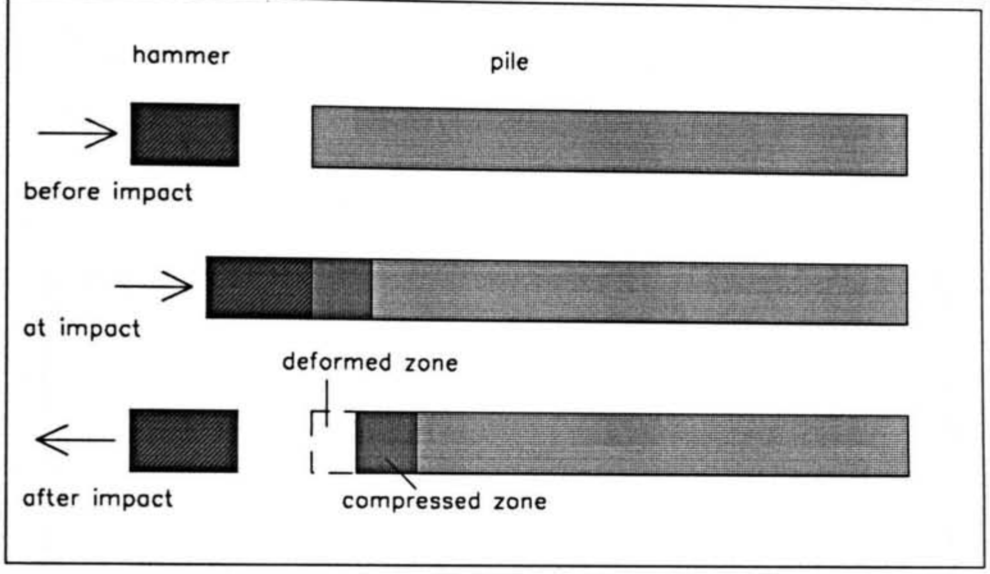


Figure (3.9) Deformation of a uniform rod under compression load

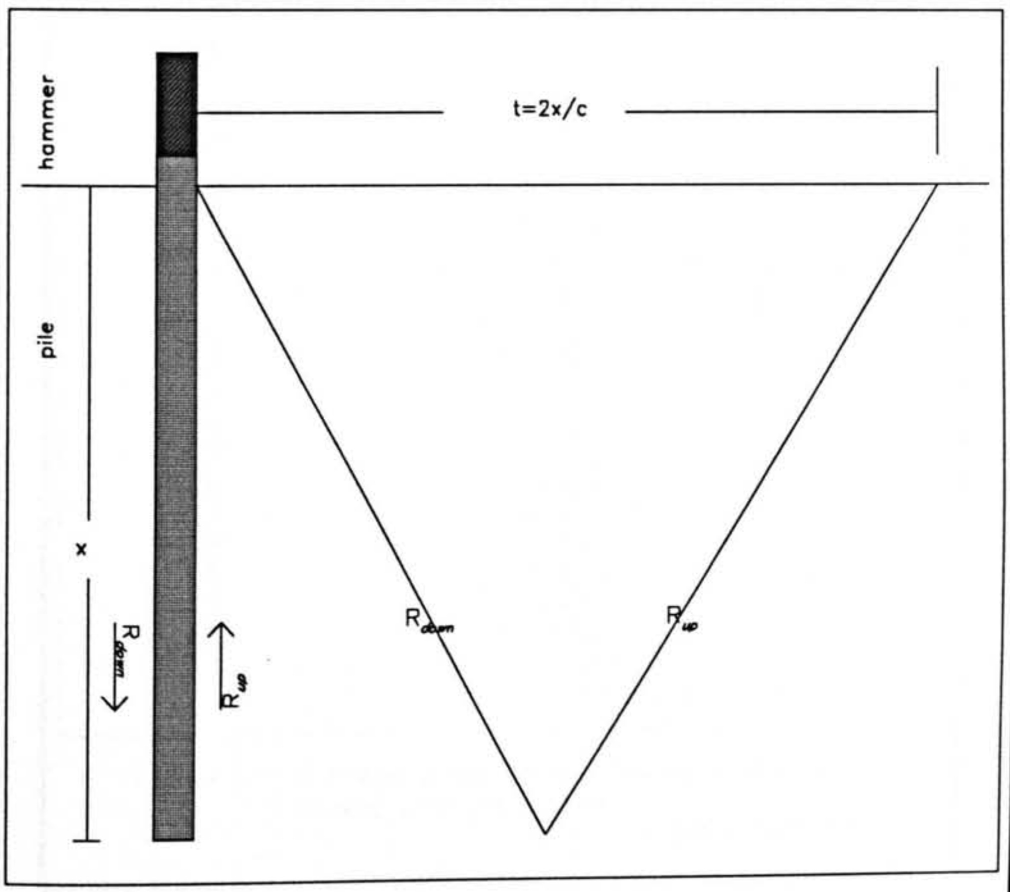


Figure (3.10) The transmission of wave through a pile

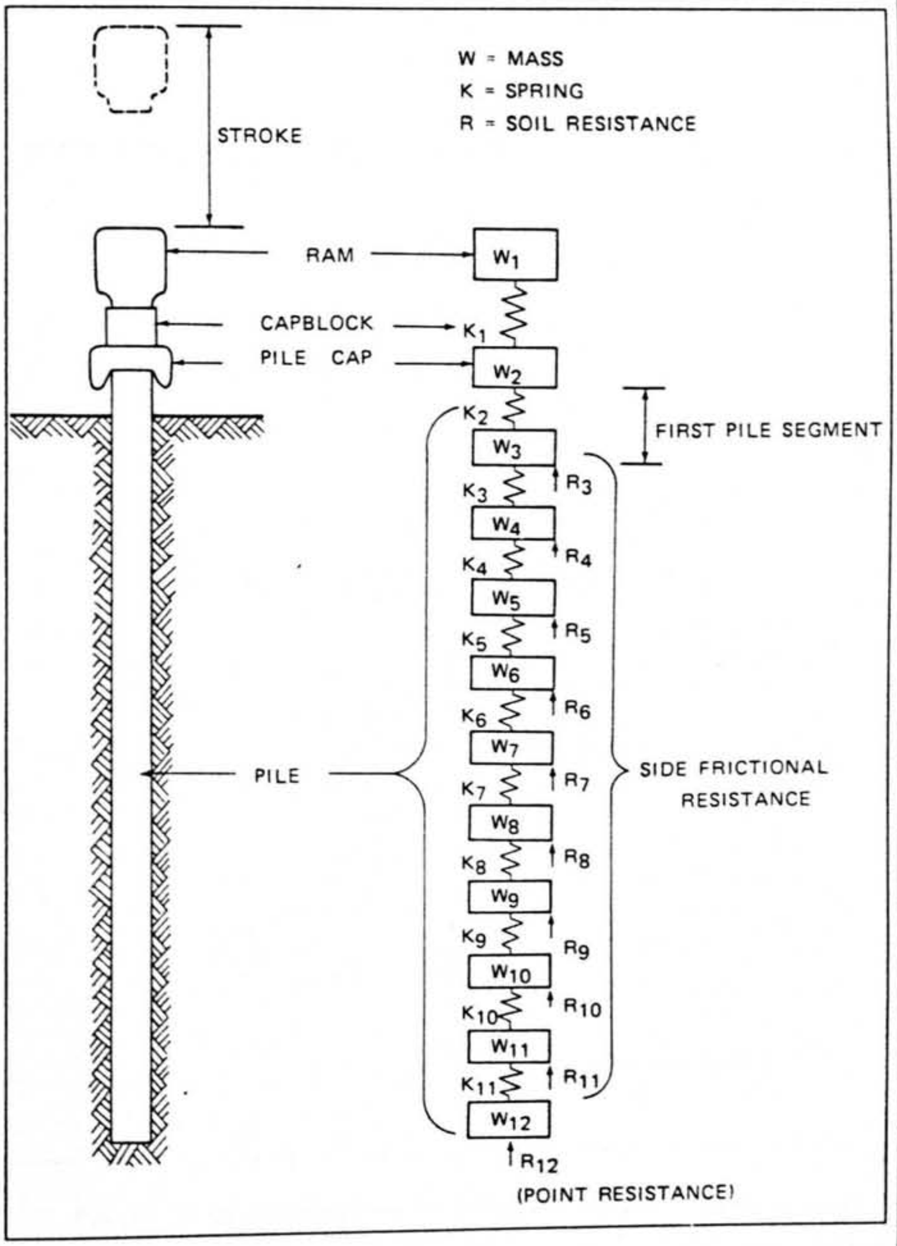


Figure (3.11) Presentation of pile driving assembly as spring–mass system

(after Fugro 1987)

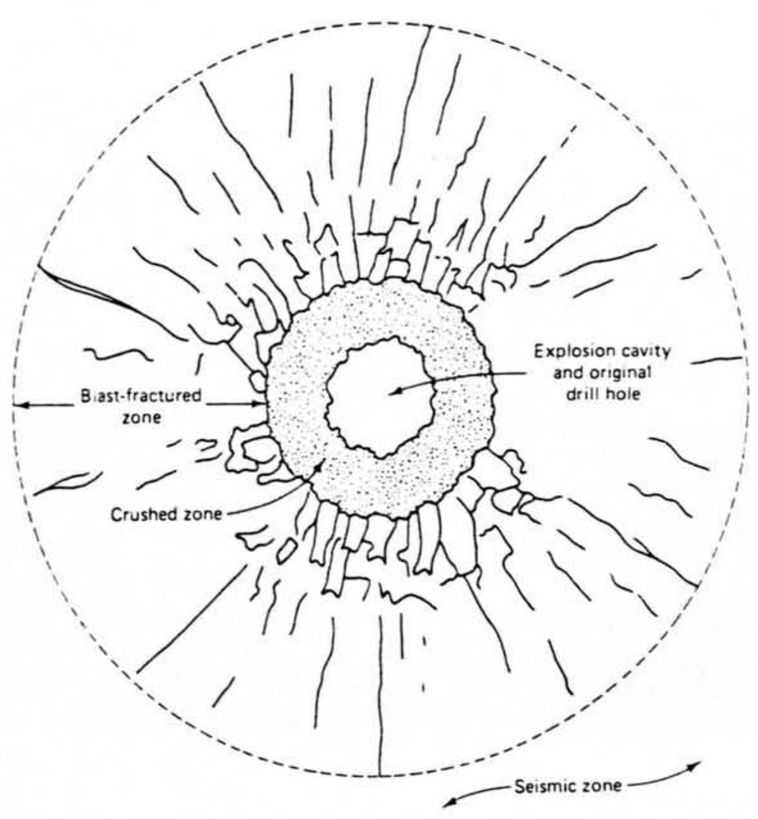


Figure (3.12) Generation of different zones around a blast hole
after Dowding 1985

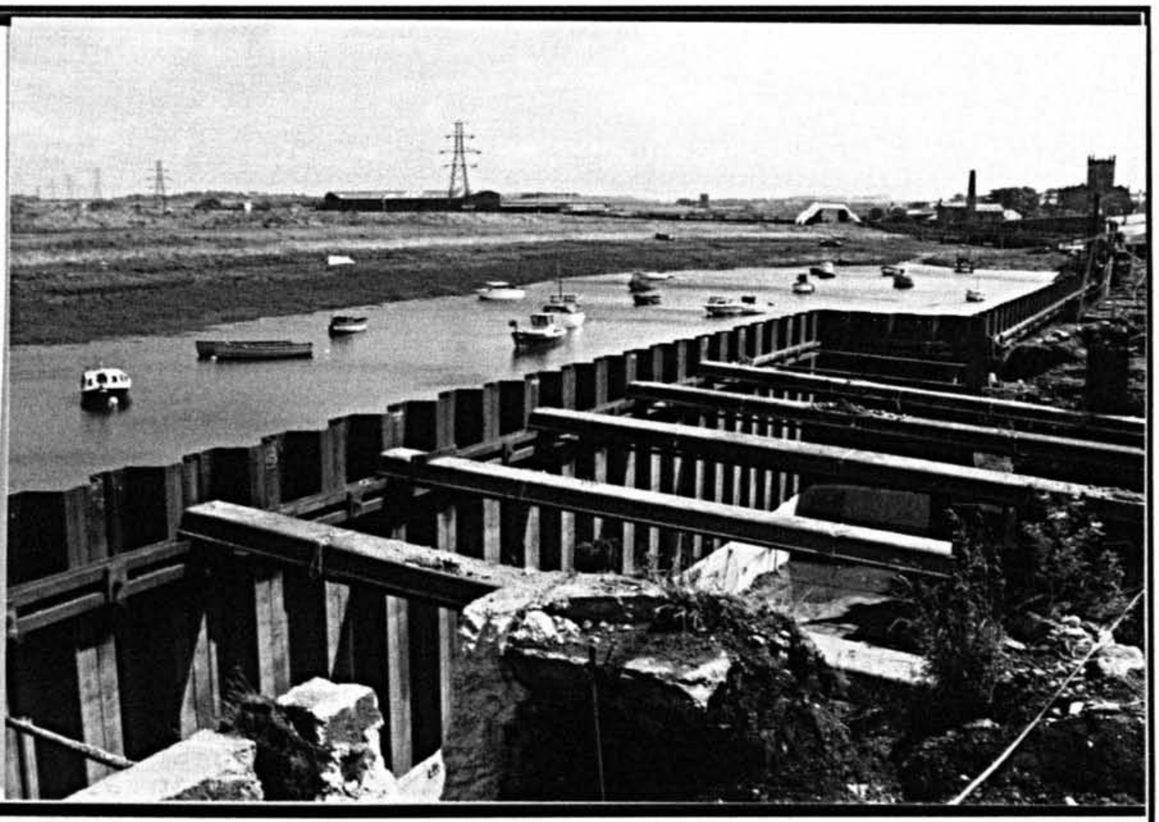


Plate (3-1) The use of sheet-piles as retaining wall along the river bank in Workington

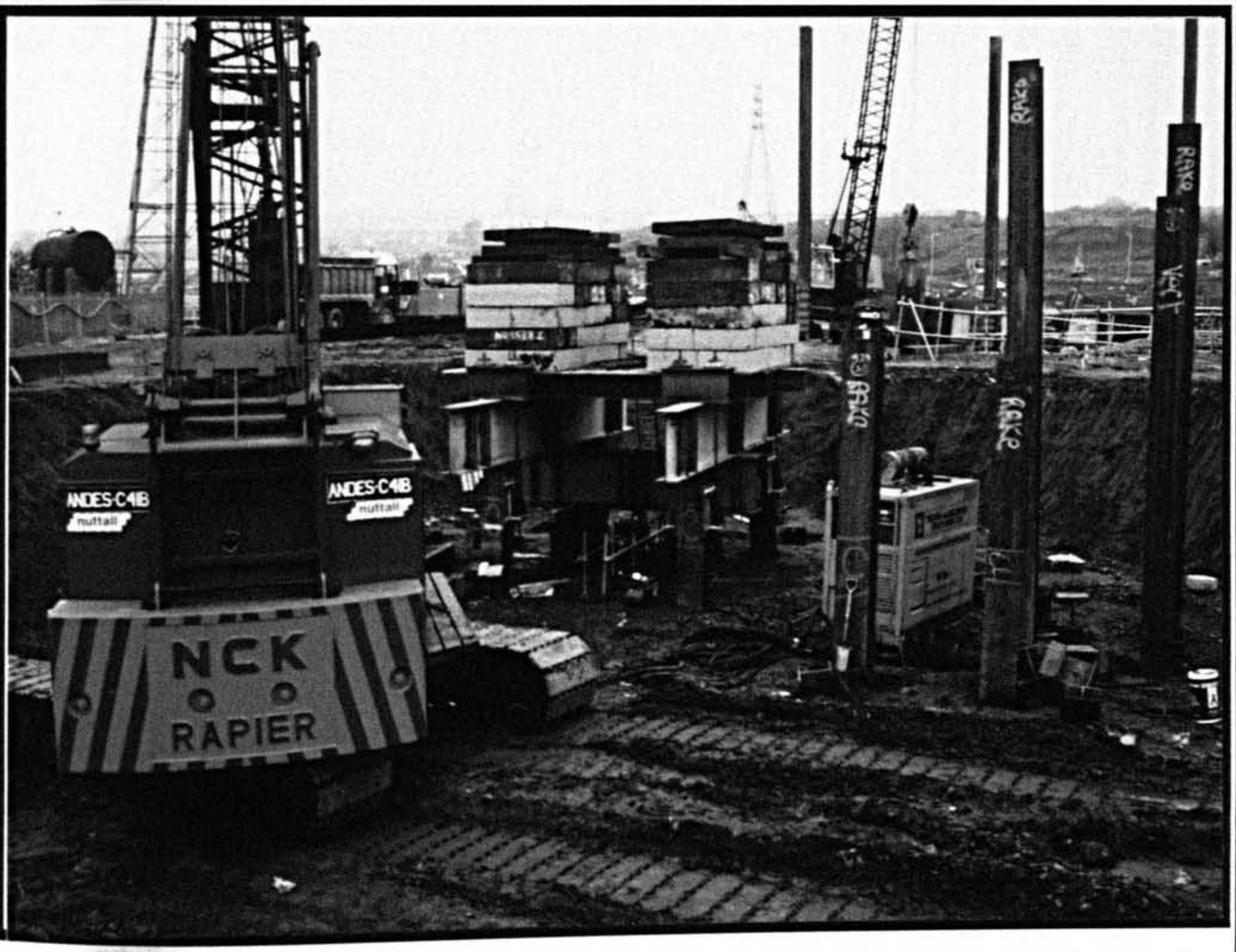


Plate (3–2) Static load test on a driven steel H–pile
at a typical construction site in Blaydon

Chapter Four

4. Vibration Acquisition Equipment

4.1 Introduction

A variety of equipment is required for monitoring the ground vibration. The measurement of the ground vibrations relies on a numbers of devices which include vibration detectors or transducers, amplifiers and recording and analysing units.

This chapter aims to describe and explain the use of equipment employed in this project for the measurement of the ground and structural vibrations. The equipment is divided into two main groups: *measuring equipment* and *recording equipment*. The measuring equipment includes geophones, accelerometers and strain gauges. These devices which are transducers, act as a medium to pick up the vibrations by converting the mechanical movements into electrical voltages which may be transferred on to a recording system. The application and the principles of these devices are described in section (4.2).

The recording equipment employed in this project included two portable digital recorders PDR1 and PDR2. These recorder/processors are used to change the analogue information received from the transducers into digital data which may be saved on floppy discs for later analysis. The recorded data then could be analysed to obtain the ground vibrations measured in terms of particle velocity, acceleration, displacement and their relevant frequencies. The results can be plotted, printed or tranferred to a PC computer for further analyses. An assembly of the ground vibration measuring equipment is shown diagrammatically in figure (4.1).

A full description of the recording equipment and the computer programs is given in section (4.3) and an operating manual is included in Appendices A3.1 and A3.2 to be used with the operations of the PDR-1 and the PDR-2 units, respectively.

4.2 Measuring Equipment

The transducers are used to convert the mechanical disturbance of the ground under the effect of vibration into electrical signals. There are several types of transducer available, which may be classified into two main groups as *active* and *passive* transducers. The active transducers are self-generating voltage instruments while the passive transducers require to be supplied by a secondary electrical input to produce an electrical output.

Transducers form the essential part of any measuring system and their performance is controlled by the following parameters, see Dowding (1985).

- *Sensitivity* of a transducer is the ratio of the electrical output to the mechanical input (in the form of displacement, velocity or acceleration), during a sinusoidal vibration parallel to a specified axis. The sensitivity of a transducer can be obtained by placing the transducer with its sensitive axis parallel to the direction of motion of a vibration generator and measuring and comparing the magnitude of the input and output vibration of the vibration generator and the transducer, respectively.
- *Resolution*: is the limiting discernible electrical ouput in response to a small mechanical signal.
- *Frequency response*: is the working range of frequency where the electrical output is constant with a constant mechanical input motion.
- *Phase shift* is the time delay between the mechanical input and the electrical output of the system.
- *Environmental sensitivity*: is the response of the transducer to humidity, temperature or field conditions.
- *Mass & size*: the increase of low-frequency sensitivity of a velocity transducer may increase with its mass and size.

The selection of an appropriate transducer for a particular application depends on the maximum amplitude of mechanical disturbance, the desirable accuracy, environmental conditions, the required electrical output, possible frequency range and type of the applied vibration.

In the following sections the types, mechanism and calibration of transducers used in this project (geophones, accelerometers & strain gauges) are described.

4.2.1 Geophones

A geophone is an active type of transducer and its operation is broadly similar to a spring-mass-dashpot system with a single degree of freedom motion (see figure (4.2)). The system consists of a mass, a damper, spring and a vibrating base. When the ground is subjected to vibration the springs transfer the applied vibration from the base to the mass with damping of the applied vibration of the system. The differential vibration between the base and the mass can be written as

$$\frac{\delta}{u} = \frac{1}{\sqrt{[1-(w/w_n)^2)]^2 + [2\gamma(w/w_n)]^2}}$$

u : maximum vibration of the base

δ : relative vibration of the mass

γ : damping ratio

w : frequency of the excitation

w_n : natural frequency of the system

The electrical signal output from a geophone is generated by a coil moving in a permanent magnet (the reverse arrangement of moving magnet and fixed coil is also used). According to *Faraday's law*†, a moving magnet in a coil of wires induces an *electro-motive force* (EMF) in the coil. The magnitude of the EMF(volt) is proportional to the velocity of the magnet movement which in the case of geophone, is proportional to the ground vibration. Since the geophone uses this simple principle, and because of its robust construction, it was found to be the most suitable transducer for measuring the ground vibration.

The following parameters should be considered in selecting a velocity transducer; sensitivity, resolution, frequency response, mass and size. The values of geophone natural frequency should be in the range of 4Hz or less and damping factor of 60%

† See Heurelen (1986) and Herceg (1976)

of the critical damping. Each geophone is supplied with a frequency response curve which can be used to characterise the geophone, an example is shown in figure (4.3).

Usually geophones are manufactured to be robust, water proof and cheap in comparison to other types of transducer. Two types of geophone (*Geosource* & *Mark*) were employed in this project throughout all the ground vibration measurements.

4.2.1.1 Geosource Sensor (SM-6)

This geophone operates on the principle of axial movement of a permanent magnet within an enclosed coil which induces DC voltage into the coil. The induced voltage is proportional to the product of the number of windings of the wire in the coil, and the number of lines of forces generated by the permanent magnet.

The cross-section of a geophone is shown schematically in figure (4.4a) in which a magnetic core occupies the middle part surrounded by two coils coaxially wound on a cylindrical former. The coil structure is housed in a magnetically shielded stainless steel case, and the top and bottom parts are sealed with rubber sleeves to minimize any possible failure and to provide watersealing capabilities.

The geophones model (SM-6) which are used in this project have a natural frequency of 4.5 Hz and maximum output voltage of 0.7 v/in/s. The maximum movement of the magnetic core is 4mm. The components of a **geosource geophone** are shown in figure (4.4b). The supplied geophones are manufactured for vertical or horizontal measurements. Three geophones (two horizontal and one vertical) were mounted orthogonally on a 30cm long strip of dexion, to measure the three components (*radial, transverse* & *vertical*) of the vibration in three orthogonal directions (see plate (4-1)).

Another set of three geophones was assembled in a steel case to provide a single compact unit for vibration measurement in three orthogonal directions. The detail of this assembly is shown in plate (4-2). The geophones were positioned orthogonally into a specially designed base which was made of **Acetal Plastic**. The whole components were housed in a stainless steel case. The case comprised three separated segments which could fit together. The case segments included *bottom, middle* &

top parts; the bottom part was designed to cover the radial geophone, the middle part forms an open ended tube which contains the geophones and slides into both the bottom and the top parts. The top part has a narrow hole for a cable to pass through. The steel case was then tightened to a steel plate with two Jubilee clips. The plate was supplied with three small spikes to provide stability to the base when positioned on the ground. A six core screened PVC cable (two cables for a single geophone), was used for connecting the geophones to a recorder unit. The other end of the cable was connected to three UHF plugs where each end was coloured with red, blue and green representing the radial, transverse and vertical geophones, respectively. The length of the cables varied from 5m to 35m.

4.2.1.2 Mark Product L-4

The `Model L-4` geohone is a high sensitivity geophone of 1Hz natural frequency. It has an output of up to 6.9 v/in/sec. This model is normally supplied with a smooth surface case as a horizontal or vertical geophone. The horizontal unit has a levelling base and a level bubble attached to it for precise levelling.

The principle of operation of this geophone is similar to ~~taht~~ that of the geosource model, except that the coils move in between fixed magnet elements. Figure (4.5) shows the cross-section of the geophones in which the magnet elements occupy the central part of the cylinder and the coils are located around the magnet cores. The whole component is cased in a metal cover.

More information of the character and specifications of the geosource and Mark geophones are included in Appendix (A3.3).

4.2.1.3 Geophone Calibration

The geophones were calibrated at intervals during the project. The calibration figures of the `Mark Product` geophones were supplied. The `Geosource` geophones were calibrated using a method described by British Standard `BS 6955:part 0:1988` as *comparison calibration method* in which an accelerometer with known calibration was used as a reference for the calibration of the geophones. According to this method, the two transducers were rigidly mounted back-to-back on to an electrodynamic vibration generator with their sensing axes parallel with the direction of applied motion in which both transducers were subjected to the same input vibration. The calibration procedure was achieved by mounting each individual geophone either horizontally or vertically on a vibration generator (shaker). The reference accelerometer (Bruel & Kjaer, type 8306), was placed back-to-back on the geophone. An input vibration of known frequency was fed into the vibration generator by means of a power amplifier. The frequency of the input vibration was also checked on a frequency meter. As the geophone and the accelerometer oscillated, the output voltages emitted were recorded on a digital voltmeter. The reading was taken for frequencies at 20, 50 & 70 Hz. The sinusoidal vibration output of the geophone was precisely compared against the output of the reference accelerometer using an oscilloscope. A display of equipment used in the calibration of two sets of geophones is shown in plates (4-4) and (4-5).

Since the induced vibration was in the form of a simple harmonic motion, the equations of motion are as follows;

$$displacement = Rsin(wt) \qquad 4.1$$

$$velocity = wRcos(wt) \qquad 4.2$$

$$acceleration = -w^2 Rsin(wt) \qquad 4.3$$

The particle velocity is at its peak when ($\omega t = 90^o$ or 270^o), and the particle acceleration is at its peak when ($\omega t = 0^o$ or 180^o). Then Eq(4.2) & (4.3) can be written as:

$$\hat{v} = \pm \omega R \qquad \hat{a} = \pm \omega^2 R$$

$$\hat{v} = \frac{1}{\omega}\hat{a} = \frac{1}{2\pi f}\hat{a}$$

where $\hat{a}$ and $\hat{v}$ are peak particle acceleration and velocity respectively.

For a vibration of known frequency (f), the peak particle acceleration can be calculated from the known calibration constant of the accelerometer which leads to the calculation of the geophone calibration constant. (the accelerometer calibration constant for the model of accelerometer used in this experiment is 9.82 volts/g)

$$p.p.acceleration = \frac{acceleration\ voltage\ output}{accelerometer\ calibration\ constant} \qquad 4.4$$

$$p.p.velocity = \frac{geophone\ voltage\ output}{geophone\ calibration\ constant} \qquad 4.5$$

from Eq(4.4 & 4.5)

$$geophone\ calibration\ constant = (2\pi f)\frac{geophone\ voltage\ output \times accelerometer\ calibration\ constant}{accelerometer\ voltage\ output}$$

Since the quoted calibration for the PDR recorder given by the *Microprocessor Centre* is:

$$\pm 5 \quad volts = \pm 2048 \quad recorder\ units$$

then the following formula is used to calculate the calibration factor for each geophone.

$$B = \frac{5000}{2048} \times \frac{1}{C}$$

where B : is the calibration factor

C : is the geophone calibration constant

A list of the calibrations for all geophones is given in table (T4-1).

4.2.2 Accelerometers

An accelerometer is a vibration measuring instrument that provides a direct measure of acceleration. Different types of accelerometer are available. The most widely used accelerometer is the *piezoelectric* type which behaves as an active transducer.

The piezoelectric accelerometer uses a number of piezoelectric crystal discs as force sensing elements which support a relatively heavy mass. The mass is preloaded by a stiff spring and the whole assembly is sealed in a metal housing with a thick base. The basic components of two types of accelerometer are shown in figure (4.6).

When the accelerometer is subjected to a vibration, the mass exerts a variable force on the piezoelectric discs causing electric charge to be developed across the discs which is proportional to the applied force and therefore to the acceleration of the mass. The ratio of the accelerometer electrical output to the mechanical input is defined as the sensitivity which is expressed in term of charge per acceleration unit (pc/g). Since the charge produced by the piezoelectric discs is very small in magnitude, and cannot be monitered by any standard measuring equipment, a *charge amplifier* is used to convert the output signal to a voltage which can be monitored by recording equipment.

In this project, accelerometers were used to measure the energy transmitted to the pile head by a driving hammer together with strain gauges. Because of the high frequencies and high acceleration caused by the applied energy at impact and to suit the environmental condition of the pile driving site, a small size and rugged accelerometer type `A/23/TS` manufactured by D.J.Birchall was chosen. The accelometer calibration figure is dialled into the charge amplifier, so as to give output voltage directly related to acceleration.

The charge amplifier consists of three `CA/23/FH` units and also was supplied with a peak storage meter `PM/04`, an output selector switch `OS/04`, a power meter `PU/04/B` and a level meter `RM/04/B`.

4.2.3 Strain Gauge

Strain gauges are passive transducers which are used to measure strain in a system or component by converting the mechanical changes (strain) of the system into a change in electrical resistance.

The basic component of a strain gauge is shown in figure(4.7a) and it consists of a *carrier* and *sensing foils.* The carrier, which is made of thermoplastic film[‡], used to support and protect the sensing foils from possible mechanical and environmental damages, and it is the part of the gauge which is glued to the specimen and transmits the strain from the test object to the sensing foil. The sensing foil is made of copper-nickel alloy (`Constantan`)[⊕], and forms the gauge grid which is accurately produced

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‡ Also the carrier can be made of 1.organic material, 2.polyamide resin, 3.epoxy glass, 4.paper material, or 5.metallic material

⊕ The sensing foil also can be made of: 1. modified chrome-nickel alloy(stabilloy), 2.nickel-chrome alloy(dynalloy), or 3.platinum-tungsten alloy(platinum) by photo-etching techniques.

4.2.3.1 Strain Gauge Principle

The principle of strain gauge operation is based on the fact that the change of the electrical resistance of the gauge is related to the changes in the applied strain of the system. A change in strain is accompained by a change in the system (**Hooke's Law** $E = \sigma/\epsilon$)[⊙]. Also change in electric resistance ($\Delta R/R$) is related to the strain ($\Delta L/L$) via the following equation:

$$\frac{\Delta R}{R} = k\frac{\Delta L}{L}$$

where k is a constant factor known as *gauge factor*.

Usually the strain gauge is sensitive to strain along one axis only, so the elongation or shortening of the gauge along the sensitive axis produces an increase or decrease in the electrical resistance of the gauge which results in changes of the output voltage. According to *Ohm's Law*[⊘], the electrical resistance of an object depends on the resistivity of the material of which it is made and on its dimension.

$$R = \rho\frac{L}{A}$$

Where R	:	electrical resistance	(ohms)
L	:	length of the foil	(mm)
A	:	cross-sectional area of the foil	(mm^2)
ρ	:	material resistivity	(ohms.mm)

A precise strain measurement is usually achieved by means of an electric bridge circuit similar to that which was designed by **Wheatstone** in 1843. The Wheatstone bridge provides a highly accurate measurement of small resistance changes. Figure (4.7b) shows an example of **Wheatstone** bridge cicuit, where R is the unknown resistance (strain gauge under test) and R_1, R_2 & R_3 are fixed resistors (known resistance), and a known input voltage, V_i is applied to the bridge circuit. When

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⊙ See Waltham (1980)

⊘ See Heurelen (1986)

the strain gauge undergoes some strain, the gauge length will change to $L \pm \Delta L$ and the resistance will change to $R \pm \Delta R$, then there will be a generation of an electrical output voltage V_o which is proportional to the unit change in the resistance of the gauge, and therefore the output voltage will be proportional to the strain (ϵ). In order to suit the required measurements, and depending on enviromental conditions, the strain gauges may be connected into the **Wheatstone** bridge circuit in full, half or quarter active bridge.

Strain gauges are widely used for different static and dynamic measurements. In this project, strain gauges were used for two purposes:

1. to measure the dynamic strains in brick walls during pile driving.
2. to calculate the applied forces to the pile-head during pile driving using the **CASE** method.

4.2.3.2 Strain Gauge Amplifier

A strain gauge attached to an object produces a very small change in resistance when the object is affected by an external force, and so an amplifier is used to enhance the output voltage. The amplifier unit must provide a high stability input voltage and also must be designed to limit the effect of possible noise on the measuring system.

The strain gauge amplifier used in this project, was designed and assembled by the *Microprocessor Centre* at Durham University. The unit was housed in a rectangular aluminum frame (dimensions=45 $\times$ 32 $\times$ 13.5cm, weight=9.5kg) and contained 12 individual electric circuit cards (modules) which slid into the sub-rack frame via the module guides. A quarter-bridge circuit was used for strain gauge connection. The rear panel of each card was fitted with a 32-way connector plug into a 24-way socket fixed at the rear of the sub-rack panel. The front panel of each card was fitted with a

- balance indicator (the balance is zero when the needle is placed between the two red triangles)
- balance control button (when it is pushed in, the needle on the indicator shows

the gauge calibration)

- balance adjuster (a 10 mm potentionmeter to adjust the gauge calibration)
- gain control (gain 1 or 10 can be selected)
- handle (for insertion or extraction of the card in or out of the sub-rack frame).

Each card was fixed to the sub-rack frame by two locking screws located at the top and bottom of the card. The strain gauge cables were connected to the rear panel of the amplifier unit using 4-way fanning strip which located into a 4-way barrier strip using screw connections. A BNC socket was available for each individual channel at the back of the unit, used to send the gauge output information to a recorder unit or to an oscilloscope. Also a 23 way D connection socket is fitted to the rear of the unit to take out all the gauge output information to the PDR2 recorder unit. The unit runs on 240 volts alternating current (AC) which can be supplied from any main current or a generator. A transformer is used to supply the amplifier with 8 volts DC. To reduce the effect of possible noise on the output results, the transformer is seperated from the main unit. Plate (4-6) shows the features and components of the amplifier from three different angles.

4.2.3.3 Strain Gauge Calibration

Two strain gauges type (FLA-3-11), length 3mm, resistance $120 \pm 0.3\Omega$, and gauge factor of 2.12, similar to those used in field tests, were attached to a rectangular steel bar of cross-section($18.5 \times 8mm$) and length 128cm. The bar was clamped at one end while a maximum of 20kg load was applied to the cantilever tip. The gauge cables of one of the strain gauges was taken to a gauge transducer (Model HW1-D) to read the magnitude of the strain in the bar, and the other gauge cable was connected to the PDR2 unit via the strain gauge amplifier. The gain factor on the strain gauge amplifier card was adjusted until one 'PDR-2 unit' was equal to one microstrain as indicated by the gauge transducer. So the figures on the PDR2 unit (while using option 11, see section 4.3.2.2) corresponded to the magnitude of strain in the bar.

4.3 Recording Equipment

The aim of this section is to describe the equipment used in recording the ground vibration data. The equipment includes two prototypes of *portable digital recorder* PDR1 and PDR2. The recording technique of the PDR units is based on digitizing the analogue voltage signals defining ground vibration received from the transducer. The first model PDR1 was built by the *Microprocessor Centre* in early 1985. The unit was supplied with two programs to be used during the recording and analysing procedures. The recording program was used with the PDR1 to record the data, while the analysing program was used with a micro-computer DUET-16 to process the data. The unit was successfully used for monitoring and recording ground vibration in various sites until a more advanced model PDR2 was built in early 1987. The PDR2 forms a complete and independent unit in recording as well as processing and analysing the recorded data allowing the final result to be processed even on the site. Further information about these two units is given in the following section. Lists of the program's commands are presented at end of this section and a full description of the use of the programs is given in Appendix A3.

4.3.1. The PDR1 Unit

4.3.1.1 Introduction

The PDR1 (portable digital recorder) is a vibration recording device with analogue to digital converter facilities. The unit has the facility for recording data by storing temporarily the captured data received from geophones on its microprocessor board, and these can be stored on to floppy disc if required. The collected data on the disc is then transferred to another floppy disc to be used with a personal computer DUET-16 for processing and analysing the data. The ground vibration results can then be presented in terms of peak particle velocity of the three orthogonal axes and their relevant frequencies. By connecting the DUET-16 to a plotter and printer a permanent copy of the results can be obtained.

4.3.1.2 Specification

1. **Data capture**: includes 16 channels multiplexer, 12 bit analogue to digital converter (ADC), a 16 bit processor chip (Motorola 68000), and 256k RAM.
2. **Discdrive**: a single 5.25 inch floppy disc drive.
3. **Screen**: a small liquid crystal display (LCD) screen with 40 characters in each of two lines.
4. **Keyboard**: 16 key alphanumerics pad.
5. **Connection**: To a manifold (small diecast box($12 \times 12 \times 8cm$)) with 16 UHF sockets to be connected to up to 16 geophones.
6. **Casing** The unit is housed in a metal case of dimensions:($26 \times 36 \times 12cm$). and weight:(8.4kg).
7. **Power Supplies**: can be powered either from;

a. Mains current via a transformer to supply the unit with 2×13 and 1×5 volts. The transformer uses 240 volt AC input supplied either from a generator or from a standard mains source.

b. Detachable portable battery pack housed in a case similar to that of the PDR1 unit (size=$26 \times 36 \times 12$cm, Weight=12.6kg).

A general view of the PDR-1 unit together with its battery pack is shown in plate (4-7).

4.3.1.3. Operation

In order to operate the unit, the unit is first connected to a power supply via a transformer to feed the unit with 5 and 13 volts DC power. The unit can also be powered by a dedicated battery pack, but experience proved its unreliablity after a short life. In later work a portable Honda generator supplied 240v to the transformer. The connection cable from the transformer to the unit was very sensitive especially at the contact surface of the plug and socket, which had to be kept clean during site measurement. By switching on the unit and the disc-drive, the indicators on the left hand side of the discdrive will turn on. If some of the indicators did not turn on, it meant that the connection was faulty and needed to be checked.

When the PDR1 unit was ready for operation, a pre-formatted and pre-programed 5.25 inch floppy disc was inserted and the disc drive was switched on (the lever was turned clockwise downwards), and after few seconds the following information was displayed on the screen.

enter main option number

This showed the unit was ready to receive the user commands. The A and D keys of the unit had the following functions:

[A] : return or run

[D] : delete or cancel

4.3.1.4 Software Programs

Two main software programs were written in FORTRAN77 by *J.Swift* from the *Microprocessor Centre*, and supplied with the unit for recording and analysing the data. The recording program was used with the PDR1 unit while the analysing program was used with a DUET-16 microcomputer available in the department. The details of the programs are briefly explained in the following sections. A full explanation is given in Appendix (A3.1).

a. Recording Program

This program is used to record the vibration data received from the transducers. The data first will be stored on the processor board of the unit and then may be saved on formatted floppy discs if required. The recording program contains seven options and their functions are described in table (T4.2).

The first three options deal with setting up the configuration data in which *option(2)* loads an existing configuration data from the disc into the memory, *option(1)* modifies the set up data and *option(3)* stores the new configuration set-up into the disc. The next three options deal with recording data where *option(5)* clears the memory, *option(6)* captures data and *option(4)* stores the captured data into a provided disc. Finally *option(7)* is used to monitor the maximum voltage signals of the first three channels on the screen in terms of the PDR1 units which can simply be calculated to obtain the level of vibration of the site, see Appendix (A3.1.1).

Option 1 contains 31 parameters. These parameters control the set up of the configuration data for example, trigger level, sampling length, sample interval...etc. A list of these parameters with a brief description of their functions is given in table (T4.3).

b. Analaysing Program

A microcomputer (SDC DUET-16) was used to analyse the data collected by either PDR1 or PDR2⊙. The microcomputer DUET-16 comprises a high resolution coloured VDU for text and graphic display, double disc-drive, keyboard and connections facilities to printer and plotter. Two analyses programs were used together with the system disc program MS-DOS(8086). The programs are;

1. MAIN16 : *transfers data from* PDR *disc to* DUET *disc*
2. CAL16 : *analyses the data on* DUET *disc*

These two programs were written in FORTRAN 77 by *J.Swift* from Microprocessor Centre. The program contains a number of commands, where the MAIN16 commands are listed in table (T4-4) and the CAL16 commands in table (T4-5).

1. MAIN-16

This program must always be used first to transfer the recorded vibration data from the field disc to a DUET disc. The field data disc should be inserted into drive A and the other disc into drive B of the Duet-16 unit. Then the program is loaded to the unit⊖, and the sequence of commands listed in table (T4-4) is used to complete the procedure of transferring the data. A full description of the program operation is given in Appendix (A1.2.1).

⊙ See option 10 from section 4.2.2

⊖ the DUET disc should already be loaded with the MAIN16 program

2. CAL-16

The program is used to process and analyse the vibration data recorded on the site in terms of peak particle velocities and the dependent frequencies regarding their calibration factors. The data processing provides the following facilities:

1. colour displaying and plotting of the recorded vibration as a function of time in the form of a single or group of channels with a line of title with 60 characters.
2. calculation of the time dependent peak particle resultant vector of three orthognal vibrations registered in three individual channels.
3. calculation of frequency on either a natural or log base using the fast fourier transform analysis.
4. printing the output results using a dot-matrix printer.

The list of the CAL-16 commands is displayed in table (T4-5) and the detail of program operation is given in appendix (A3.1.2).

4.3.2. The PDR2 Unit

4.3.2.1 Introduction

The portable digital recorder/processor PDR2, is the modified and developed version of the original model PDR1 which has been discussed in the preceding section. The PDR2 unit contains a computer processor board (Motorola 68020) and uses four analogue to digital convertors each with multiplexer for its recording system. On receiving analogue information from the transducers, the PDR2 can store the data as digital information on its processor boards RAM, and traces can also be displayed graphically on a screen provided within the unit. The raw data then can be copied onto floppy discs if required to be used for the analysis procedure. The process of data analysis provides the measurements of the ground vibration in terms of peak particle velocity, acceleration and displacement, vector combination of orthogonal signals, frequency spectra using fast fourier transform analysis (FFT), windowing and filtering facilities, plotting of single or groups of single channels with their relative information using a multicolour pen plotter and finally the print out of all the resolved results.

Selby & Swift (1989), summarized the general features and facilities of the PDR-2 unit in the following points:

1. Application of calibration factors for the various transducers.
2. Colour plotting of the recorded vibrations as a function of time, scaled as required and with different signals collected on to one plot. Full titles, scaled axes etc.
3. Time-based vector resolution of three orthogonal signals.
4. FFT analysis of any signal, with windowing, on either a natural or a log base of frequency.
5. Integration of velocity signals to give displacement.
6. Differentiation and filtering to give transient acceleration.
7. General arithmetic operation on combinations of signals.

The procedure of data processing is shown schematically in figure (4.1).

The PDR-2 unit is built to withstand the conditions of pile driving sites. Plate (4.8) illustrates a general feature of the unit in three different views. Also the components and dimensions of the unit are shown in figure (4.8). The whole assembly is housed in a wooden box. On the upper part of the box is a lid which contains a backlit screen. The top panel of the box comprises a key board, a double disc-drive, a switch key, a set of function keys, and four sockets used with serial connectors to plotter, printer, strain gauge amplifier and an external computer. The back panel contains 30 UHF sockets, a pair of filters, and a standard mains socket. Two handle grips are fitted to the sides of the box.

A full description of the unit specification, operation and programs is given in the following section.

4.3.2.2 Specification

Capacity processor board is `Motorola 68020` chip with 32bit bus one Mbyte of static RAM *(Hitachi HN 62256, LP-10)*, 4×12 bit A/D convertors with multiplexers to allow up to 64 standard channels or 32 standard channels plus 4×1.6 μs channels.

Transformer econoflex(FXT 90/15) open frame. 220V input, 5V output and temperature range ($-0^oC \quad +60^oC$).

Disk drive dual drive with two 5.25 inch single sided disk drives. The drives are supplied with LED light indicaters which turn on when the drive is accessed.

Keyboard flexible membrane key board. The surface is impervious to dust or liquids which makes it withstand a hostile environment. An on board tone generator provides audible key press feed back with a small integral speaker.

Screen initially LCD flat screen($28 \times 12.5cm$), displaying graphics and text in 80 character by 20 lines(640×200 dot). This screen was replaced by a backlit screen.

Fan axial flow fans*(120mm diameter)* to pressurize the interior of the box to assist in exclusion of dust.

Filter consists of *inner plate* with steel mesh, *replacement filter* with 5 microns particle size filter and *outer cover* in plastic with integral grille.

Dimension the dimensions of overall wooden box are $51 \times 33 \times 45cm$, see figure (4.8) for more detail.

Weight the weight of the complete unit is 31.00 kg.

Switch Key two-position rotary switch key

Connectors through *Parallel cable strips* connected to:

1. *Plotter*: 8-pen, A4, Hewlett Packard Colorpro plotter.
2. *Printer*: dot matrix Citizen (MSP-10E)
3. *PC Computer* or any external VDU terminal
4. *Strain gauge amplifier*.

4.3.3.3 Operation

The PDR2 unit runs on 240v alternating current (AC) supplied either from a standard mains current or by a portable generator. Usually a mains filter is used between the power supplies and the unit to filter out any spiky signals. To operate the unit, the key switch should be turned clockwise. The switch has two positions, the first enabling the *reset* and *abort* push buttons to be used, while the second disables them. In the laboratory, or while processing the stored data, it may be convenient to leave the reset facility active, but in the field the key switch should be fully clockwise so that accidental operation of the reset button does not cause loss of data.

When the PDR2 is switched on, the following message will display on the sreen:

```
(data section initialised, code = 001f)

Durham University
Microprocessor Centre
M68020 monitor, version 5.01 (ram top = 0 × 100000)

.
```

The prompt "." shown means the operating system is ready to recieve the operation commands. If an external terminal (VDU) is to be connected to the unit, the following command should be first typed in immediately after the unit is switched on;

```
ass con line0 (return)
```

The prompt"." will transfer to the terminal screen and the PDR2 commands can operate through the terminal.

4.3.3.4 Programs

There are three main programs used to run the PDR2 unit. The programs are written in "C" language by J.Swift, M.Kolar and P.Baxendale from the *microprocessor centre.* These programs include:

a. Monitor Disc Program

b. Recording Program(pdr)

c. Analysing Program(DANA)

Each of these programs contains a range of commands which provide different functions. The description of the programs is reviewed in the following sections.

a. Monitor Disc Program

This program is stored on the processor board `ROM` (*read only memory*) of the unit and includes a number of commands most of which have applications similar to any `MS-DOS` commands. When the `PDR2` unit is switched on, type **`help`**, then press the **`return`** key, causes a list of commands to be displayed on the screen. This program is used to format a blank disc to either the `IBM` or `DUET` system. The program also allows the operator to load, list, delete, copy, or save any file of an inserted disc into either disc-drive `0` or `1`. Some of the most applicable commands are listed in table `(T4-6)`. More details of the commands applications and their use are given in Appendix `(A3.2.1)`.

b. Recording Program (pdr)

This program is used to record the vibration data send to the `PDR2` unit via the transducers in the field. The program includes 13 options which provide a range of facilities within the recording system. On running the program these options will display on the screen. A list of these options is given in table `(T4-7)` and are fully explained in Appendix `(A3.2.2)`. A brief description of their functions is given below:

option 0 : changes and modifies the configuration set-up file. This can be done by the use of the nine parameters which will display on the screen once option(0) is used. These parameters control the speed of recording, sampling time, points before and after trigger, number of triggered channels and selection of the channels to be triggered.

option 1 : loads the default configuration into the currently used disc.

option 2 : clears the memory of any possible registered data.

option 3 : captures the induced vibration data via the transducers.

option 4 : displays the captured raw data on the screen. This is very a useful facility in checking and monitoring the recorded data on site where the magnitude of the induced vibration can also be calculated.

option 5 : saves the modified configuration set-up (by option 0) into the loaded disc.

option 6 : loads any configuration set-up file from the loaded disc into the memory.

option 7 : saves the recently collected data onto the loaded disc. This option should be used immediately after the use of option 3 and 4.

option 8 : reloads any data file specified by a name from the disc into the memory.

option 9 : changes the currently used drive number to either 0 or 1.

option 10 : writes the collected data on a disc loaded in drive 1 to be processed with the `DUET-16`.

option 11 : reviews the maximum and minimum amplitude of the connected transducers on the screen. Again this option can be used to calculate the amplitude of vibration recieved in any particular channel. The values are presented in `"PDR units"` which can easily be converted to ppv values. Also the displayed information can be used to identify any possible faulty transducer connected to the unit.

option 12 : returns to the operating system program.

option 13 : displays the input power supply voltage.

The display of the above functions indicates the advantages and the flexibility of the program in recording the ground vibrations on site.

c. Analysing Program (DANA)

This program is used to process the data recorded by the PDR2 unit. The name DANA is taken from **DATA ANALYSER** and is followed by a figure e.g. DANA3 or DANA5, which represents the latest modified version. The program was written in C by *J.Swift* and *M.Kolar*, is stored on floppy discs and is specific to the PDR2 unit. The data may be transferred to any personal computer by means of special commands available within the program.

The DANA program is used to process the data recorded by the PDR2 received from velocity transducers (geophones), to obtain the ground vibration measurements in terms of peak particle velocity($mm.s^{-1}$). The data may then be integrated or differentiated with respect to time to obtain the peak particle displacement(mm) and acceleration($mm.s^{-2}$), respectively. Also the program enables calculation of the relevant peak particle resultant vectors as a function of time for any three specified orthogonal channels. The program uses the fast fourier transform (FFT) analysis to obtain the power spectrum to either natural or logarithmic bases for the measured vibration frequencies (Hz). Other features of the program include graphical and digital display of the processed data, filtering spiky signals, plotting the graphic and text information when connected to a plotter and finally printing the output results via a printer. Also the program can provide direct measurement of strain or acceleration when the PDR2 unit is connected to strain gauges or accelerometers respectively as the active transducers.

The DANA program is formed by a number of subroutines which provide a wide range of options. The functions of these commands are briefly described in tables (T4-8). More details of the commands operation can be found in Appendix (A3.2.3).

Table (T4-1A)

Orien-tation	Geo. No.	Input Freq.(Hz)	Geo. Output Voltage(v)	Acce. Output Voltage(v)	Geo. Calib. Constant		Geo. Calib. Factor
					Calculated	Average	
Set (A)							
Radial	H5	20	0.806	3.609	27.15		
		50	0.241	2.752	25.64	26.48	0.0921
		70	0.151	2.452	26.65		
Transverse	H6	20	0.761	3.466	27.15		
		50	0.200	2.520	25.64	26.28	0.0929
		70	0.245	4.069	26.06		
Vertical	V3	20	0.122	0.593	25.44		
		50	0.216	2.655	25.15	24.97	0.0978
		70	0.138	2.455	24.32		
Set (B)							
Radial	H2	20	0.782	3.546	27.27		
		50	0.223	2.621	26.30	26.70	0.0914
		70	0.146	2.381	26.54		
Transverse	H9	20	1.105	5.196	26.36		
		50	0.207	2.485	25.75	25.63	0.0952
		70	0.134	2.340	24.78		
Vertical	V5	20	0.131	0.588	27.55		
		50	0.210	2.355	27.56	27.20	0.0897
		70	0.132	2.155	26.50		
Set (D)							
Radial	H8	20	0.700	3.150	27.48		
		50	0.252	2.890	26.95	27.06	0.0902
		70	0.163	2.638	26.74		
Transverse	H7	20	0.771	3.527	27.03		
		50	0.222	2.615	26.24	26.44	0.0923
		70	0.145	2.409	26.05		
Vertical	V4	20	0.758	3.415	27.45		
		50	0.228	2.625	26.85	26.80	0.0910
		70	0.146	2.420	26.11		

Table (T4.1B)

Orientation	Geo. No.	Input Freq.(Hz)	Geo. Output Voltage(v)	Acce. Output Voltage(v)	Geo. Calib. Constant Calculated	Geo. Calib. Constant Average	Geo. Calib. Factor
Set (E)							
Radial	H3	20	0.670	3.070	26.99		
		50	0.216	2.525	26.45	26.46	0.0922
		70	0.142	2.369	25.94		
Transverse	H4	20	1.252	5.643	27.43		
		50	0.251	2.856	27.17	27.33	0.0893
		70	0.146	2.308	27.38		
Vertical	V2	20	0.718	3.563	24.92		
		50	0.235	2.990	24.29	24.29	0.1005
		70	0.150	2.744	23.66		

Set (C)

Mark-product Geophones

Orientation	Geophone No.	Geo. Calib. Constant Supplied	Geo. Calib. Constant Calculated	Geo. Calib. Factor
Radial	H1(6373)	275	281	0.0087
Transvrse	H2(6372)	280	277	0.0088
Vertical	V1(6374)	279	274	0.0089

Table (T4-2)

List of the PDR-1 Recording Commands		
Option number	Functions	Drive's mode
1	modifies the set-up data	off
2	loads the set-up data from the disc	on
3	saves the set-up data to the disc	on
4	copies the captured data to a disc	on
5	clears the PDR1 memory	off
6	starts capturing data	on
7	monitors the vibration level	off

Table (T4-3)

List of the Parameters, Option (1), PDR-1	
Param. no.	Parameter's Function
0	trigger level, channel one
1	trigger level, channel two
2	trigger level, channel three
3	sample length (sample points)
4	points before trigger
5	sample interval(10 microseconds)
6	user integer one (date)
7	user integer two (time)
8	user integer three (site)
9	user integer four (direction)
10	number of channels to be sampled
11	not used
12	not used
13	not used (delay before trigger)
14	number of data set
15	monitor time period (sec)
16	monitor the 1st channel (chan 0)
17	monitor the 2nd channel (chan 1)
18	monitor the 3rd channel (chan 2)
..	...
..	...
31	monitor the 15th channel (chan 14)

Table (T4-4)

Commands of the MAIN-16 program, PDR-1		
Commands list	Functions	Drive's mode
READHOME	reads home block content from the PDR1 formated disc	on
DISPHOME	displays the home block content on the screen	off
FILEREAD	loads a data file from the PDR1 disc into the memory	on
FILEWRIT	writes the loaded file into a DUET disc	on
EXIT	terminates the MAIN16 programme	off
USE	calls a pre-written multi-commands file from the loaded disc	on

Table (T4-5)

Commands of the CAL-16 program, PDR-1		
Commands list	Functions	Drive's mode
READFILE	reads a file from the disc	on
GETSET	reads a data set number from the file	on
GETCAL	reads the calibration file from the disc	on
DISPCAL	displays the calibration file on screen	on
DISPNUM	displays the number of drawing channels	on
DISPMAX	displays the maximum values for channels	on
DISPREG	draws the contents of the register	on
DISPSPEC	draws the calculated spectrum	on
DRAW	draws the uncalibrated data	on
DRAWCAL	draws the calibrated data	on
CALMAX	calculates the maximum of calibrated channels	on
REGMAX	displays the maximum values obtained by CALMAX	off
COPY	copies a channel data into the register	on
SUMSQ	adds the squared calibrated data into the register	on
ROOT	takes the square root of the registered data	on
SPECTRUM	calculate the power spectrum of registered data using FFT	on
LOGSPEC	takes the natural log of the registered data	on
REGCLEAR	clears the register from any data	off
SCRCLEAR	clears the screen from any data	off
SETDCHAN	sets the current channel to user channel	off
SETCOL	sets the current channel colour into user colour	off
CONTROL	displays the file configuration set-up	on
STSPEC	allows a point other than one to be used for start of data display	on
USE	activates a pre-created file for fast running CAL-16 procedure	on
HPDRAW	sends the calibrated data to a plotter	on
TITLE	allows to write a text title	on
PRINT	sends the calibrated data to a printer	on
NOPRINT	allows the data to printed on a printer	on
SCDUMP	allows the graphic data to be printed	on
EXIT	terminates the running programme and return to MS-DOS system	off

Table (T4-6)

List of *Monitor Disc Program* Commands, PDR-2		
Commands names	Functions	Disc-drive mode
drive	changes the current disc-drive number	off
dir	lists the directory of the disc file	on
del	delets a file from current disc	on
mkdir	clears all files from the current disc	on
load	loads a file from disc into memory	on
save	copys a file from memory into disc	on
run	activates a loaded program	on
go	resumes an interrupted program	on
history	lists last used 20 commands	off
help	list the commands name and functions	off
format	formats a new disc	on
dcopy	copys the contents of a disc to another	on

Table (T4-7)

List of *Recording Program* Commands, PDR-2		
Options list	Functions	Disc-drive mode
0	changes the configuration data	on
1	sets the default configuration	off
2	clears the memory	off
3	collects the vibration data	off
4	displays the data on the screen	off
5	saves the configuration data	on
6	reloads the stored configuration data	on
7	saves the collected data on floppy disc	on
8	reloads the stored data from the disc	on
9	sets the current disc-drive number	off
10	writes data on drive 1 for DUIT-16 disc	on
11	monitors the max. and min. data on the screen	off
12	returns to the monitor disc system programme	off
13	displays the input power supply voltage	off

Table (T4.8A)

Command list	Functions	Discdrive mode
	Screen Control Commands	
HELP	lists the program commands	off
DRV	selects the disc-drive number	off
DIR	displays the disc contents on the screen	on
CS	clears the screen	off
EXIT	terminates the running program	off
	Calibration Array Commands	
SCALBR	shows the loaded calibration file	off
LOADCAL	loads the calibration file from the disc	on
EDITCAL	allows edit of the calibration file	off
SAVECAL	saves the calibration file on the disc	on
DEFCAL	loads the default calibration file	off
PCALBR	prints the calibration file	off
	Legend Control Commands	
TITLE	enters one line test title	off
DATE	enters the test date	off
CHAR	controls size & orientation of characters	off
TXT	controls position and enters text information	off
TEXT	enters text at the head of plot	off
BOX	draws a framing box and plot the text	off
XLBL	enters x-axis lables	off
YLBL	enters y-axis lables	off
SLEG	shows the legend information	off
	The Use Control Commands	
USE	activates the use command	on
PAUSE	pauses the running program	off
WT	keeps the program waiting	off
lcded	edits and forms a multicommand program	on

Table (T4.8B)

Command list	Functions	Discdrive mode
	Data Control Commands	
LOADDATA	loads the data from the disc to the memory	on
LOADCON	loads the configuration file	on
SCON	displays the configuration file	off
PCON	prints the configuration file	off
DTSET	controls the data set number	off
WIN	shows the window's information	off
WINS	controls the horizontal border of the window	off
WINR	resets the default window	off
FACT	controls the drawing scale	off
KOL	controls the pen's colour & axes	off
KLIP	controls the vertical limits of the plot	off
FILTER	filters spiky signals	off
	Display Data Commands	
EDC	edits display channels	off
SDC	shows display channels	off
DISPNUM	controls the number of channel in the register	off
SETDCHAN	controls the channel number to be displayed	off
SETCOL	sets the colour number for displayed channel	off
DCAL	draws a single x-axis data	off
DCALM	draws multiple x-axes data	off
DRAW	draws uncalibrated data	off
SSS	controls the set skip steps	off
	Plotting Control Commands	
PL	toggles the plot-on/plot-off	off
PLOT	toggles the plot-on/plot-off	off
PLOTON	directs graphics output to the plotter	off
PLOTOFF	directs graphics output to the LCD screen	off
HPTST	draws a test graphic frame	off

Table (T4.8C)

Commands list	Functions	Discdrive mode
Register Calculations Commands		
COPY	copies a data channel to the register	on
DREG	draws the registered data on the screen	off
PREG	prints the registered data	off
CALMAX	calculates PPV for any specified channnel	on
VMAX	calculates PPV for 15 channels	on
AMAX	calculates PPA for 15 channels	on
DMAX	calculates PPD for 15 channels	on
SMAX	displays the maximum registered data	off
PMAX	prints the maximum registered data	off
DISPMAX	displays the max. register	off
REGCLEAR	clears the register from any data	off
ACCEL2	differentiates the register data	off
BINTEG	integrates the register data	off
SUMSQ	sums square of the register	off
SUBSQ	subtracts square of the register	off
SUMCH	sums the registered channel	off
SUBCH	subtracts the reg. channel	off
INV	inverts the sines of registered data	off
ROOT	calculates the root of the squared data	off
VECT	calculates velocity vector	off
VACC	calculates acceleration vector	off
VDISP	calculates displacement vector	off
SPECTRUM	calculates the power spectrum of the data	off
LOGSPEC	calculates the natural log of the spectrum	off
DISPEC	draws the FFT graph	off
PSPEC	prints the FFT results	off
The Communication Commands		
SNDCHAN	sends a channel data to a PC unit	on
SNDCONF	sends a calibration file to a PC unit	on

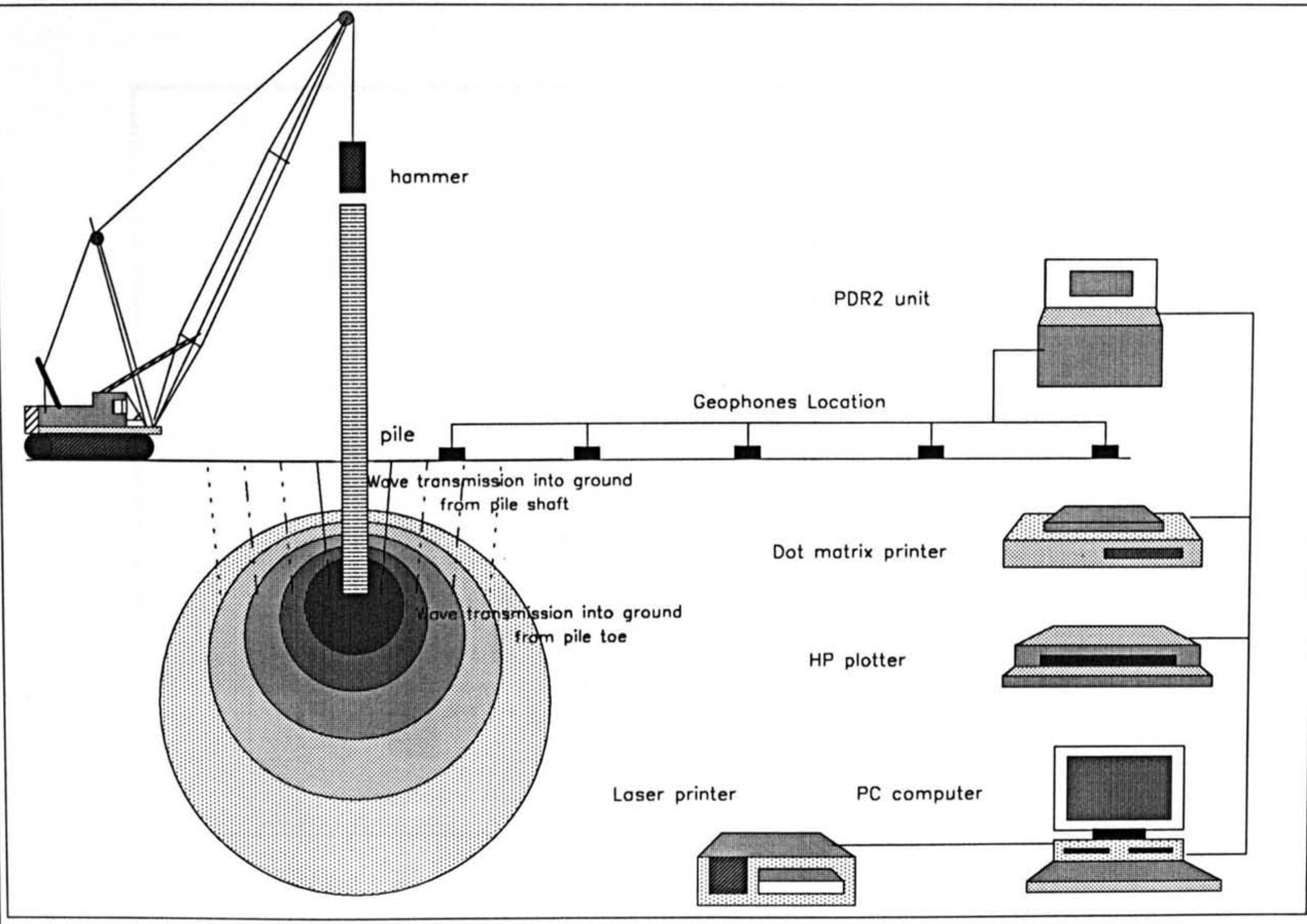


Figure (4.1) Display of equipment used in measuring and processing the ground vibrations

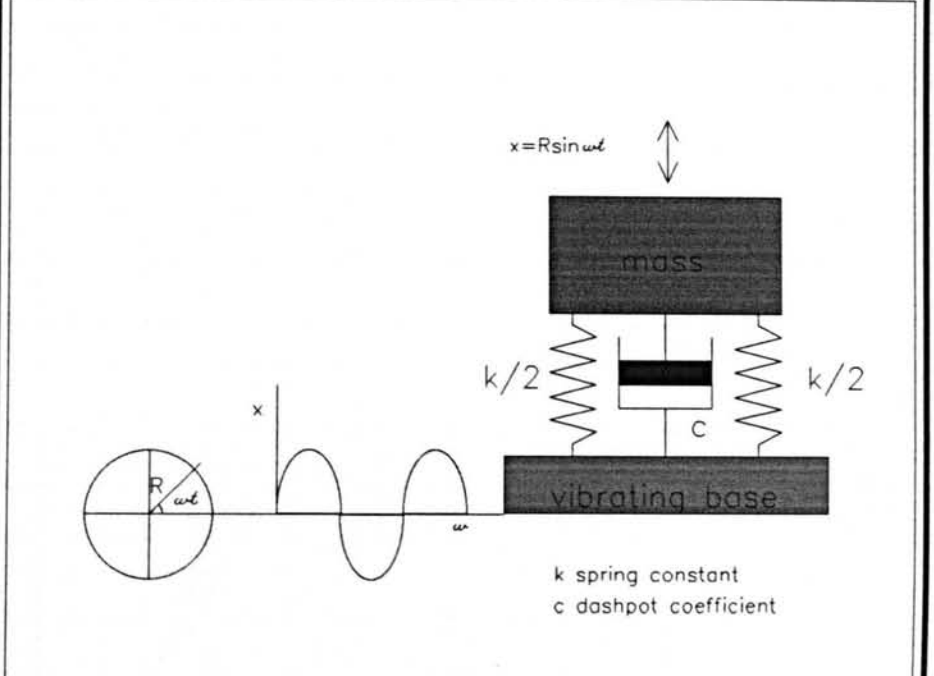
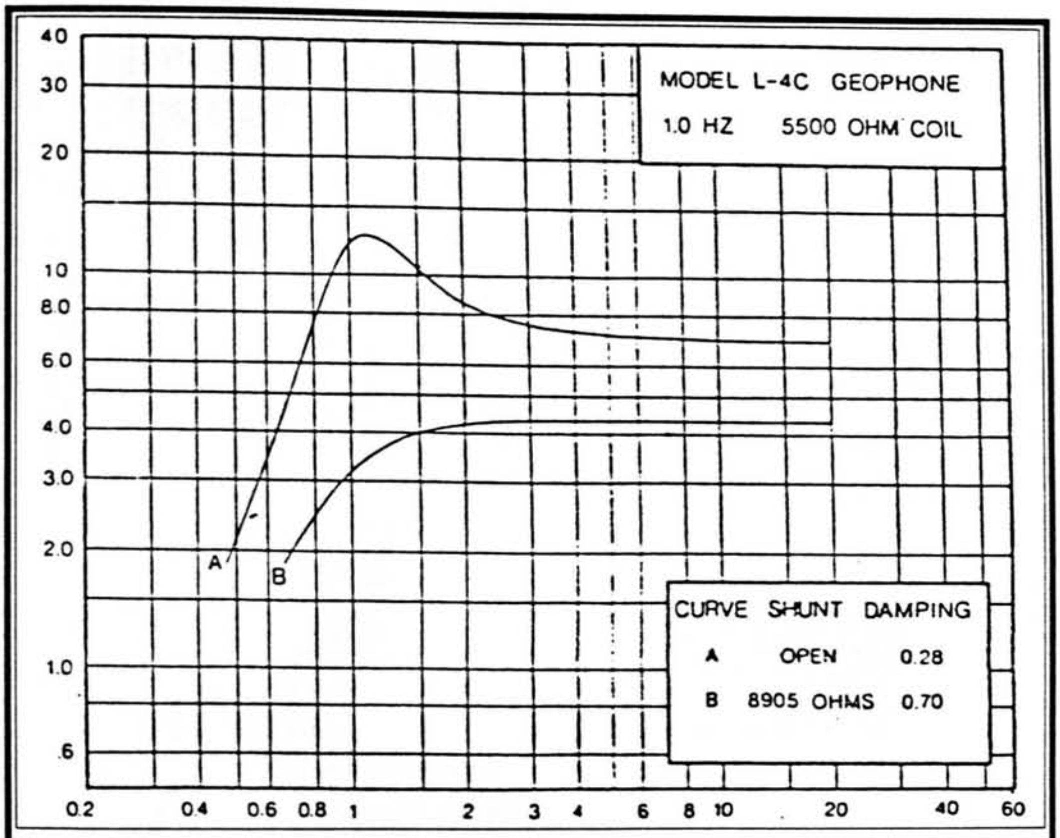


Figure (4.2) Representation of a velocity transducer as spring–mass–dashpot system



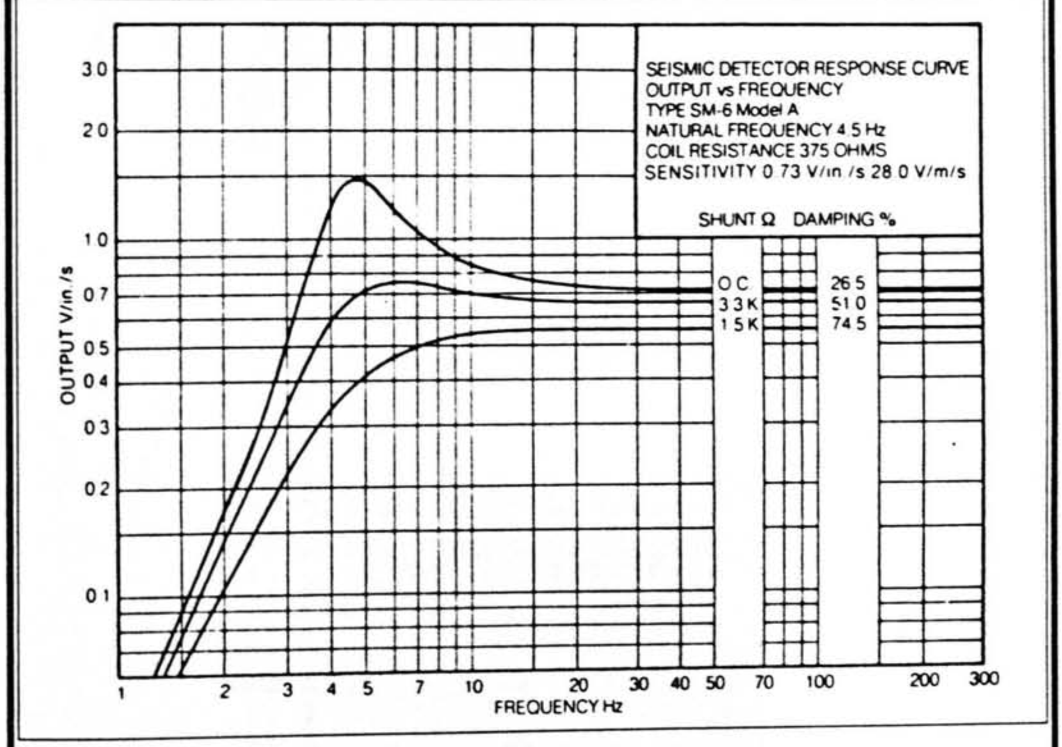


Figure (4.3) Geophone frequency response characters

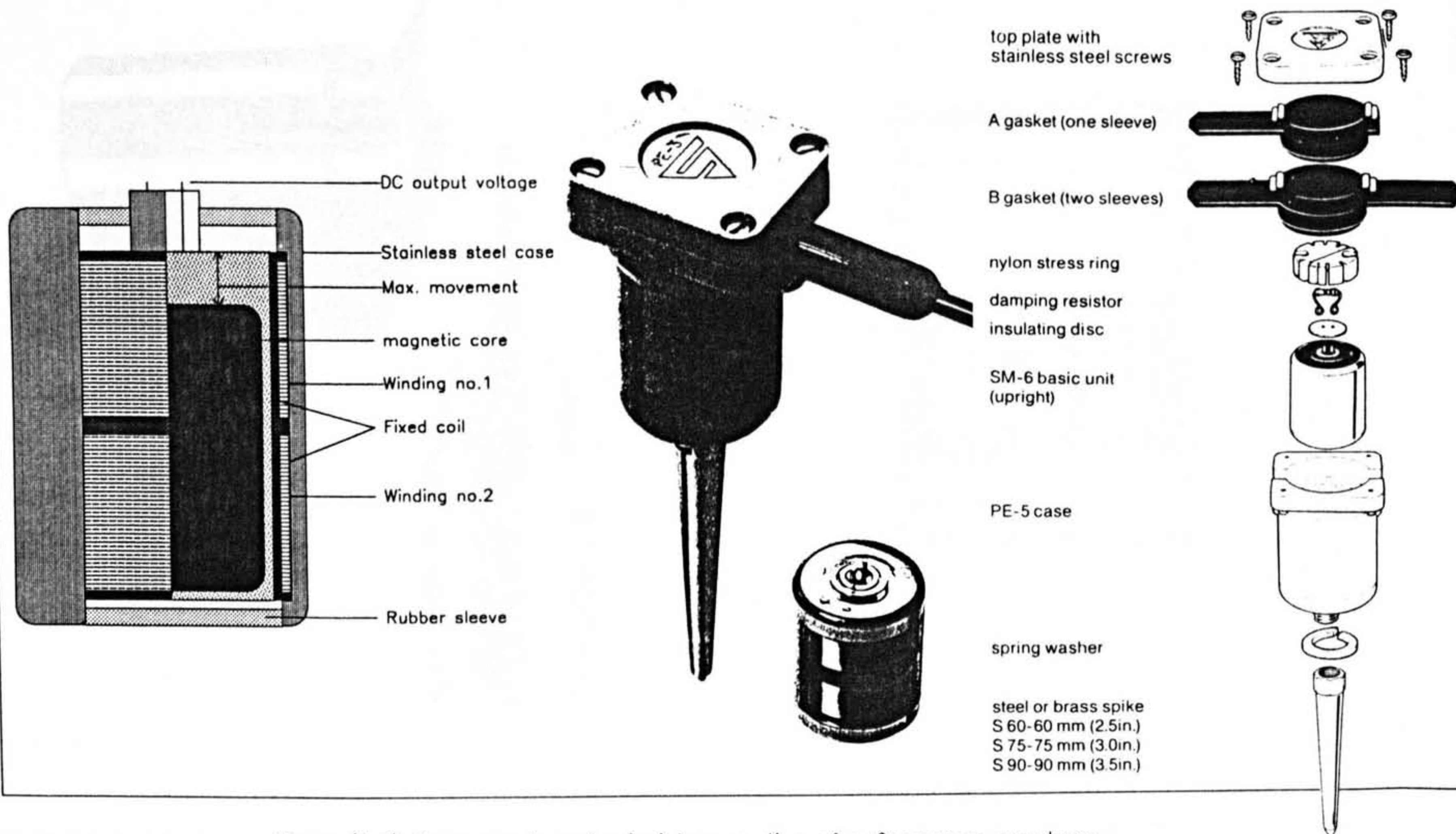


Figure (4.4) Components and principle operation of a Geosource geophone

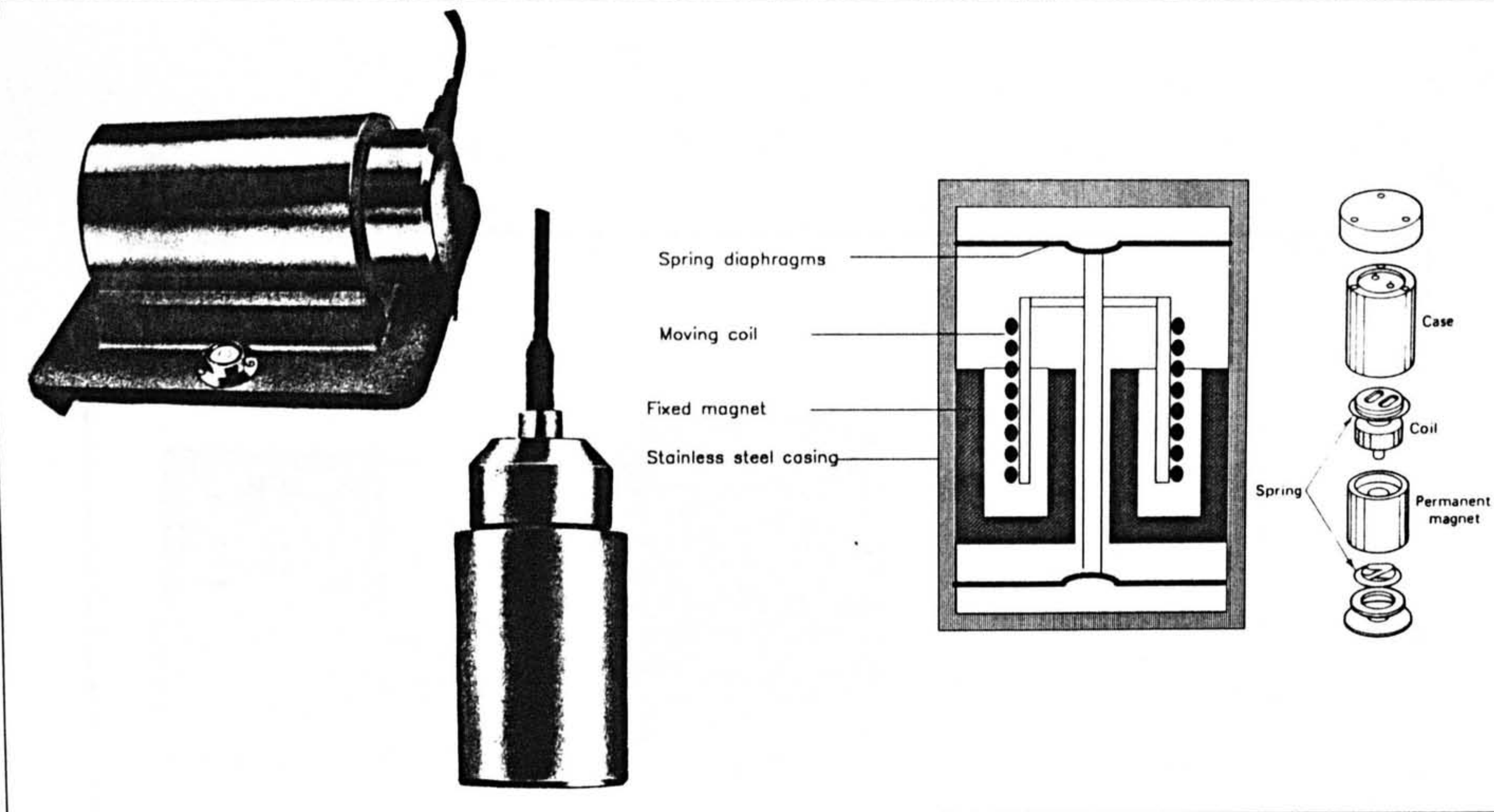
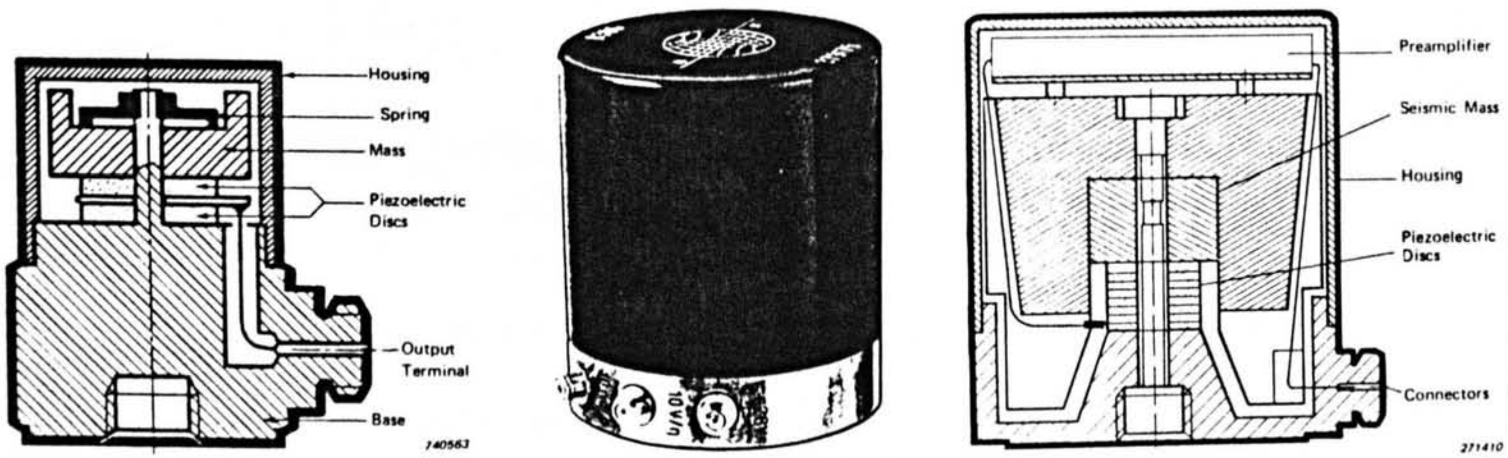


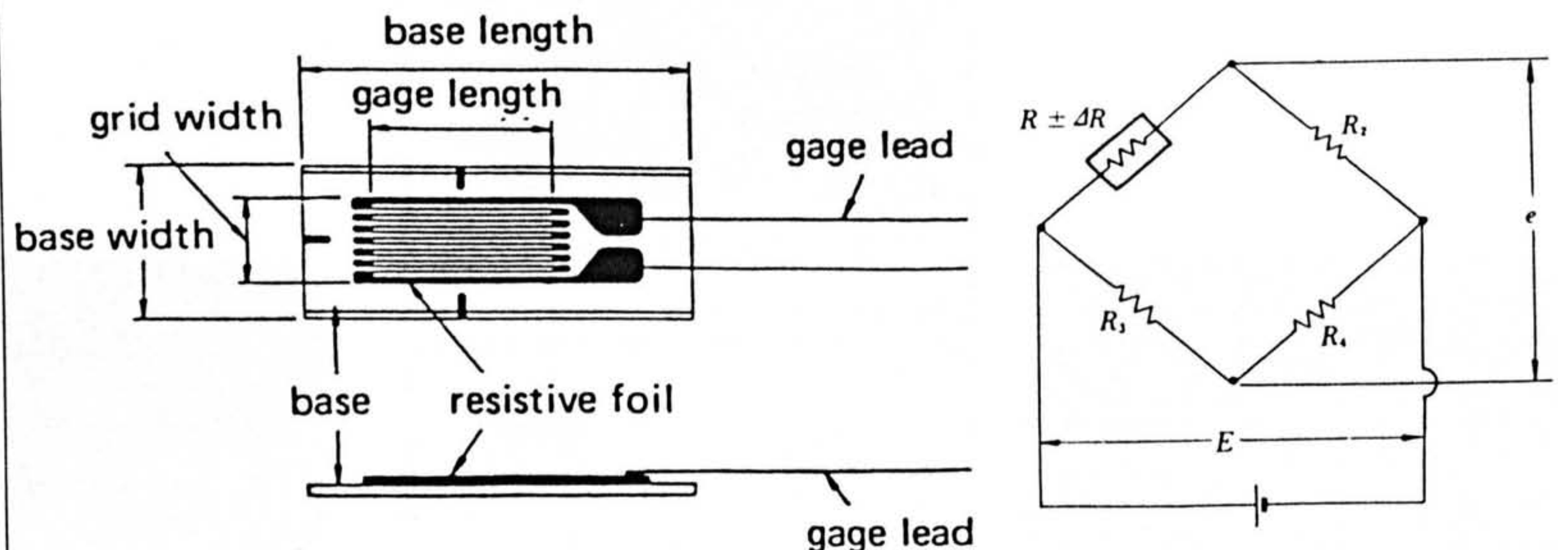
Figure (4.5) Components and principle operation of a Mark–product geophone



a. Schematic construction of piezoelectric accelerometer

b. Low g accelerometer type 8306

Figure (4.**6**) Components and principle operation of accelerometer



a.construction of strain gauge

b.schematic display of Wheatsone bridge circuit

Figure (4.7) Components and principle operation of an electrical resistance strain gauge

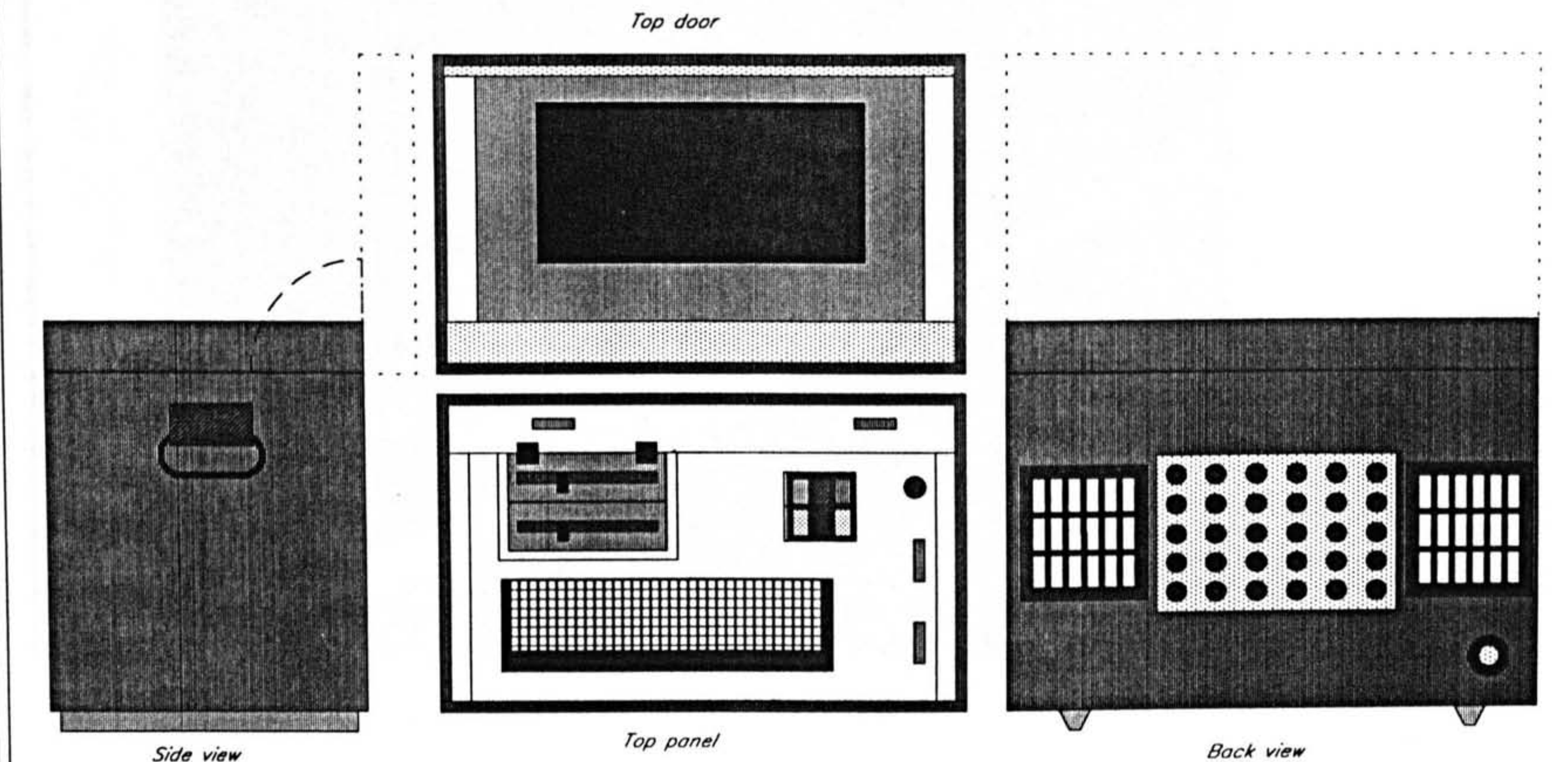


Figure (4 8) Display of different views of the PDR-2 recorder/processor unit

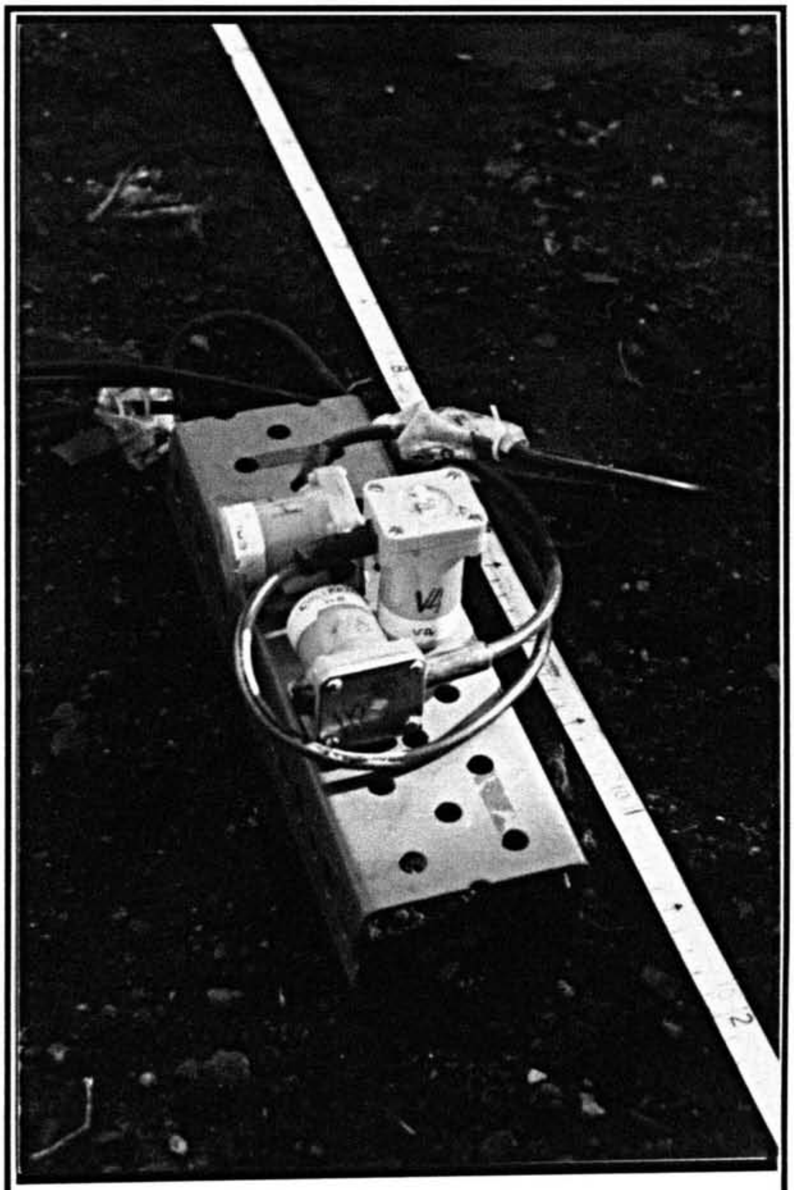


Plate (4–1) Orthogonal mounting of three geophones on a 30cm length of dexion

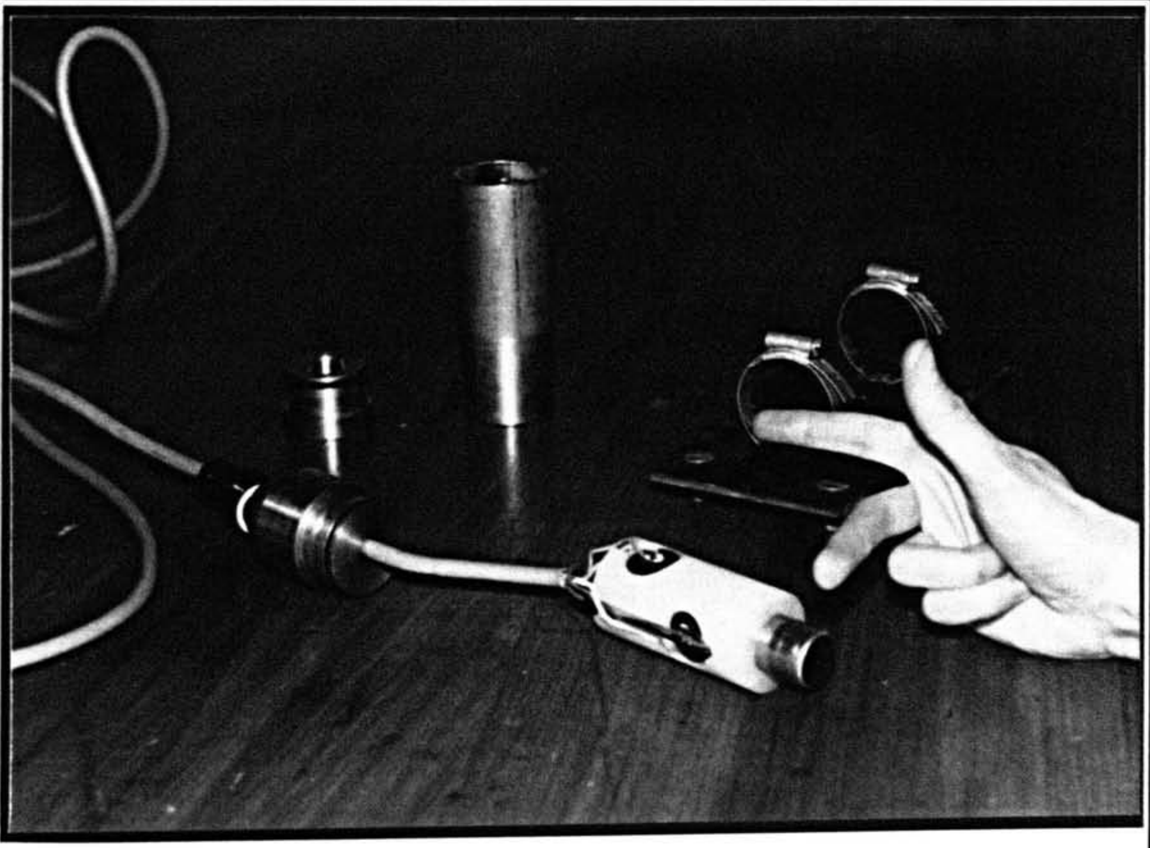


Plate (4–2) Components and orthogonal orientation of three geophones in a steel case

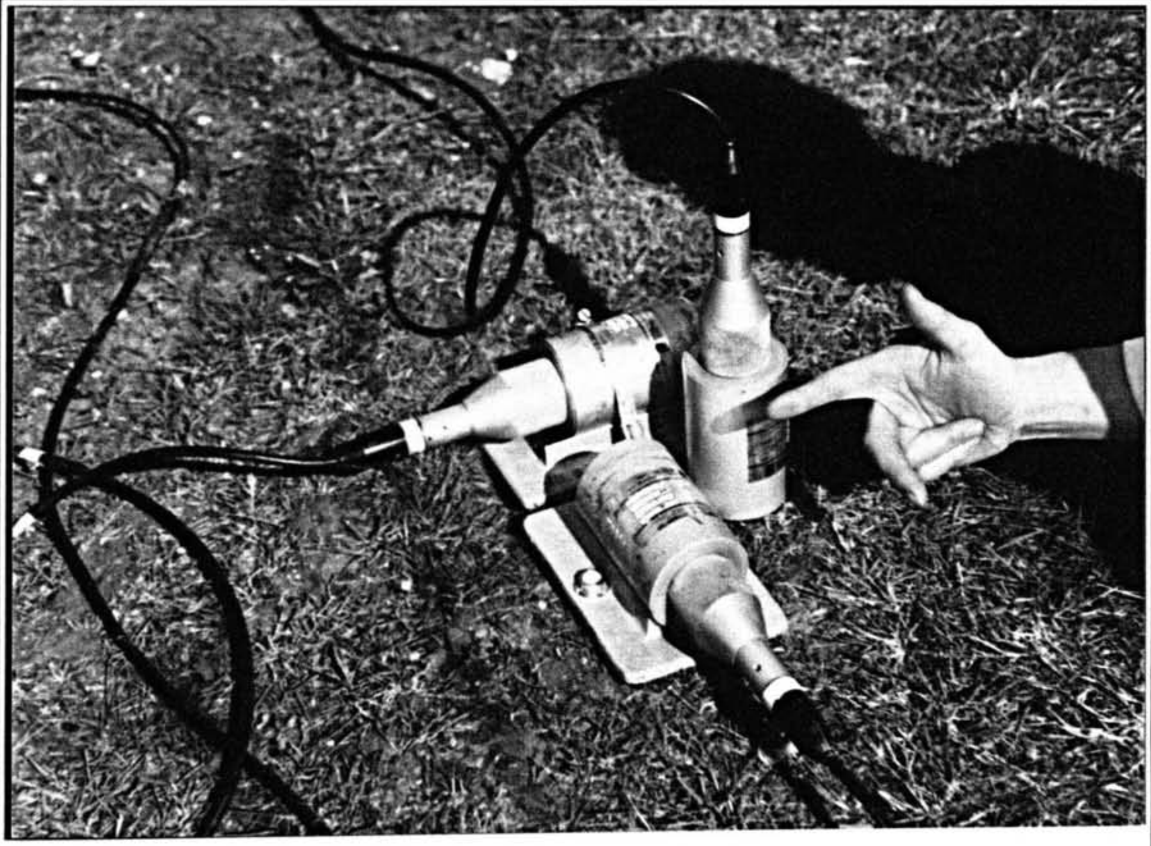


Plate (4-3) Display of three orthogonally located Mark-geophones

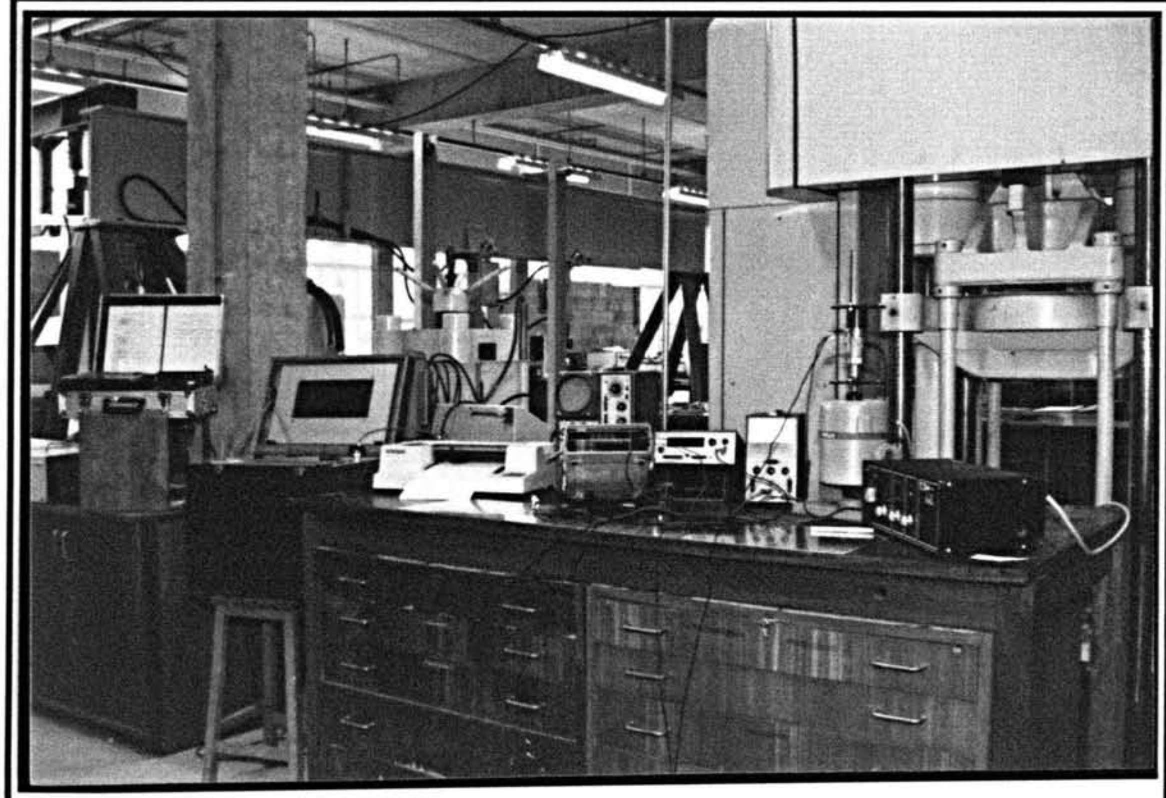


Plate (4-4) Equipment used during calibration of geosource geophones

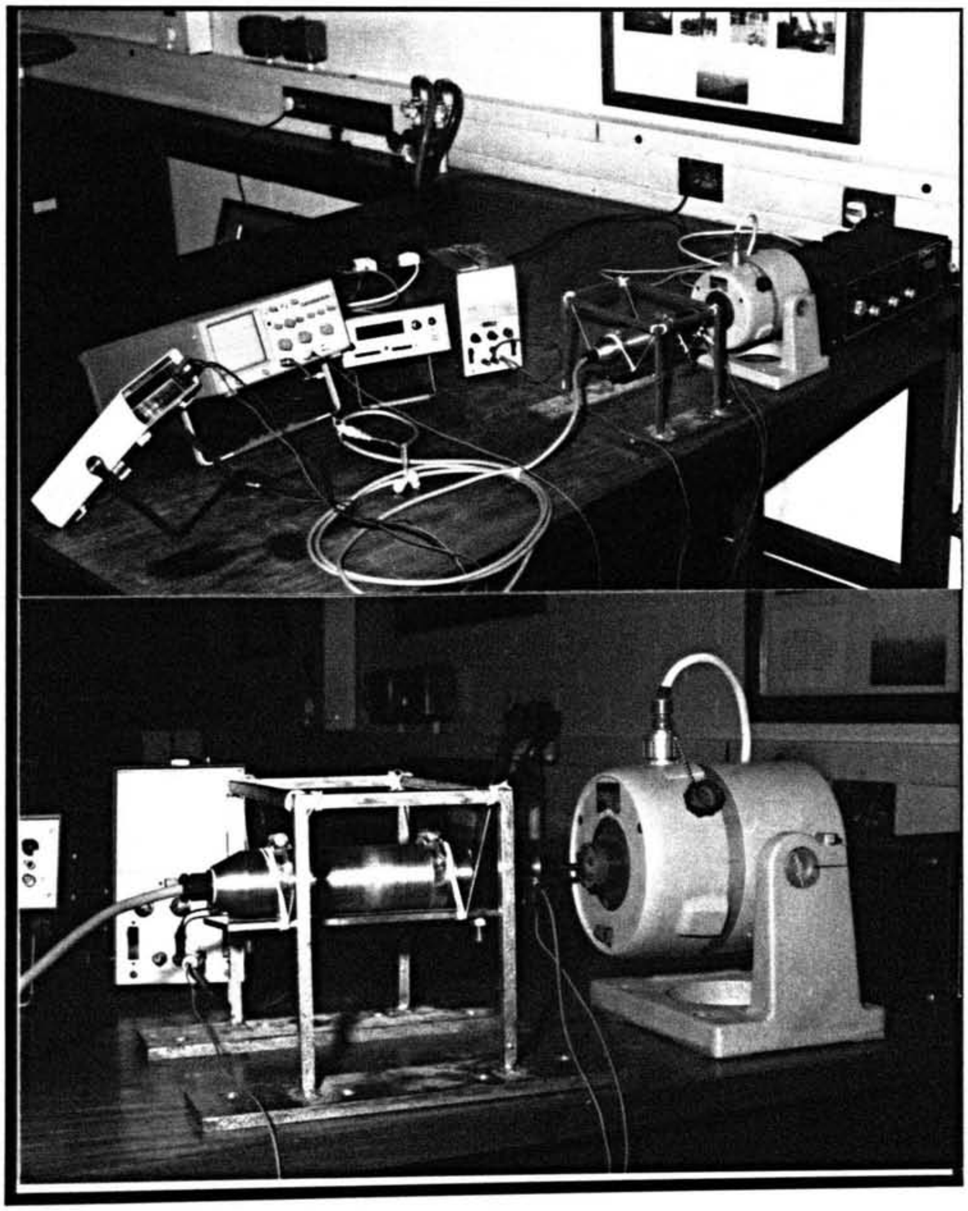


Plate (4–5) Calibration of the second set of geophones

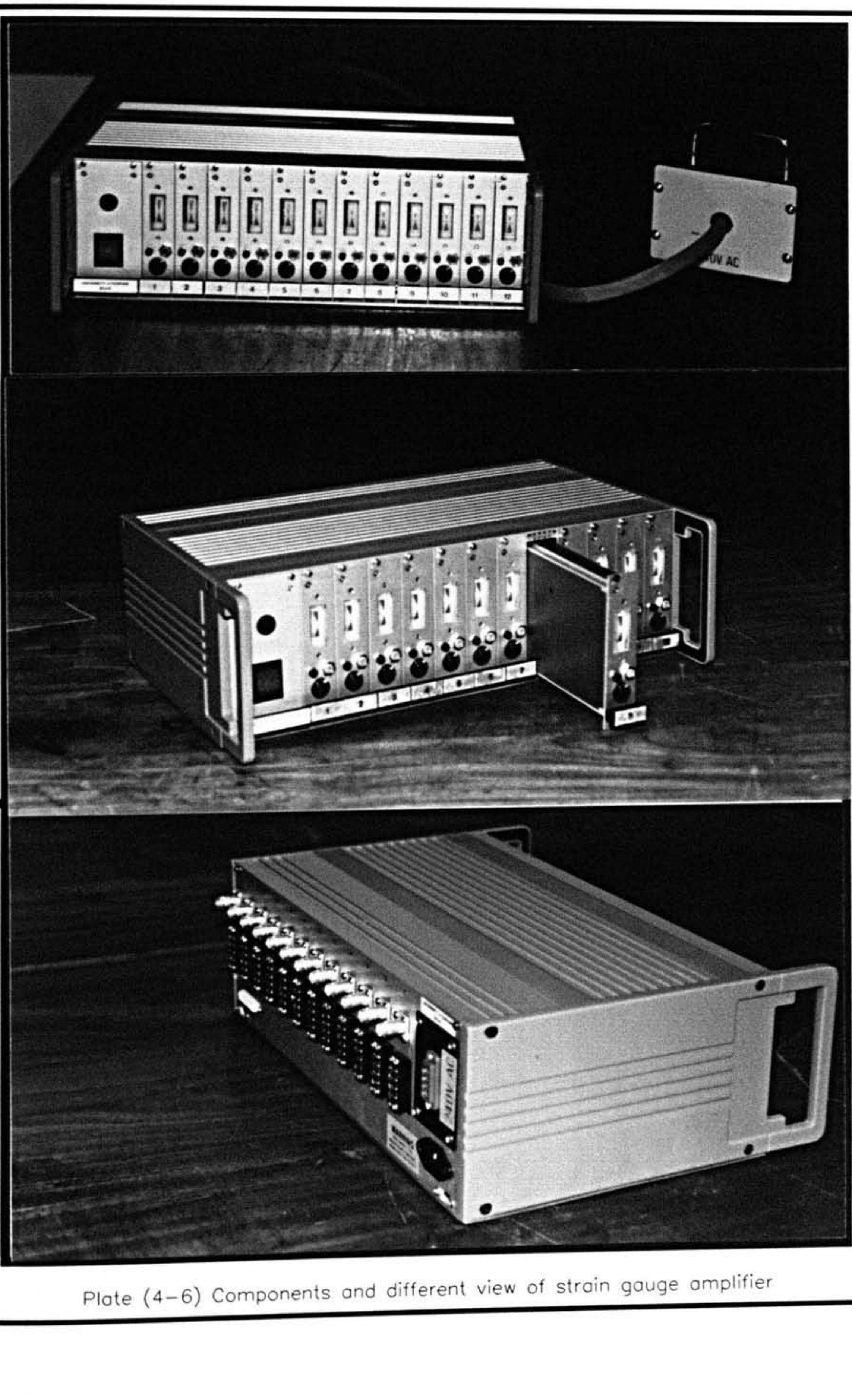


Plate (4–6) Components and different view of strain gauge amplifier

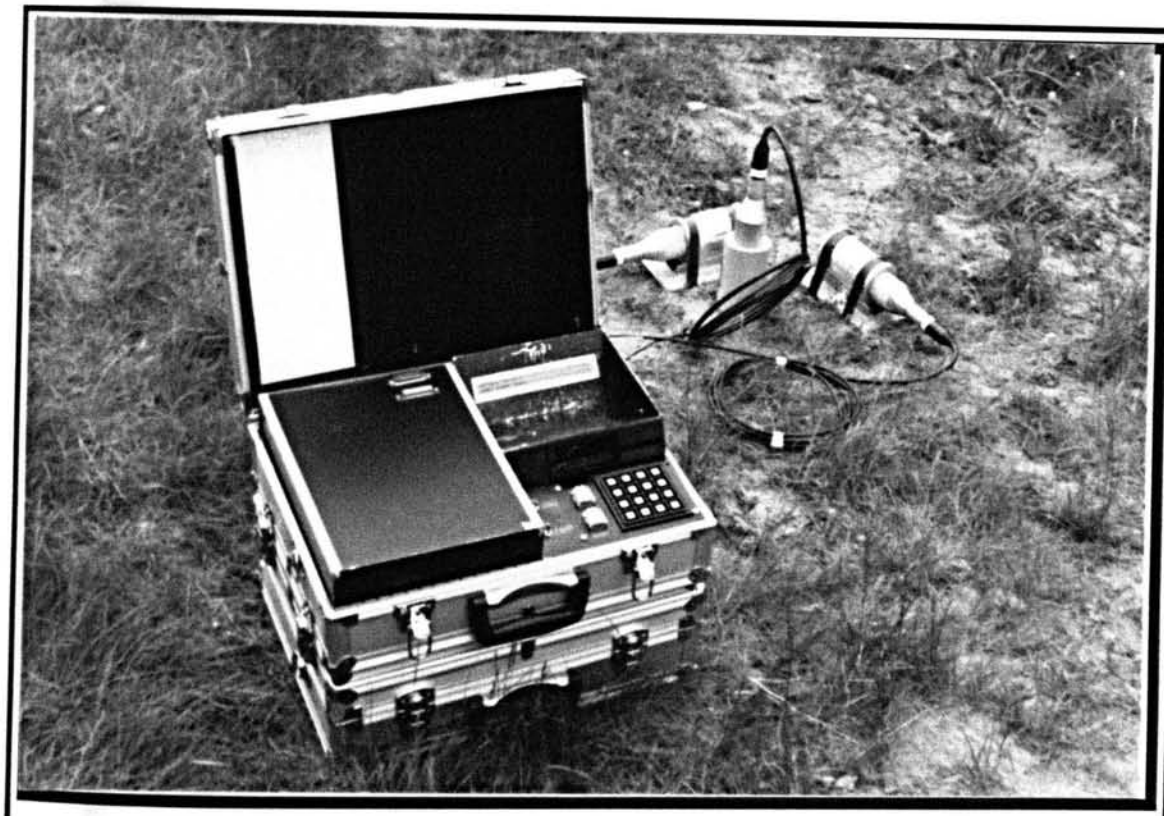
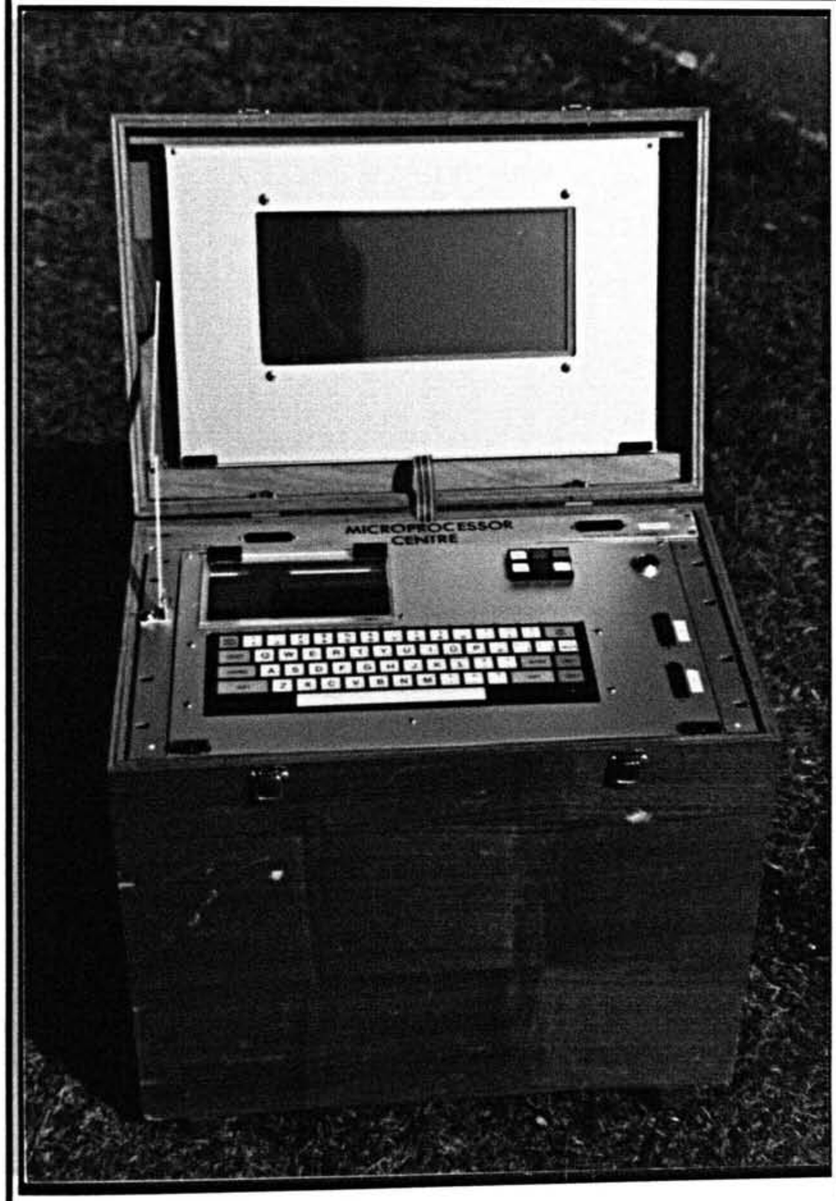


Plate (4–7) A general view of the PDR–1 unit together with its battery pack



Plate(4–8a) A general view of the PDR–2 unit,(front view)

Plate (4–8b) A general view of the PDR–2 unit, (back view)

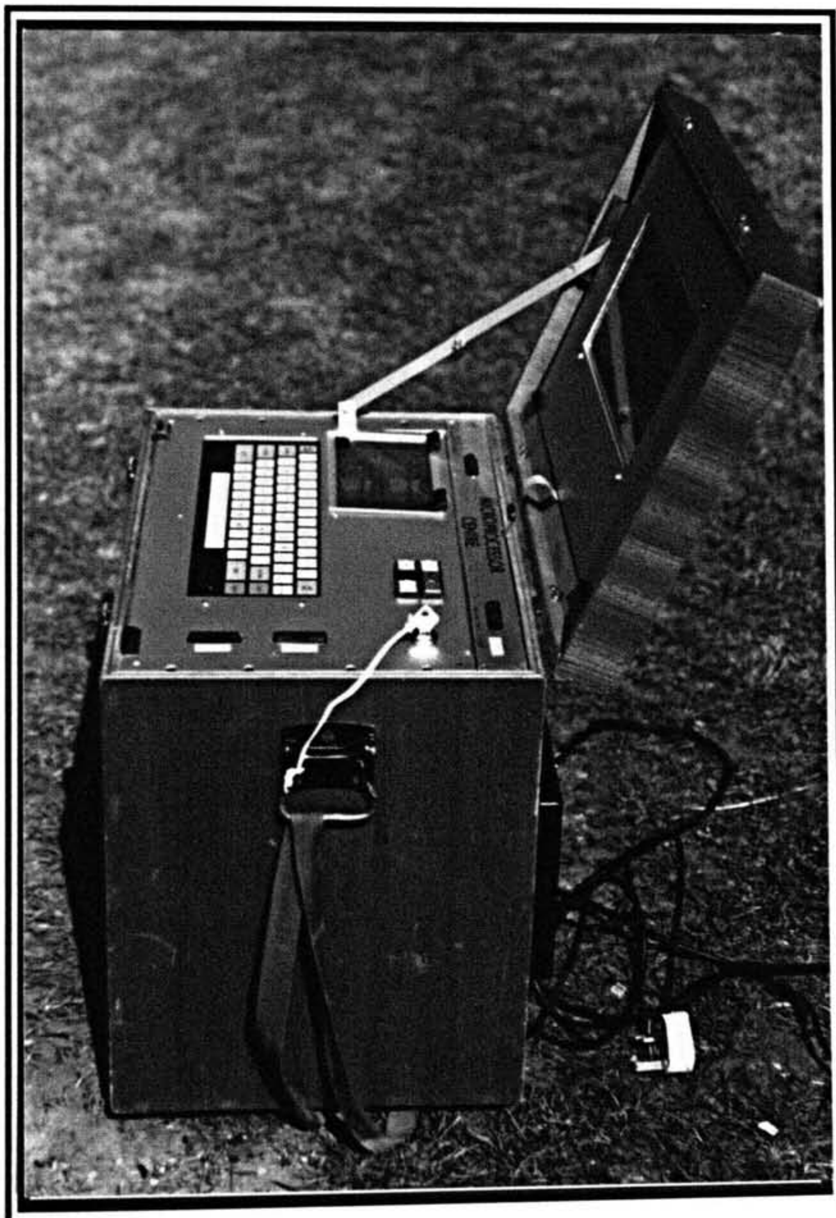


Plate (4–8c) A general view of the PDR–2 unit, (side view)

Chapter Five

5. Site Measurements and Data Interpretations

5.1 Introduction

In order to measure the ground vibrations produced from various sources, for example, road and rail traffic, quarry blasting and pile driving, and to investigate the effects of different ground conditions, a number of visits were carried out to different sites. The locations of the sites are shown in figure (5.1) and lists of the site names, dates of visits and their other relevant information are displayed in table (T5-1). Many of the sites, which were associated with pile driving activity, were recommended by the British Steel Technical Services at Scunthorpe. Arrangements were made with the site engineer prior to each visit.

Site vibration measurement forms the essential part of this study and all analyses were interpreted from the recorded field data. The basic measurements of the ground vibrations were recorded in terms of particle velocity via the use of velocity transducers (geophones). The PDR1 and PDR2 units were used in all stages of recording and processing the data.

The aim of this chapter is to review the site measurement activities. The preparation of necessary equipment used on sites is given in section(5.2). Also, experiences obtained from site visits are explained and a suggestion is given on reporting the ground vibration records. Section (5.3) describes the methods used in interpretation of the data including the differentiation and integration of the velocity records, and the calculation of the resultant vectors, vibration frequencies, wave velocities and wave lengths. The presentation of the vibration data using tables and plots is explained in section (5.4). Field measurements at different sites are reviewed in section (5.5) where a brief history of the visit, discussion of the recorded data and reference to relevant tables and graphs is also given. The ground vibration measurements at all sites are summarised in section (5.6). Finally, conclusions derived from the recorded data are included in section (5.7).

The reader should refer to the previous chapters for more details about the use of the equipment and other data processing procedures.

5.2 Equipment Preparation

Since the vibration measuring equipment comprises several sensitive devices, their serviceability was checked and examined frequently and normally before each site visit. The preparation and maintenance of the equipment is explained in the following sections.

5.2.1 Transducers

As has been discussed in Chapter (4), five sets of three geophones were used for the measurements of the ground vibration. Four sets included three `Geosource` geophones which were orthogonally mounted on a 30cm long strip of dexion angle to measure the three components (*radial, transverse* & *vertical*) of the ground vibration. The sets were supplied with three spikes to keep the geophones securely in contact with soft ground. In the case of hard ground (for example tarmac or concrete), the spikes were removed and the dexion base formed a flat contact surface (see plate (5-1)). Three `Mark` geophones were placed individually in orthogonal orientation close together on the ground. The geophone sets were marked as "A" to "E" and were usually positioned in an array lying in the range of 2 to 22m stand-off from the source of vibration. Sometimes extension leads were used for measurements over greater distances. The direction of wave propagation using the *right-hand-rule* convention, was indicated on each set†, where the peak of the arrow was directed towards the source of vibration.

Because the calibration figure of each geophone is different, it was very important to note the connection of the geophones to the channel number of the PDR. Usually sets A to E were sequentially connected to channels 0 to 14, but in some circumstances

† See section (6.3.3) for further details.

according to the site situation the connections were varied.

The geophone plug-cable connection is the weakest part of the transducer system, so this part of each geophone was always checked before and during the vibration measurement. The plug-socket contact surface was kept clean and the plug had to be screwed correctly and tightly into the socket. The safety of the geophone connection would then be checked on the PDR2 screen while running option 11 of the recording programme (see section 4.3.2).

5.2.3 Recording Units

The data recorders PDR1 & PDR2 contain many sensitive parts, and therefore great care was given to their safety during all stages of site activities. While travelling, the unit was placed on soft 'Sorbo' rubber material to absorb the vibrations from the vehicle, and, on the site, the unit was usually placed on firm and flat ground and was protected from any possible accident. In bad weather a plastic sheet was used to cover the unit during rain. Occasionally, the unit was affected by high levels of vibration in the ground, in which case it was kept away from direct contact with the ground by placing it inside a vehicle.

The disc-drives were always kept clean from dust or damp, and the head recorder was frequently cleaned by a head cleaning disk.

5.2.3 Discs and Programs

Prior to each visit, a number of 5.25 inch floppy discs were formatted either on the PDR2 unit or on the DUET-16 microcomputer. The recording programs then were copied on to the discs and sometimes a configuration file data was also loaded on to the disc, although some modification of the configuration could easily be made on the site if required. Due to the environment conditions of the sites some spare formatted floppy discs were kept available in case of failure. The discs were labelled and marked with relevant information.

5.2.4 Power Supply (generator)

Two types of portable generator were used (Honda IV300E & Honda EC1500E) to supply the PDR unit with a 240V AC current. Because of its light weight and compact size the Honda IV300E was more frequently used in most of the site visits. The position of the generator was always kept far away from the PDR unit and the geophones to reduce any effect of noise on the recording system. A filter unit was used between the generator and the PDR unit to filter out any spikey signal. Usually an extra petrol tank was taken to refuel the generator in the case of a long running job.

5.2.5 Site Information Sheet

It was found very helpful to keep all the site information of each visit in a formatted sheet. An example of a suggested form is presented in table (T5-2). The form is divided into the following three sections:

Section One, General Information

This section is divided into four sub-divisions which include:

- site location, date of visit, time of recording, disc number♡ and file name⊙.
- ground conditions at the surface and subsurface deposits strata.
- pile type, dimensions and length.
- hammer model, type, and energy.

Section Two, Geophone Stand-off

It is very important to identify the location of the geophones from the driven pile and the connection of each individual geophone-set to the recorder unit.

Section Three, Data Collection

This section includes three columns representing file number, toe-depth and

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♡ Each disc is usually named and classified according to sequence of the other disc's names and numbers in the office, for example, PDR2-G and PDR2-M

⊙ The file name usually has some indication of the site and type of the used hammer and pile, for example BAH indicates Blaydon, Air-hammer and H-pile some relevant comments such as the speed of driving (penetration per blow or penetration level per second), ground behaviour during driving, alignment of pile and other non-standard events. Usually up to ten files were recorded on one single sided double density disc when they were used to record ground vibration from 15 channels. The number of recorded files per disc was less when the number of recorded channels increased.

5.2.6 Additional Equipment

1. Safety Equipment: it was very important to consider the safety measures on the pile driving site where heavy plant was active. The safety equipment used on most sites included hard-hat, gloves, ear-protectors waterproof jacket and wellingtons or boots.

2. Measuring Device: usually a metric tape 30m long was used to measure the positions of the geophones with reference to the location of the pile being driven. Also a 2m tape was used to measure the pile set per blow.

3. Tool Box: this included a soldering iron, solder, cutter, screwdriver, voltmeter, and general tools which were used to check and repair the equipment on the site if required.

5.3 Interpretation of the Ground Vibration Records

As described before, the ground vibration measurements throughout this work were recorded simultaneously by five sets of three geophones which were located at different distance from the source. The geophones were orientated towards the source so as to measure the induced vibration in radial, transverse and vertical directions. The multichannel simultaneous recording of a single vibration event was essential for the estimation of the vibration attenuation in the surrounding ground. The procedure of processing the recorded data has been explained in the previous chapter. The raw data was stored digitally on 5.25 inch floppy discs for further processing. These discs are available in the SEAS† at Durham University.

5.3.1 Display of Peak Particle Components

According to the purpose of study, the ground vibration records can be presented in terms of peak particle velocity, displacement or acceleration. A useful presentation is the display of the vibration records as a function of time, which also is known as a *time history* plot.

Since velocity transducers were used in the recording of ground vibrations at site, the data, after processing by the PDR units, are presented in terms of particle velocities. Figures (5.2) and (5.3) display two examples of transient and periodic vibrations taken during pile driving by impact-hammer and vibrodriver, respectively. The three components of the vibration known as *radial, transverse & vertical waves* are shown in pink, orange and green, respectively. Also, other information relevant to recorded data is illustrated in each graph. A combination of five individual traces of vibration recorded simultaneously in one of the above (RTV) directions can also be displayed on a single graph. An example of such presentation is shown in figures (5.6) and (5.7). This form of display is found to be helpful in displaying the attenuation of vibration with respect to time at five different stations.

In addition, using the facilities of available programs within the PDR2 unit, the velocity data could be integrated or differentiated, so allowing the information to be presented as particle displacement or particle acceleration, respectively♣.

For a pure sinusoidal vibration, the acceleration trace leads the velocity and the displacement by $\pi/2$ and π respectively. The relations between these three factors can be expressed as:

displacement	$=Asin(wt)$	$\widehat{d} = U$
velocity	$=wAsin(wt+\pi/2)$	$\widehat{v} = U(2\pi f)$
acceleration	$=w^2Asin(wt+\pi)$	$\widehat{a} = U(2\pi f)^2$

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♣ Only the data recorded and stored by the PDR-2 unit could be processed in this way where A is the vibration displacement amplitude and w is the angular frequency ($w = 2\pi f$) and $\widehat{d}$, $\widehat{v}$ and $\widehat{a}$ are peak particle displacement, velocity and acceleration, respectively. Although the above expressions are valid only for a purely sinusoidal vibration an approximate evaluation of vibration caused by an impact hammer may also follow the above procedure. Accurate calculation of peak particle displacement or acceleration should, however, be derived by the computation procedure. Figure (5.4) illustrates a typical example of the PDR-2 derivation of particle acceleration and displacement traces deduced from a measured particle velocity record for a vertical wave. The records were taken in Waltham-Cross during driving of a pair of sheet-piles by a hydraulic-hammer.

The amplitude of peak particle displacement was computed by integration of the area below the velocity curve from the beginning of the motion up to any selected time. For example, the area between time 1 and time 3 in figure (5.4) can be found by summing the product of the average velocity between two timing lines and the interval between them. The approximate value of peak displacement can also be calculated by using the following expression[⊘].

$$ppd = \frac{ppv}{2\pi f} = \frac{56}{2 \times 3.14 \times 20} = 0.45mm$$

The amplitude of peak particle acceleration can be obtained by differentiation of the velocity which is represented by the slope of velocity curve at any time. Referring to figure (5.4), at time 1 the acceleration is at peak and is equal to the slope between points 1 and 2. Also the amplitude of the peak acceleration can be approximately calculated using the following equation[⊘].

$$ppa = ppv \times 2\pi f = 56 \times 2 \times 3.14 \times 20 = 7037mm.s^{-2}$$

The detail of the differentiation and integration theory is reviewed in several mathematics textbooks (see for example Spivak (1967)).

5.3.2 Calculation of Peak Resultant Vector

⊘ See Dowding (1985)

The ground vibration measurements may also be presented in terms of the resultant vector of the three orthogonal components of the vibration.

There are two methods of producing resultant vector values. One is the square root of the sum of the square of peak values of the three orthogonal channels independent of their time of occurrence which needed a simple calculation as

$$V_r = \sqrt{R^2 + T^2 + V^2}$$

Alternatively, the true resultant vector value is the square root of the sum squares of the three vibration components with respect to the time of occurrence. This can be achieved by an available program within the PDR-2 unit$^{\Delta}$.

$$V_{rt} = \sqrt{R_t^2 + T_t^2 + V_t^2}$$

For an explanation of the difference between the methods, consider the example of ground vibration shown in figure (5.2). The vibration is dominated by the radial wave which shows its peak ($19.08 mm/s$) at time $0.04 sec$ while the peak values for vertical ($5.87 mm/s$) and transverse ($6.41 mm/s$) waves appears at times $0.065 sec$ and $0.07 sec$, respectively. The calculations of the resultant vector of these components, using both methods, are shown in the following table.

Calculation of Peak Particle Resultant Velocity				
Vibration components	independent of time V_r		with respect to time V_{rt}	
	sec	mm/s	sec	mm/s
Radial	0.040	19.08	0.040	19.08
Transverse	0.070	6.41	0.040	2.20
Vertical	0.065	5.87	0.040	2.50
Resultant		21.00	0.040	19.37

The method adopted throughout this work is based on the calculation of the true resultant vector with respect to their time of occurrence. It is a method used

$^{\Delta}$ See Appendix A3, section A3.2.3 where commands VECT, VACC & VDISP are used for the calculation of V_{rt} of the particle velocity, acceleration and displacement components, respectively in most engineering works especially when considering the effect of vibration on buildings.

5.3.4 Calculation of Dominant Frequency

Frequency is a significant parameter in the definition of the vibration particularly in describing the vibration effect on human senses and risk of damage in buildings. Earthquakes, landslides and large explosions caused by nuclear and military activity or surface mining, when measured at a certain distance from the source, usually induce vibration with a lower frequency than those of pile driving or traffic.

There are several ways for evaluating the induced vibration frequency. The more commons ways are given below:

Periodic Vibrations

The frequency from this form of vibrations could be calculated by counting the number of cycles per unit time.

$$f(\mathtt{Hz}) = \frac{\text{number of cycle}}{\text{time(sec)}}$$

An example for the above calculation is shown on figure (5.5a) for a typical periodic vibration taken in Newark during driving sheet-pile (16W) by a vibrodriver (PTC-13HF). There are six vibration cycles between times 0.015-0.365sec, hence the frequency for this record is $f = 6/0.35 = 17\mathtt{Hz}$.

Transient Vibrations

To calculate the frequency from this type of vibration, measure the time difference which corresponds to the dominant vibration cycle (oscillation), then the frequency is

$$f(\mathtt{Hz}) = \frac{\text{one oscillation}}{\text{relevant time(sec)}}$$

Figure (5.5b) displays an example of transient vibration taken at Newark during driving of an H-pile by a drop-hammer. The dominant vibration cycle occurred between times 0.062sec to 0.092sec, so $t = 0.092 - 0.062 = 0.030sec$, and then the frequency is $f = 1/t = 33\text{Hz}$.

`FFT Analysis`

The *fast fourier transform* analysis can be used for the calculation of the dominant frequency. This method is used to calculate dominant frequency from the relevant time domain vibration data (in terms of particle velocity, acceleration or dispacement) (see Papoulis (1962)). The method is a rapid computational way for frequency calculation. An FFT subroutine is available for data processing by both the PDR-2 unit and the DUET-16 microcomputer. An example of a frequency spectrum curve is shown in figure (5.5c). This FFT analysis was derived from particle velocity data recorded in Blaydon during driving of an H-pile by hydraulic-hammer (see figures (5.23). and (5.24)).

5.3.5 Calculation of Wave-velocity and Wave-length

Ground surface vibration measurements are also defined by their wave-velocity and wave-length, especially when considering the risk of damage to buildings. The effect of vibration on buildings is briefly described in section (6.4) of the next chapter. Here the derivation of wave velocity (c) and wave length (λ) from ground vibration records is explained. Figures (5.6) and (5.7) display two sets of vibration records which were taken during the driving of H-piles by hydraulic-hammer and by vibrodriver, at Blaydon and Newark, respectively. The attenuation of vibration records with respect to time is displayed for different stand-offs. To estimate an **approximate** value of the wave-velocity, first the difference in time of occurrence of two peaks at two distances should be calculated.

$$c = \frac{x_2 - x_1}{t_2 - t_1}$$

Then, from the dominant frequency of the applied vibration, the calculation of the wave-length can be achieved.

$$\lambda = c/f$$

The calculations of (c) and (λ) for the two above examples are demonstrated below where the dominant frequencies are 16Hz and 18Hz respectively.

figure (5.6)

$$c = \frac{18-3}{0.070-0.026} = \frac{15}{0.044} = 340m.s^{-1}$$
$$\lambda = c/f = 340/16 = 21m$$

figure (5.7)

$$c = \frac{12-3}{0.061-0.031} = \frac{9}{0.03} = 300m.s^{-1}$$
$$\lambda = c/f = 300/18 = 17m$$

5.4 Presentation of the Vibration Records

The ground vibration records are presented throughout this chapter in terms of peak particle velocity as a function of stand-off distance from the source in both tables and plots.

5.4.1 Tables

It was found to be useful to keep all the recorded ground vibration data on printed tables which can be used either for data presentation or for storing the data for later processing. A form of table was designed and modified by time to contain all the necessary information. Examples of such tables are included in the following sections. Each table contains two sections, where the top section includes information about the site, ground, pile and hammer, while the lower section includes the values of the ground vibration records.

The magnitudes of the ground vibrations, in most tables, are presented in terms of peak particle velocity but the induced peak particle acceleration and displacement are also given in some tables. The peak particle values represent the zero-to-peak amplitude of the corresponding vibration and are shown as positive numbers although they may have negative signs. The true resultant vector for each three orthogonal components is calculated with respect to the time (as described in section 5.3.3), by the PDR-2 unit.

5.4.2 Attenuation Plots

The attenuation of the vibration with respect to stand-off distance from the source is provided by plotting the peak particle velocity amplitudes against the stand-off of the corresponded geophone. This simple form of presentation, in which data recorded by 15 geophones are plotted on a single graph, was found to be very helpful in comparing, individually, the attenuation of radial, transverse and vertical wave with increments of distance. Examples of this form of plot are included within the next section

5.5 Site Visits

As was shown in table (T5-1), a total number of 95 visits was made to 25 different sites between September 1986 and March 1989. The primary aim of the work was to examine the effect of pile driving on the surrounding area, so about 85 visits were carried out during pile driving activities. Also, ground vibration measurements were taken during blasting operations, 8 visits being made to different sites involved with this activity. Finally two visits were made to different sites for measuring rail and road traffic vibrations. Some sites, for example Blaydon, Keighley and Newark which involved major construction projects using various types of piles and hammers, were visited many times during all the stages of pile driving.

The field measurements of ground vibrations were accompanied by a number of difficulties, especially those involved with pile driving operations. For example, some of the sites were located at large distances from the university and long drives were needed to reach these destinations, where the arrival time had to be matched with the working hours of the construction sites. The ground conditons and the layout of the sites also affected the measuring procedures; for example, in the Rotherhithe site, the recording equipment was lowered by crane from the quayside 12m down to the bank of the River Thames at low tide. Breakdown of the driving hammers was a major cause in delaying and even cancelling the driving procedures on several sites. Other problems which affected site measurements included the tidal conditions, temperature, ground water, rain, and dust on the site.

A brief review of each site in alphabetical order, is given in the following sections. The review includes a brief description of the site location, date of visit, ground conditions, positions of geophones and type of equipment used. Some comments are given on the derived data. Only a few examples of vibration records are presented in this section; these reflect a small part of the time and effort spent on recording and processing the captured data. The original records which include an extensive amount of plots, graphs, diagrams, soil data and floppy discs are stored in the SEAS†. Simplified ground conditions extracted from the available borehole logs are displayed together with a schematic layout of the site for a better understanding of the conditions of the site during the data measurements. Also the location and conditions of some of the sites visited are demonstrated through a number of photographs.

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5.5.1. Blaydon

As part of the new development of the traffic system around the Tyneside area, construction of the new Newcastle Western Bypass was started in 1987. The project included the driving of a large number of different types of steel pile for the foundation constructions of the one mile long Blaydon Haughs Viaduct and the piers of the new Blaydon Bridge over the River Tyne. The new bypass joins the existing "A69" by a number of road connections in the Chain Bridge area. The new bypass was designed to divert the south-north traffic away from the central part of the City of Newcastle-upon-Tyne.

A general view of the construction site is illustrated in figure (5.8). As the figure shows, several structures lie fairly close to the piling locations. The site was divided into three areas. Area (A1) was bounded to the south by the Newcastle-Hexham railway line and to the north by Chainbridge road. Three main gas pipes and two main sewer pipes were located in the area close to the pile driving positions. Area (A2) was bounded to the south by Chainbridge road and to the north by the south side of the river Tyne. The main structures included in this area were the Dutton Forshaw offices, the Creamery of Northern Dairies, British Gas main pipe and pumping and regulator stations, and other local warehouses and storage buildings. Area (A3) was located on the both sides of the River Tyne where in the northern bank some local industrial estates are positioned. Areas (A1) & (A2) were parts of the route which include the viaduct foundations while area (A3) includes the foundation of the Blaydon Bridge.

A preliminary ground investigation was carried out by B.B.Drilling between October & December 1983 and a main ground investigation was later carried out by Soil Mechanics Ltd between January & April 1985. A simplified geological section is shown in figure (5.9) where the correlation of the ground conditions of the areas is also demonstrated. The depth to bedrock from the ground surface, in areas (A1), (A2) & (A3) are 42m, 37 & 23m, respectively. The bedrock contains sandstone and mudstone interbedded with layers of coal. The ground conditions above the bedrock consist of alluvial and glacial deposits.

A large number of steel H-piles (($356 \times 368 \times 152$kg/m), of Grade (50B) to BS4360 were driven to the bedrock to establish the foundations of the viaduct. The length of each pile segment was 21m but the length was extended by welding to match the required penetration depth which varied according to the location of the bedrock, between 19m and 37m for areas A1 and A3, respectively. Also a number of steel sheet piles was used in temporary works to support the ground and act as retaining walls during the excavation of the pier foundation. A large selection of hammers were used to suit the pile driving conditions. The hammers used in this site included: diesel-hammers, hydraulic-hammers, air-hammers, standard vibrodrivers and a hydraulic-vibrodriver.

The pile driving operation was divided into three main contracts, where contract (1) was involved in driving trial piles in areas 1, 2 & 3, while the main pile driving and construction of the viaduct was included in contract (2), and finally, contract (3) included the driving of a number of piles to support the foundations of the bridge at the interchange with the A69 bypass.

All the ground vibration measurements were taken by Durham University and a large amount of data was obtained during the driving of a large number of piles using different types of hammers. More than 30 visits were made to this site during the pile driving activities of all three contracts. A brief review of field measurements and discussion of the results obtained are given in the following sections.

5.5.1.1 Contract One (trial piling)

The trial piling was carried out by contractor J. Howard in the autumn of 1986 to investigate several important aspects related to the design and construction of the piled foundations. The information obtained could be used in detailed design and could then be supplied to the main contractor to assist the construction work.

A total number of nine piles was driven (three piles in each area) during the operation of contract (1). The piles were steel H-section ($356 \times 368 \times 152$kg/m) and were driven to bedrock using a diesel-hammer(BSP-50c) and vibrodrivers (PTC-50)

& (PTC-25). Seven successful visits were carried out to the site to monitor ground vibration levels. The list of visits is shown in the table below:

Contract One: Trial Piling					
Visits	Date	Area	Pile	Hammer	Comments
1	25.09.1986	A1	H-pile	Diesel	
2	26.09.1986	A1	H-pile	Diesel	
3	03.11.1986	A2	Tube-p	Vibrodriver	
4	06.11.1986	A2	H-pile	Vibrodriver	first part
5	11.11.1986	A2	H-pile	Diesel	second Part
6	04.12.1986	A3	H-pile	Vibrodriver	
7	05.12.1986	A3	H-pile	Diesel	

The *portable digital recorder* (PDR1) and standard sets of 15 geophones were used for the vibration measurements throughout these visits.

Two visits were made to area (A1) on 25th and 26th of Sept. 1986, during the driving of a steel H-pile ($356 \times 368 \times 152$kg/m) by a diesel-hammer (DS-50c) having a maximum input energy per blow of 61kJ. The pile was driven 36.4m into the ground in the location shown in figure (5.10) where the positions of the geophone sets are also shown. A summary of the results is shown in tables (T5-3) and (T5-4). The measured vibration levels were in the range of 2-12mm/s for stand-offs 17m to 2m, respectively. The vertical and the radial axes of vibration showed a higher level of vibration than did the transverse axis. Figure (5.11) shows the attenuation of the three components of the ground vibration of two files taken for pile toe depths 20m and 36.4m. The figures indicate that there were some increments in the magnitudes of the radial wave as the distance from the pile increased. The dominant induced frequencies in the ground were in the range of 20-25Hz.

On 3rd Nov. 1986 a visit was made to area (A2) during the driving of a casing pile using a vibrodriver (PTC-50). The casing was a steel tubular open ended pile 20m long and 740mm in diameter and was driven to a depth of 15.4m. The use of a a temporary tube casing is a method widely used to increase the bearing capacity of end-bearing piles subject to down drag from settling soils.

The piling site was located 20m to the west of the Dutton Forshaw two storey block of offices. The geophone sets were placed on the carpark surface in an array at 2, 5, 8, 10 & 15m from the pile towards the A69 road (see figure (5.12a)). The recorded results are shown in table (T5-5). The measured vibrations were in the range of 15-26mm/s, although in one file a maximum of 55mm/s was recorded for a transverse channel (see HOW4). The table also shows that the magnitude of vibrations decreased as the stand-off increased. The attenuation of the measured vibration with respect to stand-off distance from the pile, taken at two toe depths of 2m and 15.4m, is shown in figure (5.13). The figure shows that at a shallow penetration, vertical and transverse waves have larger vibration magnitudes than that of the radial wave and the attenuation was more uniform, but as the depth of toe penetration increased there was some increase in radial magnitude and the attenuation was not uniform. A large settlement of soil elements was observed on the site around the piling location and the level of the soil inside the tube at the end of driving was 2m below the ground surface. The vibration frequency induced by the vibrodriver was approximately 30Hz.

Area (A2) was visited again on 6th and 11th of Nov.1986, during driving of a steel H-pile ($356 \times 368 \times 152kg/m$) at a rake of 1/6 from the vertical. The pile was first driven to a depth of 15m using a vibrodriver (PTC-50), then a diesel hammer (DS-50c) was used to penetrate the pile 27m into the ground. The geophones were positioned at 2, 5, 8, 12 & 18 m from the pile. The locations of the geophones from the pile are illustrated in figure (5.12b). A summary of the results obtained is shown in tables (T5-6) and (T5-7). From the tables, it can be seen that the vibration level caused by the vibrodriver decreased sharply as the distance from the pile increased, where a maximum velocity resultant recorded at 2m stand-off was 40mm/s while at 18m the measured vibration was only 1.3mm/s (see file RAK8). Also the table showed that as the depth of pile penetration increased, so the level of recorded vibration decreased. On the other hand the record obtained during the operation of the diesel hammer indicated that the vibration level was in the range of 8-11mm/s and generally the level of the ground vibration decreased slowly as the stand-off increased. The attenuation of the ground vibration as a function of the horizontal distance for two files taken during the operation of the vibrodriver and the diesel-hammer are shown in figure (5.14).

The operation of the vibrodriver caused a low frequncy of 12Hz at the start of driving and as the driving continued the induced vibration frequency increased to about 30Hz. For the diesel-hammer, a frequecy of 50Hz was calculated from the vibration records taken by geophone close to the pile, while at distance, the frequency levels dropped to 22Hz.

Area (A3) was visited on 4th Dec.1986 during the first stage of driving a steel H-pile to a depth of 11m into the ground using a vibrodriver (PTC-25). The pile was located some 100m from the south bank of the River Tyne. The geophone sets were placed on the ground surface at 2, 5, 8, 14 & 20m from the pile. A summary of the results is shown in table (T5-8). From the table it can be observed that the level of the recorded vibrations was in the range of 15-49mm/s and frequency of 20-37Hz. As in other records, the level of vibration decreased sharply as the stand-off increased.

The last visit to the site was on 5th Dec.1986 during driving of the second part of the pile mentioned above. The geophones were positioned at 3, 6, 8, 14 & 20m from the piling location. A diesel hammer(BSP-50c) was used to drive the pile 23.25m down to bedrock. A summary of the results is shown in table (T5-9). The recorded vibration levels were in the range of 10-13mm/s and the relevant frequencies were in the range of 30-50Hz. The vibration was dominant along the transverse axis in which the level of vibration decreased as the distance increased. However the radial axis of vibration showed some increases in magnitude as the distance increased, and the vibration recorded by the vertical axis was almost uniform at all the stations. Again, a comparison of the the attenuation of the recorded vibration taken during driving the H-pile by the vibrodriver and the diesel-hammer is demonstrated in figure (5.15).

5.5.1.2 Contract Two (main piling)

The work on the main piling contract began in Feb. 1988. Two types of steel H-section piles ($356 \times 368 \times 152$kg/m) and sheet-piles (Larssen, 16W & 12W) were used as permanent and temporary piles, respectively. Except for the two first records which were taken by the PDR1 unit, the other vibrations records were taken by the PDR2 unit. A total number of 16 visits[⊕] was made to the construction site which included areas 1, 2 & 3 mentioned above. Records of vibration level were also taken during the Rosenstock Shock Blasting operation carried out in the pier construction. A list of the visits is shown in the following table.

Contract Two. Main Pile Driving					
Hammer		Date	Pile	File	Comments
Type	Model				
Vibrodriver	ABI	04.05.1988	Larssen(16W)	BLV	Dutton-Forshaw
Vibrodriver	PTC50	24.05.1989	H-pile	BB	close to DF offices
	PTC50	24.05.1989	H-pile	BFV	
Air-hammer	BSP900N	05.05.1988	H-pile	BAH	S.River Tyne
	BSP900N	28.06.1988	H-pile	BLA	next to DF offices
	BSP600N	20.07.1988	Larssen(16W)	BSA	close to the Creamery
Hydraulic-hammer	BSP357	12.05.1989	H-pile	BL	
				PL	
		28.06.1989		BLY	
		28.06.1989		BLN	
		20.07.1989		BRH	raking pile
		10.08.1989		BHC	next to CO-OP Creamery
Diesel-hammer	Delmag	10.08.1989		BSD	pier cofferdam
		23.11.1989		BHD	next to the railway

In the following sections, the description of each site visit is reported briefly, according to the type of operating hammer.

⊕ Three visits are not reported here, because the data taken from two visits were lost due the failure in the recording units and no pile driving took place in the third visit

a. *Hydraulic-vibrodriver* (ABI)

This hammer was used to drive steel sheet piles (Larssen 16W) for the construction of a cofferdam to house a single pier of the proposed viaduct. The driving site was located close to the Dutton Forshaw offices and adjacent to a gas pumping station. The piles were 9m long and were driven some 8m into the ground. The sets of geophones were placed in an array at 4, 6, 12, 17 & 21m from the pile. The measured vibration was in the range of 2-5mm/s. The frequencies relevant to these vibrations, and which were calculated from the velocity traces, were in the order of 38Hz. The records also showed that the level of vibration imposed by this hammer was low, and unlikely to cause any damage to the nearby buildings.

b. *Vibrodriver* (PTC)

The ground vibration levels were recorded on 24th May 1988 during the use of a vibrodriver(PTC-50). Three piles were driven into ground at the base of an excavation and the geophones were placed on the ground surface some 2m above the level of piling. The location of the site, piles and the geophones are indicated in figure (5.16) where piles (1) and (3) were driven to a rake of 1/6 towards the north and south respectively, and pile (2) was driven vertically into the ground. A summary of the vibration measurements is shown in tables (T5-10). The table showed a small level of vibration of 1-2mm/s. This was probably due either to the location of the geophones which did not respond to the real vibration induced in the ground, or because the transmission of the vibration to the ground surface was indeed very small, and which would cause no harm to the surrounding buildings.

Another set of vibrations was recorded during driving of a single vertical pile to deeper penetration. Again the vibration measurements were very small, in the range of 1-2mm/s. A summary of the records is shown in table (T5-11).

c. *Air-hammer*

Three records of ground vibration were taken during the operation of air hammers. The first record was taken on 5 May 1988 where a double acting air hammer

(BSP-900N) was employed to drive H-piles 15.3m deep into the ground in area (A3). The results of the recorded vibrations are given in table (T5-12). The table shows that the level of maximum vibrations was in the range of 12mm/s at 2m stand-off which reduced to 7mm/s at 15m. The table also shows that the dominant vibrations were recorded in the direction of the transverse axis, while the vibrations recorded in the radial and the vertical axes show a relatively smaller magnitude.

The ground vibrations induced by the operation of the same hammer were measured again on 28 June 1988. The site was located close to the Dutton Forshaw offices, on the north side of Chainbridge road (A69). The geophone sets were placed on the ground surface some 4m above the pile driving location at 4, 8, 11, 17 & 22m from the pile, alongside the (A69). The pile was H-section (356 × 568 × 152kg/m) and length of 32m, and was driven by the air-hammer to a maximum depth of 29m. A summary of the vibrations obtained from this visit is displayed in table (T5-13). Regarding the depth of pile-toe and the locations of the geophones the recorded vibrations were very low, in the range of 0.8-2mm/s. The attenuation of vibration traces, recorded at different stations, is shown in figure (5.17a) and the three components of the vibration recorded at 11m stand-off are given in figure (5.17b). It can be seen that the vibration traces in station three which were recorded by the highly sensitive geophones (Mark product) had a smoother output than those recorded by the Geosource geophones. Dominant frequencies of 22-32Hz were calculated for vibration taken at 4m and 22m from the pile, respectively. An example of frequency spectrum using the FFT analysis is illustrated in figure (5.18).

Further records of vibrations were taken from an air-hammer (BSP-600N) during driving 9m long steel sheet-piles (Larssen-16W). The driving location was adjacent to the Blaydon Creamery and the geophone sets were placed at 2, 4, 8, 13 and 22m from the piles. A summary of the data obtained is shown in table (T5-14). An example of vibration attenuation of five sets of vertical waves taken at 2m to 22m from the pile are presented in figure (5.19a). The vibration frequency deduced from this display is about 31Hz. Another display of three orthogonal components of vibration is shown in figure (5.19b). A comparison of attenuation pattern of three vibration components with respect to horizontal distance is plotted in figure (5.20). The figure shows a uniform attenuation of the vertical wave while the radial wave shows some increase in amplitude at 8m distance and then decreased with distance.

d. Hydraulic-hammer

The hydraulic impact-hammer model (BSP-357) was widely used for pile driving in this site because of its efficiency and flexibility at work. A 5000kg ram weight was usually chosen for driving long piles to bedrock. A huge leader, 45m long, was employed to guide and support the long piles during the operation (see plate (5-2)). The height of the striking blow was adjusted during the driving according to the ground conditions and was varied between 400mm to 1100mm. A number of visits was made during the operation of this hammer to monitor the vibrations levels of the ground. The details of the pile specification (type, length & size), hammer, geophones stand-off and the summary of the measured vibration are given in tables (T5-15) to (T5-21). The displays of vibration records as time history plots are given in figures (5.21) to (5.27). Two examples of attenuation curves of the vibration records with respect to the horizontal stand-off distances are shown in figures (5.28) and (5.29). The range of the calculated vibration frequencies were 20-45Hz. The following results can be concluded from the tables:

1. the highest level of vibration was dominated by the radial and the vertical waves while the transverse wave was relatively smaller in magnitude.
2. for toe depths over 10m, the radial wave showed some increase in magnitude as the distance from the pile increased and after this critical distance (8-12m) the magnitude reduced.
3. the vertical level of vibration decreased steadily as the distance from the pile increased.

e. Diesel Hammer

Three visits were made to the site during the use of diesel-hammers in driving of both sheet and H piles (see table (T5-1)). Due to failure of the recording unit the recorded data taken in the first visit were lost during the processing procedure. The second set of data was unreliable because of some mis-arrangement in the parameters of the recording file where the duration of the sampling time was very short. No records were taken on the third visit due to failure of the driving hammer.

f. Blasting

Ground vibrations were measured during blasting. The RSB♠ techique was used to shatter the bedrock surface to allow penetration of sheet piles for the construction of a cofferdam on the south bank of the River Tyne. First a number of steel sheet-piles were driven around the proposed area, then a series of holes was drilled 12m deep into the ground. The holes were 60mm in diameter to be later filled with 5kg of explosive in each hole and detonated electrically. Two records of vibration were taken during blasting. The first record was measured at some 400m from the source of the blast. Two sets of geophones were used in this measurement, which were placed on the concrete floor of a small factory workshop north of the River Tyne. The vibration results are shown in table (T5-22). The second visit was on 31th August 1988 and the locations of the geophones were at 32, 40, 45 & 52m from the source of the blast. The depth of the explosive was at 14.7m from the ground surface. The summary of the obtained results is given in table (T5-23). The time-history records of the three components of vibration, taken at 32m and 54m from the source, are illustrated in figures (5.30) and (5.31), respectively. A view of the construction site at the time of blasting is shown in plate (5-3).

5.5.1.3 Contract Three

As mentioned before, contract-3 included construction of the pier foundation for the bridges of the interchange with the A69 road and the Newcastle Western Bypass. A number of steel H-piles were driven into the ground by means of a hydraulic-hammer. The pile driving positions were close to the location of two main

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♠ **Rosenstock Shock Blasting**; see section 3.3 of chapter three and BSC (1986) for more information gas pipes and the ground vibration levels were measured during the pile driving operation to investigate the effect of the induced vibration on the gas pipes. Three visits were made to the site during trial piling and main piling activities as listed below:

Contract Three				
Visit	Dtae	Pile	Hammer	Comments
17	25/11/1988	H-pile	Hydraulic	trial piling
18	14/03/1989	H-pile	Hydraulic	main piling
19	20/03/1989	H-pile	Hydraulic	main piling

The first visit was carried out on 25 Nov.1988 during driving of two trial piles. The piles were steel H-section($356 \times 368 \times 152$kg/m) and 19m long. Pile 1 was driven on the road embankment and pile 2 was driven next to a local road. The two main gas pipes were located some 7m from the pile 1 position and some 2m below the ground surface. Geophone set (A) was set on the embankment at 3m from the pile, set (B) was placed on the location of the gas pipe at 7m stand-off and sets (C), (D) & (E) were positioned at 12, 15 & 18m from pile 1. A schematic layout of the site is demonstrated in figure (5.32). A hydraulic hammer (BSP-357) of 5000kg ram was used to drive the pile 17m into the ground. The height of drop varied between 500mm at the start of driving up to 1000mm when the pile had penetrated deeply into the ground. A summary of the recorded data is shown in table (T5-24). An example of the vibration records taken at the location above the gas pipes is displayed in figures (5.33). The following results are extracted from the records displayed in the table:

1. the levels of vibration on the pipe location (7m stand-off) were in the range of 7-14mm/s;
2. the magnitude of the vibration along the radial and the vertical axes showed higher values than that along the transverse axis;
3. the level of vibration attenuated as the distance increased;

4. the large magnitude of vibration recorded by the first set was probably caused by movement of loose soil at the surface of the embankment and did not represent the vibration level deeper in the ground;
5. the dominant vibration frequency of 16Hz is rather low for the operation of this type of hammer.

The second record of vibrations was taken during driving pile 2 next to the existing local road. The pile was positioned some 16m from the location of the gas pipe. The geophone sets were placed on the ground surface at 3, 6, 10 & 15m stand-off in an array from the pile, and geophone set (E) was placed on the surface of the gas pipe some 2m below the ground level at 16m stand-off from the pile position. A summary of the results is shown in table (T5-25). The levels of vibration were relatively smaller than those obtained from pile 1, perhaps because the pile was driven in undisturbed ground and the pile toe had penetrated deeper. The level of vibration on the gas pipe was in the range of 1-4mm/s and again the dominant frequency was low at about 10Hz. The attenuation of the vibration data taken at five stations is displayed in figure (5.34), and a comparison of the vibration records taken during driving pile 1 and pile 2 is given in figure (5.35).

The second visit was carried out to the site on 14th March 1989 during the main pile driving work. Again the primary aim of this visit was to monitor the ground vibration levels continously because of the presence of the two gas pipes in the area. The vibration levels, in the location of the pipes, were limited to 11mm/s ppv. The gas pipes were some 13m from the pile location. The pile was H-section steel (356 × 368 × 152kg/m), 17m long, and was driven to a depth of 13.5m by a hydraulic-hammer (BSP-357) of 5000kg ram weight. The height of hammer blows varied between 400-1200mm during the driving according to the ground conditions and the depth of penetration. The geophone sets were positioned at 2, 9, 15, 17 & 21m from the pile and covering the location of the gas pipes. A schematic plan of the site is shown in figure (5.36). A summary of the results is displayed in table (T5-26). The maximum vibration of over 50mm/s was recorded at 2m stand-off when the pile had penetrated only 3.5m into the ground. At the same time, the level of vibration at the location of the pipes was in the range of 9-7mm/s. This corresponded to a hammer drop of 1.2m at which a maximum energy of 58.8kJ was delivered to the pile-head in each hammer strike. As the depth of penetration increased, the level of vibration decreased and at a toe depth of 12m, the ppv amplitudes at the location of the gas pipes were only about 3-4mm/s. Figure (5.37) illustrates the attenuation of the ground vibration with respect to the stand-off distance from the pile for two records taken at toe depths of 3.7m and 12m from the ground surface. Also, a display of five sets of records taken at 2-21m from the pile is presented in figure (5.38) and a time-history record of three vibration components is displayed in figure (5.39). The dominant frequency relevant to these traces was between 15-34Hz.

The pile driving was considered to be safe and the records showed that the vibrations imposed on the site by pile driving was below the suggested safety level.

Finally, the third visit was made to the site on 21 March 1989 during driving of a 16.5m long H-pile of the same dimensions as before. A 5000kg ram hydraulic hammer was used to drive the pile 13.2m down into the ground. The pile was located some 30m from the main gas-pipes and the geophone sets were placed at 3, 9, 12, 17 & 21m from the pile and towards the location of the pipes. The recorded data displayed in table (T5-27) show that the levels of vibration measured on the gas pipe were in the range of 7mm/s. The vibration was dominated by the vertical axis while the other two axes (radial and transverse) showed smaller measurement levels.

5.5.2 Darlington

The site was visited on 22nd March 1989 to measure ground vibration levels during a blasting operation. The blast was used to remove an old brick and concrete building base to clear the site for a new development of the Cleveland Forge Area. The site was located in an industrial estate, to the north of Darlington City centre, and was surrounded by storage buildings and warehouses. The ground consisted of made ground overlying silty clay and alluvial deposits.

A total number of 25 holes was drilled in the concrete base to a depth of one metre, and each hole was later filled with 3oz or 4oz of Gelex explosive. All the explosive charges were blasted in a zero delay by a remotely controlled device.

The geophone sets were placed at 13, 20, 23, 32 & 35m from the source of the explosion. Figure (5.40) displays a schematic layout of the site. The maximum peak particle velocity recorded at 13m stand-off was about 50mm/s and the dominant frequencies introduced by the blast were in the range of 10-14Hz. The complete results taken from this site are shown in table (T5-28) in terms of particle velocity, acceleration and displacement. From the table, it can be seen that the level of the vibration, recorded by geophone sets A, B, C & E, decreased as the distance increased from the source of the blast. Examples of vibration records taken at 13m and at 4 different stations from the source are presented in figures (5.41a) and (5.41b), respectively.

5.5.3 Edinburgh

The site was visited twice on, 15th Sept. and 2nd Dec. 1987. The site was located at the north end of the Dundas street in Edinburgh, and involved construction of office blocks and carpark facilities. The Leith Water channel passes through the south boundary of the site and the site was surrounded to the east and north by a series of old office blocks.

A large number of steel sheet piles (Frodingham 4N) were driven to control the possible ground movements during the excavation for the building foundations to be constructed. A vibrodriver (MS50H) and a hydraulic-hammer(BSP357) were used to drive the piles to shallower and deeper penetration depths respectiviley. The ground consisted of alluvial deposits underlain by silty clay layers.

Nothing was recorded on the first visit due to failure of the hammer. In the second visit the ground vibrations were recorded during the driving of Frodingham 4N piles to a depth of 6m using a hydraulic hammer (BSP357). The piles were driven some 40m from a Victorian brick work structure. The geophone sets were placed at 2, 5, 9, 14 & 18m from the pile. Figure (5.42) demonstrates two schematic views of the site. The PDR1 unit was used for recording the data. The data were later processed and the output results are shown in table (T5.29). Because the maximum penetration depth of the pile was only about 6m, a higher level of vibration was recorded for the geophones closest to the pile while the level of vibration at further distance showed a sharp decrease.

5.5.4 Great Yarmouth

Visits were made to the site on 2nd & 3rd March 1989. The site was located within the centre of Great Yarmouth and opposite to the Town Hall. The work involved building of a new defence wall along the bank of the River Yare to replace the old timber wall. A large number of steel sheet-pile and tubular piles were used for this purpose. A general view of the site is shown on plate (5-4).

The ground vibration levels were measured during driving the tubular piles. The piles were steel open ended tubular, 21m long, 7mm in thickness and 1.3m diameter and were driven close to the position of the existing sewage system including chambers no.1 & 2 and the pump-station. They were driven in this particular position to secure the safety of the sewage system by acting as stiff cantilever piles, since ground anchors could not be used as elsewhere along the wall. The sewage chambers were constructed from reinforced concrete and the pumping house was built of brick. Figure (5.43) illustrates the location of the sewage system, summary of the ground conditions, position of the piles and location of the geophones from the pile. The main concern of the vibration measurement was to investigate the effect of pile driving on the sewage chamber. The pile was driven in combination with steel sheet-piles (Larssen 6W) which were used to join the piles together. The sides of the tubular piles were welded along their length to the interlock part of a Larssen pile.

A vibratory hammer (PTC-131HF) was used for the pile driving. The driving operation caused some settlement in the surrounding ground which was observed as fine cracks along the brick joints of the pumping-house and large cracks in the road pavement and on the road asphalt. The cracks were parallel to the river bank which indicated the direction of ground movement.

A summary of the recorded data is shown in table (T5.30) as peak particle velocities. The results show that the level of vibrations for all geophone stations were in the range of 1-2mm/s, which were small despite the appearance of the cracks which developed during the time of pile driving. It is suggested that the input of the high frequency vibration by the hammer caused some local liquefaction in the surrounding granular soil and caused large movements in the ground.

The low level of measured vibration may also be caused by the absorption of the transmitted energy by loose and granular components of the ground which acted as a damping filter.

The low level of vibration measurement may also be due to the location of the sewage chamber which acted as a gap between the measuring equipment (geophones) and the source of the input energy (piles).

5.5.5 Grimsby

The site was visited on 14,15th April and 18th June 1987 for the measurement of vibrations during the trial and the main pile driving, respectively. The site was located within the centre of Grimsby. The work was part of a new development of the traffic system of the city which involved construction of a new road to link the Deansgate flyover to East Marsh Street. The route of the road lies along the south bank of the River Freshney and is linked to East Marsh street by a new bridge which is to be constructed over the River Head. The layout of the site and locations of pile driving is indicated in figure (5.44).

The area is generally level except for a slope on the southern bank of the River Freshney. The water in the river is non-tidal and approximately 2m below the carpark level. The geological information of the site indicates that the area is on the edge of the alluvial coastal plain and consists mainly of made ground of maximum thickness of 0.5-1.5m, alluvial deposits of soft organic silty clay which extend to a maximum depth of 4.1m, boulder clay deposits to a depth of 20m below this is chalk and gravel of the bedrock. The details of the ground conditions are shown in figure (5.45a).

Trial Piling

The trial piling contract involved the driving of a single and a group of four steel sheet piles(Larssen 25W). The piles were driven one metre off-shore of the River Head by an air-hammer (BSP-700N) to approximately 10m deep in the ground and then by a double acting diesel-hammer (BSP-B15) to a maximum depth of 14m. The piles were designed to be used as foundation elements to support the bridge piers and also to retain the bank of the River Head. The PDR1 unit was used for recording the ground vibration. Plate (5-5) illustrates a general view of the site at the time of placing the air-hammer on the top of sheet pile (no.3).

During the operation of the air-hammer, five sets of geophones were placed at right angles to the width of the piles at 3, 6, 10, 15, & 20m stand-off. The piles were driven to 10m into the ground. The driving was fast where the rate of the hammer impact was at 70 blows/min and was getting slower at about 30 blows/min for deeper penetration. The induced vibration from the hammer was small (max. peak particle velocity at 6m was 4mm/s) but noise level produced by the hammer was high, which was undesirable for a town centre.

Another set of vibration records was taken during the use of the diesel hammer of 1500kg ram mass and 81 blows per minute. The geophones were set on a grassy surface around the pile at 4, 6, 9, 11, & 13m (see figure (5.45b)). The single pile was first driven to a depth of 14m, then the hammer was used to drive the other four piles (two interlocked piles together) to 14m deep. A summary of the ground vibration measures is shown in table (T5-31). It can be seen from the table that the maximum particle velocity was in the range of 15.7mm/s at depth of 13m and the level of vibration decreased as the distance from the pile increased. The frequencies relevant to the above vibrations were in the range of 18-25Hz.

During the operation of the diesel-hammer the input energy to the pile was tested by Testal using the CASE method. The results of these analyses showed that the transferred energy by the hammer to the pile was in order of 1200 kg.metres and the measurement of the stress at the pile head was in the range of 160N.m^{-2} and 130N.m^{-2} for the single and the pair of piles, respecively.

Main piling

The site was visited again during the main pile driving. A diesel-hammer (BSP B-15) was used for driving steel sheet piles (Larssen 25W) 13.5m into the ground. The geophones were placed at right angles to the piles and parallel to the river Freshney. The first four sets were placed on the loose material (gravel and broken brick) of the river bank while the last set was placed on the carpark ground. The PDR2 unit was used for the first time on the same site as the PDR1 unit in recording the ground vibration, and the result was satisfactory. A summary of the derived results from both units is shown in table (T5-32) and (T5-33), respectively. The results suggested that the vibration levels were in the range of 15-20mm/s, and ~~the recorded~~

the recorded vibrations were dominated by the radial and vertical waves. The calculations showed the frequency of the vibration records to be in the range of 20-35Hz. An example of the attenuation of the ground vibration with respect to the geophones stand-off is shown in figure (5.46).

5.5.6 Immingham

Two visits were made to the site on 28th Jan. and 3rd Feb. 1988. Ground vibrations were measured during driving a steel open ended tubular pile. The pile was part of construction of a new pier in dock no.7 of the Immingham port. The piles were 20m long, 1620mm diameter, 16mm thickness, and were driven into the ground using a double acting hydraulic hammer (IHC S-70)† of 3.5 tonnes ram weight in which the drop height was adjusted by a hand held remote control during the driving. The hammer was operating in the range of 50 blows per minute in which a maximum energy of 70kJ per blow was delivered to the pile-head. The tube piles were interlocked by a number of Larssen piles (25W). A general view of the site, piles and the hammer is shown in plate (5-5).

The piles were driven some 12m offshore of the closest bank, so the geophones sets were located at 15, 18, 21, 29 & 33m from the location of the pile. A summary of the results obtained is shown in table (T5-34). The level of the measured vibrations was low. It can be suggested that the location of the geophones and the presence of the water caused the small vibration levels.

Due to failure in the driving equipment, no pile driving was carried out on the second visit to the area.

† See Winney (1989)

5.5.7 Keighley

Construction of the *Keighley Bypass Contract* included building two bridges over the Rivers *Worth* and *Aire* in its 4 miles route to the south of the town of Keighley. Figure (5.47) illustrates a general view of the site, the route of the proposed bypass and the location of the pile driving areas. A large number of piles, including steel H-pile and sheet-piles, were driven to bedrock to establish the foundation of the bridges, and to shallower depth to retain embankments for the associated roads. The depth of the bedrock in River Worth site `Area-1` was about 32m, and in the River Aire site `Area-2` was about 26m deep. A simplified geological condition of the ground is given in figure (5.48).

Since the construction site was located in a residential area, especially in `Area-1`, the measurement of the induced vibration level by the driving equipment was important. Measurements of the ground vibration were taken by Durham University on a number of visits to the site during pile driving operations. A summary of the site visits is listed below:

Visit	Date	Area	Pile	Hammer	Comments
1	29.02.87				no measurements
2	02.03.87	A1	H-pile H-pile	Hydraulic Hydraulic	pile no.1 pile no.7
3	10.03.87	A2			failure in PDR1
4	13.03.87	A2			failure in PDR1
5	23.03.87	A1			no driving
6	02.04.87	A1	H-pile	Hydraulic	
7	28.04.87	A1	Sh-pile H-pile	Vibrodriver Hydraulic	close to houses on the river bank
8	18.05.87	A2	H-pile	Vibrodriver	
9	21.05.87	A2	H-pile	Diesel	

Area(1)

A schematic layout of the this site is shown in figure (5.49) which also indicates the position of the piles near the surrounding houses. Four visits were made to this area during the trial and main pile driving.

On 2nd March 1987 the first visit was made to the site. Two trial steel H-piles ($305 \times 305 \times 126$kg/m) were driven some 31m into the ground using a hydraulic hammer (BSP357) of 3000kg ram weight. One of the piles was located close to the existing houses (pile no.1) and the second close to the River bank (pile no.7). The geophone sets were placed on the footpath alongside the houses at 4, 7, 11, 15 & 20m from pile no.1 and for pile no.7 the positions of the geophones were at 4, 7, 10, 15, & 20m parallel to the river bank. The PDR1 unit was used to record the vibration data.

A summary of the recorded data is shown in tables (T5-35) and (T5-36) for the piles no.1 & 7 respectively. Examples of vibrations taken at 4m stand-off for three orthogonal components of the wave is shown in figure (5.50a), and the attenuations of five radial waves taken at different stations are displayed in figure (5.50b). The range of the frequencies relevant to these vibrations was in the order of 22-35Hz. Referring to the tables, it can be seen that the levels of the measured vibration were almost the same at 4m and 20m stand-off. This may lead to the suggestion that:

1. since the piles were penetrated deeply into dense stratum (20-32m), and the radial distances between the pile-toe to the geophone locations at the ground surface were almost the same, the distribution of the transmitted energy might be estimated to be similar.†.
2. the ground around the location of the pile was excavated so the transmission of the surface wave was reduced close to the pile.

The second visit to the site was carried out on 2nd April 1987. A number

† As the input dynamic to the pile is transmitted to the surrounding soil through its toe, for a deep penetrated pile (for example 30m), the radial distances from the pile-toe to the geophone locations at horizontal distances of 5m and 15m, are 30.5m and 33.5m, respectively. In terms of $\sqrt{W}/r$ the magnitude of the transmitted energy at these two locations is 0.16 and 0.14 $kJ^{1/2}.m^{-1}$, respectively

of steel H-piles($305 \times 305 \times 126$kg/m) were driven on the west bank of the River Worth for the construction of the bridge foundation. A hydraulic hammer (BSP-357) of 3000kg weight, was used to drive the pile 27m deep into the ground. The sets of geophones were located parallel to the River and parallel to the flange of the piles at 3, 6, 10, 16 & 20m from the driving point. A summary of the results is shown in table (T5-37). The results showed that the level of vibration decreased as the stand-off from the pile increased. The average level of vibration was about 20-40mm/s at 3m stand-off which decreased to 2-4mm/s at 20m stand-off.

The third visit to this area took place on 28th April 1987 where two types of piles, steel sheet-pile (Frodingham 3N) and H-pile ($305 \times 305 \times 126$kg/m) were driven by a vibratory hammer (Muller MS25H) and a 3000kg ram hydraulic hammer (BSP 357), respectively. Plate (5-7) illustrates the procedure of sheet pile driving by the vibrodriver. The sheet piles were located alongside the surrounding houses (see figure (5.49)) and were driven to depth of 6.5m into the ground. The piles were designed as a retaining wall for the construction of the new road embankement. The geophones were placed at 2, 5, 8, 12 & 16m from the piles. The measured results are shown in table (T5-38). The table indicates that the level of the ground vibration was a function of geophone stand-off and pile depth and that as the depth of toe penetration and the distance of the geophones from the pile increased, the level of vibration reduced. Two examples of attenuation of vibration records are shown in figures (5.51a) and (5.51b). The dominant frequencies calculated from these records were in the range of 18-24Hz.

The H-piles were driven alongside the River Worth to form the bridge foundations on the East bank. The geophones were positioned at 2, 5, 9, 13 & 18m from the piles. A summary of the results is shown in table (T5-39). The discussion suggested for the previous records can also be applied here. The attenuation of vibration with respect to the horizontal distance for two records taken during the operation of the vibrodriver and the hydraulic-hammer is shown in figure (5.52).

Area (2)

The site was located alongside of a local railway line and was remote from any residential population. A number of H-piles were driven for constructing the bridge abutment on the both sides of the River Aire. Sheet-piles were also driven alongside the river bank to form a defence wall and to prevent the river bank from possible water erosion. A schematic layout of the site is illustrated in figure (5.53).

On 18th May 1987, the site was visited during the driving of steel H-piles ($356 \times 368 \times 134$kg/m) using a vibrodriver (MS25H). The piles, which were 16m long, were driven down to a depth of 13m. The geophones were placed in an excavated area of (20×5m) and at depth of 2m below the original ground level. Their positions were at 3, 5, 7, 9 & 13m from the pile and parallel to the River bank (see plate (5-8)). The ground consisted of loose to medium silty sandy material. A summary of the results is shown in table (T5.40). Two examples of time-history vibration records taken at 3m stand-off is shown in figure (5.54). The vibration frequencies calculated from these records were in the order of 24-28Hz.

The last visit to the site was carried out on 21st May 1987. 16m extensions had been welded to the original H-piles and these were driven by a Diesel-hammer (BSP-50c) to give a toe depth of 26m. The geophones were placed in the excavated area. Three set of records were taken during the driving of three different piles. A summary of the results is shown in table (T5.41), and examples of vibration traces taken at one station and at five different stations are shown in figures (5.55a) and (5.55b). The range of the calculated frequencies was 22-35Hz. A comparison of two sets of data taken from the vibrodriver and the diesel-hammer is given in figure (5.56).

5.5.8 Newark

The construction of the **Newark Relief Road** was part of the development in the traffic system of Newark City. The project involved driving hundreds of piles of several types to support bridge foundations and to retain road embankments. According to the site of construction, different sizes and lengths of H-piles were driven down to establish bridge abutment foundations by means of 5000kg drop-hammers. Both vertical and raking piles were driven for this purpose. Sheet-piles were driven by vibrodriver (long piles) and by air-hammer (short piles) to form retaining walls where they were required.

A number of visits were made to the area to measure and to examine the vibration levels introduced into the ground during pile driving operations. The visits are listed in the table below:

Visit	Date	Pile	Hammer	Comments
1	26.09.1988	H-pile	Drop	vertical
2	16.12.1988	H-pile	Drop	vertical
3	06.02.1989	H-pile	Drop	raking pile
4	15.02.1989	Larssen(25W)	Vibratory	

The first visit to the site was carried out on 26th Oct. 1988. The site was located next to the **London-Edinburgh** railway line. A schematic layout of the site together with a simplified pattern of the ground conditions is shown in figure (5.57). Two steel H-section piles of $(305 \times 305 \times 126kg/m)$ and $(305 \times 305 \times 110kg/m)$, were driven to a maximum depth of 10m by hydraulically operated drop-hammers of 5000kg and 4000kg ram weight respectively. A summary of the recorded data is shown in tables (T5-42) and (T5-43). In both cases, the geophone sets were placed at 2, 5, 9, 14 & 18m from the driving point. The maximum vibrations in terms of particle velocity were in the range of 15-35mm/s for 2m stand-off and 2-5mm/s for 18m stand-off. The dominant frequencies for these records were in the order of 22-35Hz. The recorded vibration was dominated by the radial and vertical waves while the vibration recorded in the transverse direction showed relatively smaller magnitude. An example of three vibration components is shown in figure (5.58) and an example of the derived acceleration and displacement from the original particle velocity records is illustrated in figure (5.59).

The second visit was carried out on 16th Dec. 1988. H-piles($305 \times 305 \times 186kg/m$) were driven at a 1/4 rake into the ground. The site was located alongside a local railway line (see plate (5-9)). The positions of the geophones were at 2, 4, 7, 13 & 20m from the pile. A summary of the results is shown in table (T5.44). From the table it can be noticed that the level of vibration is in the range of 20-30mm/s for 2m stand-off and decreased as the distance from the pile location was increased, to about 2-6mm/s at 20m stand-off. The attenuation of vibrations for all channels is displayed in figure (5.60).

On 6th Feb. 1989 another visit was made to the site. The ground vibration was measured during driving an H-pile($305 \times 305 \times 110kg/m$) by a drop-hammer(BANUT) of 5000kg ram weight. The geophones were placed at 4.5, 7.0, 11.0, 15.0 & 23.0m from the pile. The summary of the results is shown in table (T5-45). The pile was driven vertically into the ground and the geophones were positioned at right angles to the flanges of the pile. Radial waves dominated the vibration in these records. Figure (5.61) displays the attenuation of vibration with respect to time and stand-off distance from the pile.

The last visit to the site was carried out on 15th Feb 1989 on which steel sheet-pile (Larssen 6W) 9.5m long were driven by a vibratory-hammer (PTC 13H1/1). Two set of records were taken, during the driving of a corner-pile and a single pile. The positions of the geophones were at 3, 6, 8, 12 & 18m from the piles (see figure (5.62)). A summary of the recorded results is shown in table (T5-46), which indicates that the vibration levels decreased rapidly as the distance increased.

5.5.9 Newbiggin

The site was visited on 14th and 26th of August 1987. The project involved the building of a new sea barrier to protect the town. The pile driving contract included driving two types of steel H-section pile and sheet-piles (Larssen 20W). The sheet piles were driven in the first line facing the sea while the H-piles were driven close to an existing retaining wall. On the first visit the ground vibrations were measured during the sheet-pile driving. The piles were 5m long and driven 4.7m deep into the ground by a hydraulic-vibratory hammer(ABI). The driving procedure was fast and the output noise level was low. The hammer was also used to extract and reposition driven piles if necessary. The hammer operation was most effective for the job.

The ground consisted of coastal plain alluvial deposits one metre thick overlying boulder clay layers. The geophones were placed at 2, 5, 8, 12, & 18m from the pile at right angles to the pile width (see figure 5.32). A summary of the recorded results is shown in table (T5.47). The level of vibration recorded close to the pile was very high, 30mm/s at 2m, and decreased sharply as the distance increased down to 1mm/s at 18m (see figure (5.63)). The time-history records of vibration data recorded at this site are shown in figures (5.64a) and (5.64b). The dominant frequencies of the applied vibration were in the order of 27Hz.

5.5.10 Newton-Aycliffe

A number of visits were carried out to the site to measure the ground vibrations caused by road traffic, rail traffic and quarry blasting. The site was located within the Newton Aycliffe Industrial Estate, County Durham. The measurement of vibrations was requested by the Sedgefield District Council to assess the site information to be considered in the construction of an international (Japanese) factory which is to produce microcomputer components. The main attention was directed to investigating the effect of vibration induced by the blasting from Aycliffe Church Quarry which happened once per week, on the surrounding area. The visits to the site are listed below:

Visit	Date	Site	Comments
1	20.05.88	Heighington Lane	Rail, Road & Blast measurement
2	21.06.88	Heighington Lane	Blast Vibration Measurement
3	04.11.88	Green Field	Blast Vibration Measurement
4	15.03.89	Lyons Tetley	Blast Vibration Measurement

The first visit to the site was made on 20th May 1988 where the vibration levels caused by *road & rail traffic* and *quarry blasting* were measured. The location of the site is shown in figure (5.65). Measurements taken from the above sources are discussed in the following sections.

1. *Road Traffic*:

The measurement of vibrations from traffic on Heighington road was made by three sets of geophones which were placed on the ground surface at 0.5, 3.8 & 10m from the edge of the road where the road surface contained some irregularities (see figure (5.66a)). The measurements were taken during the passage of heavy vehicles on the nearside and the farside of the road. An example of the vibration records taken at 3.8m from the road caused by a lorry is displayed in figure (5.67a). The output of the frequency analysis of the three components of vibration records using the FFT programe are shown in figures (5.67b) to (5.67d). A summary of the vibrations measured in terms of peak particle velocity is shown in table (T5-48). The following points can be derived from the road traffic measurements:

1. the highest vibration level was recorded by the geophones placed close to the road;
2. the heavy and longer vehicles produced a higher level of vibration;
3. because the input energy to the ground during the passage of the vehicle is relatively small[⊙] the induced vibration has a local effect and its magnitude decreased sharply as the distance from the source increased.

2. *Rail Traffic*:

The ground vibrations caused by rail traffic were measured by four sets of geophones which were placed at 3.5, 7.5, 13.5 & 18.0m from a local railway line (**Darlington to Bishop-Auckland line**) (see figure (5.66b)). The ground vibrations were measured during the passage of a local 2-unit passenger train in either direction and a cargo train which included a Deltic diesel plus 15 cement wagons. Examples of ground vibration caused by rail traffic together with their relevant frequencies are shown in figures (5.68a) to (5.68d). A summary of the recorded vibration is shown in table (T5-49). The following deductions can be obtained from the table:

1. the heavier and longer trains produced a higher level of vibration;
2. the shorter and lighter trains also produced large vibrations, where the running track was in a poor state of repair;
3. the vibrations from rail traffic attenuated rapidly with the increase of the distance from the rail line.

⊙ A lorry of 20000kg weight produces only about 2kJ energy when it passes over a hump on the road surface 10mm deep

3. *Blast Vibration*:

The blast vibrations were taken by five sets of geophones at a site located to the north of Lyons Tetley Distribution Centre (see figure (5.66c)). The corner of the site (green field) was selected as a reference point and its location from the blasting source was measured from a 1:2500 scale map of the area provided by the Council in which the approximate locations of the geophones were found to be at 400, 402, 405, 411 & 419m from the source of the quarry blast. The blast was carried out in the quarry which was located to the west of the Durham-Darlington road (A167). Details of the quarry blast are explained below.

There were a total of seven holes with a 20 milliseconds delay between the detonation of explosive in each hole. Three of the holes contained 12.5kg of slurry base charge and 59kg of ANFO (*ammonium nitrate/fuel oil*) deck charge. Three more holes contained 10kg of slurry base charge and 61kg of ANFO deck charge, and the seventh hole contained 2.5kg of slurry base charge only. Apart from the last hole, the base charge heights were 4.5m or 5.4m and the deck charge height 20.7m or 28.6m, making a 27m column of explosive. Both burden and spacing were 10.8m. The blast was a typical arrangement of explosive used in the Aycliffe Church Quarry. Again, the attenuation of vibration with respect to time for the set of geophones located at 405m stand-off is illustrated in figure (5.69a) and the induced vibration frequencies of the three orthogonal waves are shown in figures (5.69b) to (5.69d). A summary of the recorded vibrations in terms of peak particle velocity, acceleration and displacement is shown in table (T5-50). The following points can be noted from the table:

1. the general range of the particle velocity as recorded was in the range of 3-5 mm/s;
2. the vibration measured by the geophones which were located near to the centre of the field showed a slightly higher level;
3. the ground vibrations were dominated by the horizontal (radial and transverse) movements.

On 21 June 1988 a second visit was made to the site to investigate the earlier recorded vibration results. The geophone sets were placed at 342, 347, 349, 376 & 412m from the source of the blast. Details of the blast were supplied by the quarry owners and explained below:

A total of 5 holes were fired with a 20 milliseconds delay between the detonation of explosive in each hole. All five of the holes contained 10kg of slurry base charge and 56kg of ANFO deck charge. The base charge heights were 4.5m and the deck charge heights were 23.4m, making a 27.9 m column of explosive. Both burden and spacing were 10.8m. It can be seen that the total charge weight was 330kg. A summary of the recorded vibration is shown in table (T5-51). The table showed that the measured vibrations were similar to those which were measured on the first visit where the recorded vibrations were again dominated by transverse and the radial axes. Again, the average magnitude of the vibration levels was in the range of 3-5mm/s.

The third visit to the site was carried out on 4th Nov.1988 for further measurement of the ground vibration. The source of vibration for this visit was located to the east of the Darlington to Durham road (A167) at *Aycliffe East Quarry*. The site on which the geophones were placed was located to the west of a local road (C187) and the distance between the quarry face and the edge of the site was approximately 1000m (see figure (5.65)). The geophones were placed in a radial array from the edge of the site nominally at 1000, 1003, 1012, 1027 & 1057m stand-off from the quarry face. There was a total of eight holes, each to a depth of 21.3m below the quarry floor. Both burden and spacing were 10.8m. Each hole was filled by 25kg of slurry explosive to a 10.8m height. Above this was 2m of water, 36.3m of ANFO weighing 75kg, followed by 10.8m of stemming up to the crest. Thus each hole was charged with 100kg of explosive to give a total charge of 800 kg. One of the holes was detonated at zero delay, and the other holes were delayed at one second intervals. The level of vibrations obtained from these measurement were in the range of 0.5mm/s. Calculations of the frequency spectra for the vertical and transverse signals were in the range of 54Hz but a maximum of 65Hz was calculated for the radial axis.

The last visit was carried out to the site on 15th March 1989 to measure the effect of blast vibrations on Lyons Tetley Distribution Centre. The positions of the geophones are indicated in the table below.

set no	*location*	*stand-off*
Set A	on the carpark area close to the C187 road	220m
Set E	near the corner of the storage building	261m
Set C	at the gate of the storage building	263m
Set B	inside the storage building	265m
Set D	inside the storage building	266m

The recorded results are shown in table (T5-52) in terms of particle velocity, acceleration and displacement. A maximum resultant of 16mm/s was recorded by the first set but the sets close to the building showed lower vibrations which were in the range of 3-8mm/s.

5.5.11 Reston

The site was visited on 23rd March and 9th April 1988 to investigate the effect of rail and road traffic vibration and pile driving vibration, respectively, on the surrounding houses. The vibration measurement was requested by the local authorities during the construction of a new bridge to replace the existing bridge no 41, over the main North Eastern Rail line. The location of the proposed bridge was surrounded by a series of houses and farm land within Reston village, north of the Scottish border.

Traffic Vibration

The layout of the area and the positions of the geophones are shown in figure (5.70). The levels of ground vibration were measured during the passage of two passenger (inter city) trains, a cargo train and the passage of a lorry over the bridge. A summary of the recorded vibrations is shown in table (T5.53). The table shows that the levels of vibration were very small and in the range of 0.3-1.2mm/s.

Pile driving

Ground vibrations were measured during pile driving operations. A number of steel sheet-pile (Frodingham 3N) were driven 5m into the ground along the embankments of the rail line, using a hydraulic-vibrodriver (ABI). The pile driving was carried out at night and early on a Sunday morning while the line was closed to all the rail traffic. Perhaps due to the freezing temperature (−5°C), the PDR2 unit failed to operate and the vibration measures were recorded by the PDR1 unit. The geophones were placed on the bridge at 3, 5, 9, 12 & 17m from the pile location. The summary of the vibration results is shown in table (T5-54). The dominant frequencies associated with these vibrations were in the order of 32-44Hz. An example of the attenuation of vibration with respect to horizontal distance from the driven pile is demonstrated in figure (5.71).

5.5.12 Rotherhithe

This site was visited on 18th & 19th April 1988 for monitoring the vibration levels of the ground during pile driving. The site was located at the south bank of the River Thames, near to the Rotherhithe tunnel. Steel sheet piles were driven along the river side to build a new defence wall as part of the construction of a block of multi-storey flats in the newly developed area of London Dockland. The ground vibration measurements were carried out with the standard sets of geophones using both PDR1 and PDR2 units.

The piles were Larssen (32W), 20m long and were driven by a vibrodriver (Muller, MS-25H) to a depth of 10m at a rake of 1/6 towards the river. Figure (5.72) illustrates a schematic layout of the site.

The sets of geophones were placed on the tidal shore of the river at 2, 4, 9, & 15m from the piles. A summary of the vibration results recorded by the PDR1 unit is shown in table (T5-55). The table showed that the vibrations were in the range of 15-25mm/s at 2m distance from the pile and decreased sharply as the geophone's stand-off and depth of pile penetration increased. The radial and the vertical vibrations were dominant while the transverse wave showed a small magnitude. A comparison of two set of records taken at toe depths of 2m and 7m is displayed in figure (5.73).

Another set of records of the ground vibrations was taken by the PDR2 unit while thr tidal level of the river was rising. The geophones were placed at 2, 4, 6, & 8m from the pile. The results are shown in table (T5-56). The same points can be extracted from this table as those mentioned above. Examples of typical three and five vibration traces are presented in figure (5.74a) and (5.74b).

The third set of vibration records was taken on the ground surface, some 11m above the location of pile driving. The geophones were positioned on the construction ground at 3, 6, 10, 14, & 20m from the pile. The results of these records are shown in table (T5-57). As was expected, the results showed that the levels of vibration were much less than those recorded on the river shore.

The vibration frequencies calculated from all the measured data were in the range of 22-28Hz.

5.5.13 Scarborough

The site was visited on 22nd Feb. 1988, to monitor ground vibrations during pile driving. As part of the reconstruction of the Scarborough fish quay, hundreds of steel sheet piles (Larssen 16W), 15m long, were driven into the ground using a double acting air-hammer (BSP-600N). A general view of the site is shown in plate (5-10).

Both the PDR1 and PDR2 units were used during the vibration recording procedure. The geophone sets were placed on the dockyard concrete quay at 2, 4, 7, 10 & 14m from the pile. Some of the results are shown in table (T5-58). The displayed results indicate that average recorded vibrations were relatively small and the highest level of vibration was dominated by the transverse waves and was in the range of 5-7mm/s for geophone stand-off of 2m. The dominant frequency calculated from these records was in the order of 17-30Hz. Figure (5.75) displays the attenuation pattern of the vibration records with respect to the distance. The figure shows that there was a sharp decrease of vibration with the increase of distance.

The small level of vibration recorded in this site may be due to the following causes:

1. the piles were driven some 1.5m in front of the exsisting quay side on which the geophones were placed;
2. the transmission of the input energy from the pile to the ground and reaching the geophones was limited because of their location on the concrete block and some 10m above the driving point;
3. as in most cases, the use of an air-hammer produced low vibrations in the ground.

5.5.14 Selby (Monk Fryston)

The site was located in *Monk-Fryston* near *Selby*. The visit was carried out on 3rd Sept. 1987. The ground vibrations were monitored while driving precast concrete piles for the construction of a Hotel building extension.

The piles were 12m long precast reinforced concrete (Balken, $245 \times 245mm$) and were driven to the bedrock after passing through a working mat of a layer of hardcore and very soft peat. The layout of the site is shown on figure (5.76). A winched drop-hammer (Banut-400) with 4000kg ram was used for pile driving. The height of the drops was adjusted during the driving and was varied between 300-400mm. The driving operation was easy and fast in the peat but became very hard and slow as the pile approched bedrock.

Two sets of data were recorded. In the first set, geophone sets A, B & C were placed on the working mat and the other two sets D & E were placed on adjacent farm land at 2, 5, 9, 14 & 20m from the pile. In the second set, only geophones E were placed on the farm land while the others were placed on the working mat.

A summary of the results is shown in tables (T5.59). The average of the measured vibration at 2m stand-off was in the range of 15-20mm/s which decreased to 1mm/s at 20m stand-off. Attenuation plots of two vibration records in terms of velocity versus stand-off is shown in figure (5.77). The figure shows a steady decrease of vibration level as the distance from the pile increased. Finally, example traces of velocity plots with respect to time are shown in figure (5.78). The relevant dominant frequencies deduced from these records were in the range of 22-35Hz.

5.5.15 Sheffield

The site was located in an industrial area, East of Sheffield. The pile driving was part of the Meadowhall Centre Development scheme which involved building a new shopping centre and associated facilities including carparks and new access bridges over the River Don. A number of site visit were made during trial and main pile driving for the construction of the Jenkin Road Bridge. Figure (5.79) shows the plan of the site where the pile driving was adjacent to the location of the cast iron sewage pipes (Don Valley Syphon) where close attention was paid to the limitation of ground vibration levels.

The ground vibration was measured on the south bank of the river on 25th Oct. 1988 during trial driving of a steel H-pile ($305 \times 305 \times 79kg/m$) to a depth of 8.5m using a double-acting diesel-hammer(B15/7). The geophones were placed at 2, 5, 7 & 15m from the pile, and a set of geophones was placed on the pipe culvert 1.2m below the ground level at 13m stand-off from the pile. Figure (5.80) a schematic layout of the site and simplified ground conditions. The summary of the results is shown in table (T5-60). Examples of time-history records of vibration are shown in figures (5.81a) and (5.81b). The induced vibration frequencies of these records were in the range of 22-28Hz.

On 27th Oct. 1988 a second visit was carried out to the site during driving of another trial pile on the north bank of the River Don. The same size of pile and the same hammer were used. The geophones were positioned at 2, 5, 8 & 12m from the pile and again a set was placed on the pipe culvert at some 4m from the pile. Geophone sets "A" and "B" were located at 2m and 5m from the pile and were positioned on very loose and uncompacted material which had been excavated from the pile driving location, geophones set "C" and "D" were placed at 8m and 12m from the pile on ground surface and geophone set "E" was placed on the pipe culvert at 4m from the pile (see figure (5.82)). A summary of the results is shown in table (T5-61). Attenuation of vibration of two records as function of horizontal distance from the pile is given in figure (5.83).

From the tables, it can be seen that the vibration level on the south bank was below the maximum peak particle velocity of 40mm/s requested by the Council. However, on the north bank the vibrations were higher, especially the signals from geophone sets "A" and "B". It is thought that the high level of vibrations of these sets was related to the movement of the ground surface elements under the effect of compaction or possibly of instability. Consequently the surface measurement in the case of geophones set "A" and "B" did not represent the real ground vibration of firm soil in the area.

To investigate the above suggestion, further measurements of ground vibration were carried out during the main pile driving at the north bank on 23rd Feb. 1989. The pile was driven to a rake of 1 to 4 from the vertical by the same hammer. A general view of the site is shown in plate (5-11) where the location of the pile in excavated ground (about 3m deep) can be noticed. Geophones set E was placed on coarse gravel in the excavated ground at 2m from the pile, set D on the river bank at 5m stand-off, and the other three sets were placed on the ground level at 7, 9 & 12m horizontal distances from the pile. A summary of the results is shown in table (T5-62). Referring to the table, it can be obsereved that the geophone set E which was set on loose gravel and boulder material showed a high vibration amplitude due to the movement of the gravel during the pile driving.

Finally, the last visit to site was on 25th Feb. 1989 where the ground measurements were taken using a vibrorecorder. The device was placed on firm ground in the excavation, and results suggested that the above very high readings were restricted to the loose soils only.

5.5.16 St.Annes

Two visits were made to this site south of Blackpool on 29th Nov. and 2nd Dec. 1986 to measure the ground vibrations during driving steel sheet piles. The piles were used as temporary work for the construction of a new pumping station as part of the development of the St.Annes drainage system which involved construction of about 7.9km of sewers and two new pumping stations.

The site was located at Sandgate about 1km north of St.Annes City Centre, alongside the sea front. The nearest houses were located some 30m from the proposed works on the east side of the North Promenade road. A general view of the site together with a simplified ground conditions is presented in figure (5.84). The site is mainly covered with blown sand overlying granular deposits which have glacial origin, and there were more clayey deposits at some depth.

Some twelve steel sheet-piles (Larssen 32W) 20m long were driven as trial piles by a vibrodriver(PTC-50H2) to an approximate depth of 9.0m and then by a 7000kg ram hydraulic-hammer(BSP-357) to maximum depth of 16m into the ground. The geophones were positioned at 2, 5, 8, 12 & 18m from the pile towards the houses on the sandy beach ground (see figure (5.85)). A summary of the results taken during pile driving by the vibrodriver are shown in table (T5-63) and those taken during the operation of the hydraulic-hammer are shown in tables (T5-64).

Referring to the tables, the maximum resultant particle velocity recorded during driving by the vibrodriver was in the range of 12-29 mm/s at stand-off up to 5m from the pile and the levels of vibration decreased rapidly as the distance increased, to a minimum of 2 mm/s at 18m stand-off. On the other hand, the records taken during the driving by the hydraulic hammer showed a higher level of ground vibration up to 43 mm/s at 2m stand-off (in case of file ANS4) and the level of vibration was still high at 8m stand-off and then decreased to some 6mm/s at 18m. The attenuation of the measured vibrations with respect to the horizontal distance from the pile, for two records taken during the operation of the hammers, are plotted in figure (5.86).

Examples of the vibration traces induced by the vibrodriver are shown in figures

(5.87a) and (5.87b). The relevant dominant frequency was in the range of 22Hz. Also, examples of records related to the hydraulic-hammer are displayed in figure (5.88). The range of the calculated frequencies was in the order of 21-26Hz. It is notable that the hydraulic-hammer was operating manually due to some mechanical problems in the automatic facility. The drop was at its maximum of 1.2m giving a high input energy to the pile equivalent to 82kJ per blow.

5.5.17 St.Helens

The site was visited on 12th Aug. and 4th Sept. 1987 to monitor the ground vibration levels during pile driving. Due to some mis-alignment of the driven piles, no pile driving was carried out on the first visit. Only a record was taken while a pile was extracted. The pile was steel sheet(Larssen 20W) and a vibro-hammer was used for the extraction. The geophones were placed at 2, 4, 6, 9, & 12m from the pile.

The pile driving was part of the construction of a new cofferdam for extending the existing sewage treatment work. Steel sheet piles (Larssen 16W) were used to support the ground during the construction of the cofferdam. The 12m long piles were driven into the ground using a double acting air-hammer(BSP-N700). The ground consisted of laminated alluvial layers mainly of silty clay interbedded with thin layers of coarse grained sand, and having a dip slope of 15°.

A schematic layout of the site and the locations of the geophones are illustrated in figure (5.89) where the first two sets were placed in the excavated ground around the pile at 2 & 5m and the other three sets were placed on the ground surface at 8, 12, & 18m from the pile.

A summary of the collected data is shown in table (T5-65) in terms of peak particle velocity. It is shown that the level of vibration was high close to the pile and decreased rapidly as the stand-off increased. The attenuation of the vibration records with distance is shown in figure (5.90). It might be suggested that the position of the three last sets of geophones which were located on the ground surface some 2m above the level of the driven pile caused the sharp reduction in the magnitude of the recorded vibrations. An example of the vibration traces is shown in the figure (5.91) and the frequency relevant to this record was in the range of 39Hz.

5.5.18 Swillington

Two visits were made to the site on 10th Dec.1987 and 10th Feb.1988. The site was located on the south end of an opencast coal mine in Swillington. The pile driving was part of the construction of a defence and retaining wall to support the stability of the ground and to prevent ground movements towards the excavated area of the mine. The ground consisted of 4.5m made ground, overlying a 2.7m layer of silty sandy deposits which became more clayey as the depth increased and finally was medium dense sand below 10m. A general layout of the site, including a simplification of the ground conditions, geophone positions and pile locations, is illustrated in figure (5.92).

Steel sheet-piles (Larssen 25W) were driven by a vibrodriver (MS-25H) to a depth of 7m. The geophones were placed at 2, 5, 9, 14 & 20m from the pile. A summary of the vibration measurements is shown in table (T5-66). The maximum level of recorded vibration was in the range of 10-15mm/s at 2m stand-off and this decreased to less than 1mm/s at 20m stand-off (see figure(5.93)). Also, the three components of the ground vibration taken at 2m stand-off are shown in figure (5.94a), while the vertical waves recorded at five different stations are displayed in figure (5.94b). The dominant frequencies calculated from these records were in the order of 16-10Hz.

5.5.19 Waltham Cross

The site was visited on 17th March 1988 for the measurement of ground vibrations during trial pile driving. The piles were to be used to form a retaining wall to support the embankment sides of a proposed road during the construction and during the life time of the road. The site was located close to a residential area, so the measurement of the ground vibration levels (and also the measurement of the noise level produced during the pile driving operation) was considered. A schematic layout of the site, location of the piles and position of the geophones, is demonstrated in figure (5.95).

The ground vibrations were measured by both PDR1 and PDR2 recorder units. The piles were pairs of interlocked steel sheet piles type (Larssen 25W) which were driven some 10m into the ground by a hydraulic hammer (BSP357) (see plate (5-12)). The hammer ram weighed 5000kg and the height of the drop was varied during the driving, from between 400-800mm. The geophone sets were placed on the ground at 3, 5, 8, 12 & 17m from the pile towards the houses.

A summary of the results is shown in table (T5-67). From the table, the following conclusions could be made:

1. the vibration levels close to the pile were high (75mm/s at 3m stand-off) and decreased sharply as the distance increased (3mm/s at 17m);
2. the vibration level increased as the pile penetrated deeper into the ground;
3. the ground vibrations were dominated by the radial and the vertical waves while the transverse wave showed smaller vibrations.

The attenuation of vibration records taken at 6m and 8m are displayed in figure (5.96). Examples of vibration traces are also shown in figures (5.97a) and (5.97b).

5.5.20 Whalley

The site was visited on 22nd September 1986 to measure ground vibrations during the driving of a number of precast concrete piles. The site was located within the residential area of Whalley and was bounded to south and west by the back gardens of the surrounding houses and to the east by the Accrington road.

The site comprised an area of land approximately 130m by 44m on which a number of houses and two storey flats were to be constructed. A series of field and laboratory soil mechanics tests were carried out to investigate the subsurface soil conditions. The water table was about 1.3m below the ground level. A simplified section of the ground conditions is shown in figure (5.98a).

Ground vibrations were measured during the driving of precast reinforced concrete piles of cross section (250 × 250mm `Herkules`). The length of each was 13m and these were jointed together to make longer piles for deeper penetration. The piles were driven by a drop hammer of 4000kg ram weight. The height of drop was adjusted during the driving and was varied between 0.3-1.0m. A cushion and helmet were used to protect the pile-head from impact damage during the driving. Plate (5-13) illustrates a general veiw of the construction site during the procedure of pile driving.

The geophones were positioned at 2, 4, 6, 10 & 15m from the pile (see figure (5.98b)). In one occasion, a set (`set E`) of geophones was placed on the adjacent stone wall to examine the effect of vibration. A summary of the results is shown in tables (`T5-68`) and (`T5-69`). The recorded vibration levels were in the range of 15-29mm/s at 2m stand-off, but at further distances the vibration levels were still in the same range. It can be suggested that, because the final set of geophones (`set E`) was placed on loose ground and on the edge of a filled land, it was the soil movement on the surface of the slope which caused the high level of vibration rather than a high wave paropagation of the ground. Examples of the recorded vibration traces taken at 2m stand-off and at five different stations are illustrated in figures (5.99a) and (5.99b), respectively.

5.5.21 Workington

This site was visited four times on 14th & 27th May, 30th June and 3rd July 1987. The work involved construction of a new retaining wall along the south bank of Workington Dockyard. Steel sheet piles(`Frodingham 2N`) were used for this purpose. The 12m long piles were driven offshore some two metres from the existing old retaining wall using a vibrodriver (`PTC 25`). The site was located behind the residential area, so the effect of vibration to the houses was considered.

Unfortunately no vibration measurement was achieved during all the four visits due to various problems which occurred on the site on the day of visit, such as the hammer failure, high tidal water in the bay, and cracking of the ground which stopped the pile driving.

5.6 Summary

A summary of the ground vibration measurement results is shown in table (T5-70). The vibration levels are displayed in terms of resultant vectors of peak particle velocities (mm/s) measured in three orthogonal directions, recorded by sets of geophones at different stand-off locations from the pile. The display of the data taken from 32 different sites are divided according to the type of hammers used for pile driving. The summary sheet also includes information about the site locations, the ground conditions and pile dimensions. This tabulated information can be used as an easy reference for estimating the ground vibration at sites with similar conditions.

A highest level of peak particle velocity of 75mm/s was recorded by geophones located some 2m stand-off distance during driving of a pair of interlocked sheet-piles 8m deep into stiff London clay by a 5000kg ram hydraulic-hammer (BSP-357) in Waltham Cross. This magnitude corresponds to a peak particle acceleration of 9000mm/s^2 or 0.9g and 1.0mm peak particle displacement. A lowest level of ppv of 1.64mm/s was recorded in Great Yarmouth during driving of a 1200mm diameter steel tubular pile 14.7m deep into a loose granular soil using a high frequency vibrodriver (PTC 23HF).

By reviewing the ground vibration measurements given in this chapter and with respect to the type of driving hammer,it can be concluded that the sequence of the following hammers† *left-to-right* generates the lowest and highest vibration levels in the ground:

Air-hammer, Vibrodriver, Diesel-hammer, Drop-hammer & Hydraulic-hammer

With respect to the level of noise, the following sequences of hammers *(left-to-right)* causes the production of the lowest and highest level of noise during their operation:

Vibrodriver, hydraulic-hammer, Drop-hammer, Diesel-hammer & Air-hammer

The attenuation of vibrations in the ground is mainly dependent on three variables comprising type of piles, type of hammer and the geoplogical conditions of

† This information is based on field measurements of the ground vibration at 5m horizontal distance from the pile during the operation of **only** the types of hammers experienced in this project

the ground. The magnitude of the ground vibration recorded during the operation of vibrodrivers attenuate rapidly with the increase of the horizontal distance, while those recorded during the operation of impact-hammers showed a longer attenuation. Examples of attenuation of the ground vibration with respect to geophone stand-off from the piles, recorded at different sites during the operation of imapct-hammers and vibrodrivers, are shown in figures (5.100) and (5.101), respectively. The name of the files is included on each plot to allow reference to the original data given in the text.

The amplitudes of ground vibrations recorded from road and rail traffic were relatively small in magnitude. Levels of vibrations of 0.5-1.8mm/s were measured from road traffic at 1m stand-off, and vibration of 2-6mm/s was measured from rail traffic at 4m stand-off. The measured vibrations from quarry blasting and other civil engineering activities showed a relatively large magnitude; for example, around 50mm/s at 13m stand-off in Darlington, 39mm/s at 32m stand-off in Blaydon, and 5mm/s at over 400m at Newton Aycliffe.

The range of the calculated frequencies for different sources of vibration which were measured at 2 to 22m horizontal distance from the vibration source are listed in the table below:

Calculated frequencies (Hz)									
Driving-hammers						Blasting		Traffic	
Drop-h.	Diesel-h.	Air-h.	Hydraulic-h.	Vibrodriver	HF-vibrodriver	Quarry	Demolition	Road	Rail
16-37	32-50	44-58	16-32	28-35	37-52	37-43	10-12	25-35	35-55

Calculated wave-lengths of the induced vibration in the ground during pile driving operation were in the order of 15-30m. As has been explained in section 5.3.5, the wave-length is a function of wave-velocity and the frequency ($\lambda = c/f$). If the velocity of wave propagation of an assumed ground is 300m/s, and considering the list of frequencies in the above table, it can be suggested that the blast causes a vibration with a larger wave-length while the high-frequency vibrodriver and air-hammer cause vibration with a smaller wave-length. The importance of wave-length calculation is discussed in sections 6.4 and 7.3.2.

5.7 Conclusions

By reviewing the ground vibration records given in this chapter, the following points are concluded. The logic behind some of the points is discussed in the next chapter.

1. Under uniform ground conditions, the level of the ground vibrations received at the ground surface normally decreases as the depth of the driven pile increases. However, in a ground with several different strata, the effect of the refraction and reflection of the transmitted vibration causes a rather complicated form where in a number of records an increase in amplitude of the ground surface vibration was observed with increase of the pile-toe depth.

2. In most cases, the ground vibrations recorded in the radial and vertical directions show higher levels than that recorded in the transverse direction. This indicates that 1. at the ground surface most of the vibration is dominated by two types of waves including the P-wave and the Rayleigh-type-wave[⊘]. 2. Because in most sites the piles were driven below the ground water table this affects the transmission of the shear waves in saturated ground, hence reducing the amplitude of the transverse wave at the ground surface. But the transverse wave showed a greater amplitude when a raked pile was driven and may cause the generation of Love-type-wave (see section 6.3.6 for details).

3. In many cases, the level of vibrations taken in the radial direction shows some increment in magnitude as the distance increases from the source and then reduces at greater distance[♡]. The vibration in the vertical direction always shows a decrease in magnitude with distance. An explanation for this behaviour is given in figure (5.102). The figure suggests that the magnitude of the ground vibrations in the radial and vertical directions is controlled by the depth of the pile-toe and the locations of the vibration detectors (geophones) on the ground surface. The effects of these two factors can be defined by angle θ, and can be

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⊘ The eliptical particle motion of a Rayleigh wave has two components in the directions of P-wave and vertical shear wave (S_v − wave)

♡ This behaviour is fully discussed in section (6.2.1) where some analytical methods are suggested expressed as

$$tan\theta = \frac{pile\text{-}toe\text{-}depth}{geophone\text{-}stand\text{-}off}$$

This angle is larger when the geophone is located closer to the pile and smaller for positions at a greater distance. The arrival of the transmitted vibration from the pile-toe to the ground surface can be represented by vertical and horizontal components which can be expressed as

$$vertical\ component = V sin\theta$$

$$radial\ component = V cos\theta$$

where V is the resultant vector of the ground vibration components.

4. In general, driving of sheet-piles shows some eccentric movement or whip which causes a high level of vibrations (for shallow penetration) on the ground surface close to the driven pile. Driving of a single or a pair of interlocked sheet-piles may cause a larger ground vibration than driving them within a panel of piles, where eccentric movements may be limited by the interlocking of the piles.
5. The use of a vibrodriver in driving large diameter tube piles may cause some settlement in the surrounding ground. This may be the result of compaction or liquefaction of the granular soil (see Blaydon and Great Yarmouth sites).
6. The topography of the ground surface and the location of the geophone sets on that surface have an influence on controlling the amount of the recorded vibration.
7. The level of vibrations induced by rail and road traffic are small in comparison to those caused by pile driving.
8. The records of the ground vibration taken during blasting operations show high magnitudes in comparison to other sources and the recorded vibration is a function of the distance and the charge of the blast from the geophone positions.

Table (T5-1A)

Site Visit Diary

No.	Date	Site	Pile	Hammer	Persons	Disc	File	Comments
1	22.09.86	Whalley	Concrete	Drop	AU & AS	DATA1	WAL	Accrington road Whalley
						DATA2	FUG	Fugro test
2	25.09.86	Blaydon	H-pile	Diesel	AU & AS	DATA3	TYN	visit to Blaydon Area 1
3	26.09.86	Blaydon	H-pile	Diesel	AU & AS	DATA3	TYN	second part of pile
4	26.09.86	Blaydon	Sh-pile	Vibro	AU & AS	DATA3	BSV	Sewerage System
5	03.10.86	Spring Well	H-pile	Diesel	AU & AS	DATA3	SHD	Harbour & General
6	07.10.86	Newcastle	Sh-pile	Air	AU & BS	DATA4	NSA	Newcastle Dockyard
7	24.10.86	Blaydon	H-pile	Vibro	AU & BS	—	—	PDR1 failed
8	30.10.86	Blaydon	H-pile	Vibro	AU & AS	DATA5	BHV	only channels 1,2,3 recorded
9	03.11.86	Blaydon	Tube	Vibro	AU & AS	DATA8	HOW	Tube case driving
10	05.11.86	Blaydon			AU & AS			Failure in the hammer
11	06.11.86	Blaydon	H-pile	Vibro	AU & AS	DATA6	RAK	Area(2), Raking pile
12	11.11.86	Blaydon	H-pile	diesel	AU & BS	DATA4	FAR	second part of pile
13	14.11.86	Blaydon			AU & BS			failure in the generator
14	25.11.86	St.Annes	Sh-pile	Vibro	AU & BS	DATA10	POL	first part
15	02.12.86	St.Annes	Sh-pile	Hydru	AU & BS	DATA10	ANS	second part
16	04.12.86	Blaydon	H-pile	Vibro	AU & AS	DATA9	RIV	Area(3), S.Tyne River
17	05.12.86	Blaydon	H-pile	Diesel	AU & SR	DATA11	DIS	Second part
18	29.02.87	Keighley	H-pile	Hydru	AU & AS	—	—	introductionary visit
19	02.03.87	Keighley	H-pile	Hydru	AU & AS	DATA12	KGL	pile number 1
			H-pile	Hydru	AU & AS	DATA13	ELY	pile number 7
20	10.03.87	Keighley	H-pile	Hydru	AU & BS	—	—	PDR1 failed
21	13.03.87	Keighley	H-pile	Vibro	AU & BS	—	—	PDR1 failed
22	23.03.87	Keighley	—	—	AU & BS			no driving
23	02.04.87	Keighley	H-pile	Hydru	AU & BS	DATA14	KRW	River Worth
24	14.04.87	Grimsby	Sh.pile	Air	AU & BS	DATA15	SAG	the pile just set up
25	15.04.87	Grimsby	Sh.pile	Air	AU & BS	DATA16	SDG	first part driving
			Sh-pile	Diesel		DATA17	GSD	second part
26	28.04.87	Keighley	Sh-pile	Vibro	AU & BS	DATA18	KVS	Close to the houses
			h-pile	Hydru		DATA19	KHH	River Worth
27	14.05.87	Workington	Sh-pile	Vibro	AU & BS			no driving
28	18.05.87	Keighley	H-pile	Vibro	AU & BS	DATA20	KVH	River Aire
29	21.05.87	Keighley	H-pile	Diesel	AU & AS	DATA21	KDH	River Aire

Table (T5-1B)

Site Visit Diary

No.	Date	Site	Pile	Hammer	Persons	Disc	File	Comments
30	27.05.87	Workington	Sh-pile	Vibro	AU & SL	—	—	crack in river bank wall
31	18.06.87	Grimsby	Sh-pile	Diesel	AU & AS	DATA22	GRD	data recorded by PDR1
						DATA23	GRS	data recorded by PDR2
32	30.06.87	Workington	Sh-pile	Vibro	AU & AS	—	—	no pile driving
33	03.07.87	Workington	Sh-pile	Vibro	AU & JO			failure in river bank
34	12.08.87	St.Helens	Sh-pile	Vibro	AU & BS	DATA24	SSV	pile extraction
35	14.08.87	Newbiggin	Sh-pile	Vibro	AU & AS	DATA25	NVS	sea defence wall
36	26.08.87	Newbiggin	Sh-pile	Vibro	AU & BS			no pile driving
37	03.09.87	Selby	Concrete	Drop	AU & AS	DATA26	SCD	1st pile
						DATA27	MCD	2nd pile
38	04.09.87	St.Helens	Sh-pile	Air	AU & BS	DATA28	SSA	cofferdam construction
39	15.09.87	Newbiggin			AU & MA			no pile driving
40	05.10.87	Edinburugh	Sh-pile	Vibro	AU & JO			Failure in the hammer
41	02.12.87	Edinburgh	Sh-pile	Hydru	AU & BS	DATA29	ESH	recording achieved
42	10.12.87	Swillington	Sh-pile	Vibro	AU & BS	DATA30	SSV	retaining wall
43	28.01.88	Immingham	Tube	Drop	AU & JO	DATA31	ITH	Pier 7, dockyard
						PDR-A	IDP	PDR2 records
44	03.02.88	Immingham	Tube	Drop	AU & BS	—	—	no driving
45	10.02.88	Swillington	Sh-pile	Vibro	AU & BS			no driving
46	21.02.88	Scarborough	Sh-pile	Air	AU & AS	DATA32	SSA	Fish dock
						PDR-B	SSA	2nd record
47	15.03.88	Waltham X	Sh-pile	Hydru	AU & JO	—	—	bad weather, no pile driving
48	17.03.88	Waltham X	Sh-pile	Hydru	AU & JO	DATA33	WSH	Trial piling
						PDR-C	WHS	second record
49	23.03.88	Reston			AU & BS	PDR-D	REV	traffic Measurement
50	09.04.88	Reston	Sh-pile	Vibro	AU & JO	DATA34	RSV	PDR2 failed
51	19.04.88	Rotherhithe	Sh-pile	Vibro	AU & BS	DATA35	RLM	records from the river shore
						PDR-E	RLV	records from the river beach
						PDR-F	RSV	records from the site ground
52	04.05.88	Blaydon	Sh-pile	ABI	AU & JO	DATA35	BLV	Dutton Forshaw
53	05.05.88	Blaydon	H-pile	Air	AU & BS	DATA36	BAH	Area 3
			H-pile	Hydru	AU & BS	DATA37	BHH	south Tyne bank
54	07.05.88	Blaydon	H.pile	Hydru	AU & AS	PDR-G	BLH	Area 3

Table (T5-1C)

Site Visit Diary

No.	Date	Site	Pile	Hammer	Persons	Disc	File	Comments
55	12.05.88	Blaydon	H.pile	Hydru	AU & CH	PDR-H	BL	Area 3
			H-pile	Hydru		PDR-I	PL	second pile
56	20.05.88	Aycliffe	—	—	AU & PA	PDR-J	ACL	blast vibration measurement
57	24.05.88	Blaydon	H-pile	Vibro	AU & CH	PDR-K	BFV	Dutton-Forshaw
			H-pile	Vibro		PDR-L	BB	area 2
58	21.06.88	Aycliffe			AU & PA	PDR-M	AFB	blast vibration
59	28.06.88	Blaydon	H-pile	Air	AU & CH	PDR-O	BLA	Area 2
			H-pile	Hydru		PDR-O	BLY	Area 3
60	29.06.88	Blaydon	H-pile	Hydru	AU & CH	PDR-N	BLN	area 2
61	20.07.88	Blaydon	H-pile	Hydru	AU & CH	PDR-P	BRH	Area 3
			Sh-pile	Air		PDR-Q	BSA	area 3
62	02.08.88	Blaydon	Sh-pile	Diesel	AU & AS	PDR-R	BSD	Area 3
63	05.08.88	Blaydon	H-pile	Hydru	AU & CH	PDR-S	BHD	second part of pile
64	10.08.88	Blaydon	H-pile	Hydru	AU & BS	PDR-T	BHC	CO-OP Site
65	25.08.88	Blaydon			AU & MW		BLS1	blast measurement
66	30.08.88	Blaydon			AU & BS		BLS2	blast measurement
67	16.09.88	Blaydon	Sh-pile	Diesel	AU & BS	—	—	North Tyne bank
68	26.09.88	Newark	H-pile	Drop	AU & BS	PDR-U	NDH	1st pile
						PDR-V,W	WDH	2nd pile
69	12.10.88	Flitwick	—	—	AU & AS	—	—	primary visit
70	16.10.88	Flitwick	—	—	AU & BS	—	—	strain gauge on wall A.B
71	17.10.88	Flitwick	H-pile	Drop	AU & AS	PDR-1.3	ABC	wall A tested
72	18.10.88	Flitwick	H-pile	Drop	AU & AS	PDR-4.9	AHD	wall A and B examined
73	19.10.88	Flitwick	H-pile	Drop	AU & AS	PDR-10	CDH	wall B and C
74	20.10.88	Flitwick	H-pile	Drop	AU & AS	PDR-15	DDH	wall D and C
75	21.10.88	Flitwick	Sh-pile	Vibro	AU & BS	PDR-25	DHC	wall D and C
76	25.10.88	Sheffield	H-pile	Diesel	AU & AS	PDR-X	FDH	South River Don
77	27.10.88	Sheffield	H-pile	Diesel	AU & AS	PDR-Y,Z	SDH	North River Don
78	04.11.88	Aycliffe			AU & PA	PDR-a	ABM	Blast Measurement
79	16.11.88	Blaydon	H-pile	Diesel	AU & AS			hammer broken
80	23.11.88	Blaydon	H-pile	Diesel	AS		BHD	Rail line
81	25.11.88	Blaydon	H-pile	Hydru	AU & BS	PDR-b,c,d	BDH	Contract 3

Table (T5-1D)

Site Visit Diary

No.	Date	Site	Pile	Hammer	Persons	Disc	File	Comments
82	16.12.88	Newark	H-pile	Drop	AU & AO	PDR-e,f	NHD	racking pile
83	06.02.89	Newark	H-pile	Drop	AU & AO	PDR-g	NEW	River Trent
84	15.02.89	Newark	Sh-pile	Vibro	AU & AO	PDR-h,i	NSV	corner and single pile
85	22.02.89	Sheffield	H-pile	Diesel	AU & AO			no pile driving
86	23.02.89	Sheffield	H-pile	Diesel	AU & AO	PDR-j,k	SHF	raking pile
87	24.02.89	Sheffield	H-pile	Diesel	AU & AO	—	—	PDR1 failed
88	25.02.89	Sheffield	H-pile	Diesel	AS	—	—	Yellow transducers used
89	02.03.89	G.Yarmouth	—	—	AU & AO			bad weather,no driving
90	03.03.89	G.Yarmouth	Tube	Vibro	AU & AO	PDR-l,m,n	YTV	River bank
91	06.03.89	Aycliffe			AU & AS			blast measurement, missed
92	14.03.89	Blaydon	H.pile	Hydru	AU & AO	PDR-o,p	GHH	contract 3
93	15.03.89	Aycliffe			AU & PA	PDR-q	BVF	blast measurement
94	21.03.89	Blaydon	H-pile	Hydru	AU & AO	PDR-r,s	MHH	Contract 3
95	22.03.89	Darlington			AU & AO	PDR-t	DBV	blast vibration

Notations:

AU: *Ali Uromeihy*
AS: *Alan Selby*
PA: *Peter Attewell*
BS: *Brain Scurr*
JO: *John Ollier*
AO: *Andrew Oliver*
SL: *Steward Lightbody*
CH: *Chris Hunter*
SR: *Steve Richardson*
MA: *Mahmmod Arta*
MW *Mike Winter*

sh-pile : sheet-pile
tube : tubular pile
H-pile : H-section pile
Hydru : hydraulic-hammer
Vibro : vibrodriver

Table (T5-2)

Site Measurements Sheet

Date	Time	Location	Disc	File

Ground Conditions	
Ground Surface	Subsurface

Pile		
Type	Dimensions	Length

Hammer		
Weight	Model	Energy

Geophones Stand-off				
A	B	C	D	E

File	Depth	Comments
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		

Table (T5-3)

Blaydon, Contract (1)

Disc no	Date	File name
DATA-3	25.09.1986	TYN
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	42m
Hammer		
Blow rate	Model	Energy/blow
47 bl/min.	Diesel-hammer (BSP 50c)	61kJ/bl.

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 5m	C 8m	D 8.7m*	E 15m
T		Radial	9.27	4.34	1.46	2.89	4.21
Y		Transverse	4.46	2.61	1.43	4.61	3.28
N	20.0	Vertical	6.75	5.47	2.78	4.43	7.77
4		Resultant	10.87	6.09	3.08	6.39	8.90
T		Radial	10.89	3.60	1.46	2.71	4.21
Y		Transverse	5.67	2.59	1.40	4.52	3.10
6	20.5	Vertical	6.75	2.59	2.78	4.44	7.57
5		Resultant	12.00	5.44	3.12	6.33	8.65
T		Radial	5.76	3.33	1.19	2.53	2.26
Y		Transverse	3.53	2.22	1.33	3.32	2.20
N	24.0	Vertical	5.67	4.18	2.24	3.80	5.46
6		Resultant	6.12	4.26	2.54	5.36	6.07
T		Radial	6.12	3.06	1.19	2.74	2.18
Y		Transverse	3.44	2.45	1.43	3.75	2.03
N	24.2	Vertical	5.57	3.95	2.07	3.88	5.56
7		Resultant	6.41	4.02	2.51	5.04	6.56
T		Radial	6.48	2.61	1.01	2.65	2.28
Y		Transverse	4.37	1.89	1.52	3.30	2.20
N	25.0	Vertical	4.69	4.08	1.80	3.61	4.96
8		Resultant	7.14	4.14	2.32	4.39	5.65

* the geophones set was placed close to the gas pump station.

Table (T5-4)

Blaydon, Contract (1)

Disc no	Date	File name
DATA-4	26.09.1986	TYN
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	42m
Hammer		
Blow rate	Model	Energy/blow
47 bl/min.	Diesel-hammer (BSP 50c)	61kJ/bl.

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 5m	C 8m	D 8.7m*	E 15m
T		Radial	11.88	1.96	1.19	1.84	2.70
Y		Transverse	4.37	1.58	2.57	3.08	2.26
N	26.0	Vertical	3.03	2.56	1.98	—	5.46
9		Resultant	12.07	2.63	2.83	3.10	5.70
T		Radial	10.08	2.49	1.01	1.58	3.35
Y		Transverse	5.20	1.31	2.38	4.09	2.17
N	26.5	Vertical	4.50	2.92	1.80	—	5.96
11		Resultant	10.36	4.22	2.66	4.12	6.09
T		Radial	8.10	1.05	1.28	1.66	2.06
Y		Transverse	3.34	1.21	1.33	1.69	1.81
N	27.0	Vertical	3.72	2.50	1.62	—	3.15
12		Resultant	8.61	2.73	1.65	1.89	3.33
T		Radial	8.28	2.51	1.19	1.98	1.41
Y		Transverse	6.69	2.00	1.05	3.23	1.58
N	29.5	Vertical	5.67	2.22	1.08	—	1.88
13		Resultant	8.93	2.71	1.37	3.31	2.17
T		Radial	7.92	3.24	1.28	1.49	1.41
Y		Transverse	5.85	1.95	1.14	2.32	1.49
N	36.4	Vertical	4.79	2.46	0.99	—	1.97
14		Resultant	8.45	2.46	1.40	2.97	2.26

* the geophones set was placed close to the gas pump station.

Table (T5-5A)

Blaydon, Contract (1)

Disc no	Date	File name
DATA-8	03.11.1986	HOW
Pile		
Type	Dimensions	Length
Tubular	steel, 740mm diameter & 7mm thickness	20m
Hammer		
Frequency	Model	Energy
27.5Hz	Vibrodriver (PTC 50)	10.7kJ/cycle

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	Geophone-set Stand-off	A 2.8m	B 4.0m	C 8.0m	D 10.0m	E 15.0m
H		Radial	19.98	18.41	6.86	3.52	3.29
O		Transverse	20.44	18.72	2.95	3.60	2.20
W	2.0	Vertical	33.06	19.07	5.57	9.55	3.49
3		Resultant	35.07	32.45	8.58	10.29	4.54
H		Radial	20.34	18.41	10.42	14.16	2.52
O		Transverse	55.65	18.72	5.53	6.65	1.04
W	2.7	Vertical	47.53	19.07	9.97	7.73	2.98
4		Resultant	61.29	31.66	15.04	15.28	3.90
H		Radial	19.71	16.36	4.57	5.48	4.37
O		Transverse	12.73	17.71	2.00	7.49	1.45
W	3.0	Vertical	21.91	16.66	5.48	3.88	0.51
5		Resultant	26.82	24.01	6.86	8.63	1.86
H		Radial	18.81	16.13	4.75	7.31	2.00
O		Transverse	13.75	18.72	3.14	5.81	0.83
W	3.5	Vertical	21.32	17.37	7.27	6.55	2.58
6		Resultant	26.26	29.62	8.68	9.74	2.83
H		Radial	13.23	2.61	1.01	2.65	2.28
O		Transverse	8.64	1.89	1.52	3.30	2.20
W	5.0	Vertical	10.95	4.08	1.80	3.61	4.96
7		Resultant	14.37	4.14	2.32	4.39	5.65

Table (T5-5B)

Blaydon, Contract (1)

Disc no	Date	File name
DATA-8	03.11.1986	HOW
	Pile	
Type	Dimensions	Length
Tubular	steel, 740mm diameter & 7mm thickness	20m
	Hammer	
Frequency	Model	Energy
27.5Hz	Vibrodriver (PTC 50)	10.7kJ/cycle

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.8m	B 4.0m	C 8.0m	D 10.0m	E 15.0m
H		Radial	14.58	6.28	0.73	3.52	1.35
O		Transverse	6.50	16.81	1.14	3.51	1.64
W	7.0	Vertical	12.23	13.14	2.07	3.55	1.48
8		Resultant	16.31	17.39	2.53	3.64	2.28
H		Radial	6.48	9.80	1.74	2.62	1.14
O		Transverse	6.41	13.96	1.33	2.95	2.03
W	9.0	Vertical	9.10	8.98	1.17	2.09	1.44
9		Resultant	11.31	17.39	2.06	3.64	2.28
H		Radial	14.32	9.76	4.02	4.06	0.98
O		Transverse	5.95	13.34	1.52	2.22	1.22
W	11.0	Vertical	10.17	10.92	4.85	5.01	1.88
10		Resultant	15.19	13.89	4.92	5.59	3.12
H		Radial	12.24	11.46	3.11	6.22	2.15
O		Transverse	13.84	18.72	2.57	5.08	1.55
W	12.5	Vertical	12.52	11.13	0.90	5.10	1.54
11		Resultant	18.58	21.92	3.15	7.07	2.45
H		Radial	15.30	11.46	4.48	6.04	1.69
O		Transverse	6.69	18.72	2.67	4.61	1.37
W	13.0	Vertical	15.45	13.16	5.21	3.28	1.64
12		Resultant	17.47	23.20	6.97	6.44	2.17

Table (T5-5C)

Blaydon, Contract (1)

Disc no	Date	File name
DATA-8	03.11.1986	HOW
Pile		
Type	Dimensions	Length
Tubular	steel, 740mm diameter & 7mm thickness	20m
Hammer		
Frequency	Model	Energy
27.5Hz	Vibrodriver (PTC 50)	10.7kJ/cycle

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.8m	B 4.0m	C 8.0m	D 10.0m	E 15.0m
H		Radial	14.85	9.14	4.11	3.43	1.45
O		Transverse	6.41	9.70	2.67	3.78	1.67
W	14.5	Vertical	11.15	10.87	3.86	2.91	2.65
13		Resultant	15.19	13.89	4.92	5.59	3.12
H		Radial	15.57	16.91	4.02	7.58	1.35
O		Transverse	10.87	18.72	3.14	5.63	0.56
W	15.4	Vertical	12.13	10.36	3.05	4.73	1.04
14		Resultant	19.31	23.90	5.21	8.75	1.38

Table (T5-6A)

Blaydon, Contract (1), Raking-pile(1:6)

Disc no	Date	File name
DATA-6	06.11.1986	RAK
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	21m
Hammer		
Frequency	Model	Energy
27.5Hz	Vibrodriver (PTC 50)	10.7kJ/cycle

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 12.0m	E 18.0m
R		Radial	23.67	11.61	2.69	8.62	1.14
A		Transverse	19.60	11.04	10.12	1.64	1.53
K	0.5	Vertical	23.17	16.04	6.56	3.60	3.41
4		Resultant	31.02	20.75	10.25	8.83	3.51
R		Radial	33.75	28.61	9.97	3.48	0.68
A		Transverse	23.41	9.42	10.10	3.58	1.18
K	1.0	Vertical	43.92	11.97	7.43	3.14	1.60
5		Resultant	49.50	28.81	13.44	4.78	2.00
R		Radial	16.29	8.23	2.47	1.85	0.59
A		Transverse	12.36	5.92	8.09	2.05	0.46
K	2.0	Vertical	15.35	3.71	3.12	1.59	0.90
6		Resultant	22.57	8.99	8.44	2.63	0.95
R		Radial	9.27	3.56	1.28	1.32	0.68
A		Transverse	7.06	3.54	1.14	1.09	0.79
K	4.0	Vertical	8.71	2.99	1.46	1.04	0.41
7		Resultant	13.73	4.24	1.69	1.65	0.65
R		Radial	26.55	7.86	11.69	2.03	0.68
A		Transverse	19.88	9.16	11.39	0.67	0.79
K	6.0	Vertical	25.91	2.39	6.07	3.28	1.11
8		Resultant	40.29	11.40	13.32	3.28	1.33

Table (T5-6B)

Blaydon, Contract (1), Raking-pile(1:6)

Disc no	Date	File name
DATA-6	06.11.1986	RAK
	Pile	
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	21m
	Hammer	
Frequency	Model	Energy
27.5Hz	Vibrodriver (PTC 50)	10.7kJ/cycle

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 12.0m	E 18.0m
R		Radial	18.81	5.03	1.58	1.85	0.87
A		Transverse	16.44	4.49	7.03	1.50	0.34
K	8.0	Vertical	9.97	4.55	3.12	1.68	0.70
9		Resultant	21.91	7.29	7.18	2.55	1.06
R		Radial	18.45	3.20	1.71	2.30	1.24
A		Transverse	12.63	2.49	1.49	1.37	1.35
K	10.0	Vertical	10.94	3.74	2.04	2.05	1.21
10		Resultant	22.51	4.50	2.57	2.64	1.53
R		Radial	16.83	2.19	1.51	2.48	1.01
A		Transverse	12.73	2.18	1.22	1.46	0.82
K	12.0	Vertical	12.71	4.55	1.52	2.77	1.24
11		Resultant	21.67	4.81	1.99	3.40	1.43
R		Radial	6.84	4.57	0.84	1.58	0.70
A		Transverse	10.40	2.87	1.15	1.31	0.79
K	13.5	Vertical	6.15	4.61	1.56	1.41	0.91
12		Resultant	10.74	5.86	1.56	1.95	1.62
R		Radial	7.56	3.56	1.74	1.76	0.70
A		Transverse	5.48	2.49	1.79	2.51	1.00
K	15.0	Vertical	4.98	2.19	0.91	1.87	0.90
13		Resultant	8.34	4.50	2.47	3.05	1.08

Table (T5-7A)

Blaydon, Contract (1), Raking-pile(1:6)

Disc no	Date	File name
DATA-6	06.11.1986	RAK
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	32m
Hammer		
Blow rate	Model	Energy/blow
47 bl/min.	Diesel-hammer (BSP 50c)	61kJ/bl.

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 12.0m	E 18.0m
RAK 14	16.0	Radial	9.45	3.93	1.78	3.38	1.25
		Transverse	5.30	4.87	2.74	2.75	1.50
		Vertical	8.91	4.34	1.79	3.05	2.12
		Resultant	11.57	6.17	3.13	5.36	2.29
RAK 15	16.2	Radial	10.53	4.20	1.70	4.73	1.25
		Transverse	6.13	6.69	1.46	1.92	1.42
		Vertical	7.03	3.71	1.71	3.14	2.02
		Resultant	12.20	6.91	1.97	4.78	2.30
RAK 16	16.8	Radial	14.22	6.67	3.56	5.90	1.44
		Transverse	12.73	5.99	2.03	2.29	1.95
		Vertical	9.09	4.16	3.96	6.96	3.22
		Resultant	15.32	7.15	4.30	8.35	3.36
RAK 17	17.0	Radial	13.23	4.84	2.16	4.91	1.07
		Transverse	11.61	8.40	2.11	2.14	1.59
		Vertical	10.75	5.15	2.43	4.51	2.82
		Resultant	17.13	8.54	3.26	6.09	2.90
RAK 18	17.5	Radial	9.09	4.66	2.45	3.47	0.51
		Transverse	8.27	4.56	2.20	1.46	1.35
		Vertical	8.40	4.34	2.41	3.51	2.42
		Resultant	11.33	5.93	3.44	4.74	2.52

Table (T5-7B)

Blaydon, Contract (1), Raking-pile(1:6)

Disc no	Date	File name
DATA-4	11.11.1986	FAR
	Pile	
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	32m
	Hammer	
Blow rate	Model	Energy/blow
47 bl/min.	Diesel-hammer (BSP 50c)	61kJ/bl.

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 12.0m	E 18.0m
F		Radial	5.31	7.59	5.39	7.71	1.81
A		Transverse	5.57	3.64	2.32	2.57	1.71
R	19.5	Vertical	7.74	5.69	3.24	5.05	3.22
4		Resultant	8.24	8.59	5.45	8.16	3.71
F		Radial	7.92	7.04	4.92	5.72	1.61
A		Transverse	6.60	3.40	1.61	2.42	1.18
R	21.0	Vertical	8.22	5.15	2.90	3.96	2.62
5		Resultant	9.40	8.28	4.95	6.01	2.95
F		Radial	6.21	6.67	4.13	4.37	2.71
A		Transverse	6.69	3.61	1.60	2.05	1.41
R	22.8	Vertical	8.01	3.89	2.62	3.14	3.72
6		Resultant	10.56	7.20	4.15	4.48	4.40
F		Radial	11.16	6.58	3.88	4.10	3.17
A		Transverse	8.55	4.11	2.38	1.92	1.50
R	25.0	Vertical	10.96	5.45	2.02	3.59	2.72
7		Resultant	13.59	7.30	4.10	5.14	4.06
F		Radial	6.48	5.12	2.75	4.73	2.71
A		Transverse	8.83	3.42	2.88	1.83	1.41
R	27.0	Vertical	5.19	3.11	1.78	1.68	2.00
8		Resultant	10.08	5.53	3.87	4.85	3.28

Table (T5-8A)

Blaydon, Contract (1)

Disc no	Date	File name
DATA-9	04.12.1986	RIV
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	13m
Hammer		
Frequency	Model	Energy
27.5Hz	Vibrodriver (PTC 25)	6.9kJ/cycle

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3.0m	B 6.0m	C 8.0m	D 14.0m	E 20.0m
R		Radial	28.35	17.81	8.41	5.68	3.27
I		Transverse	13.56	5.40	6.58	2.49	2.44
V	0.2	Vertical	27.48	9.92	8.80	5.22	3.73
4		Resultant	32.59	18.72	10.92	6.98	4.24
R		Radial	48.06	11.27	9.78	2.62	2.17
I		Transverse	28.71	6.40	9.05	1.94	1.63
V	0.3	Vertical	26.31	8.48	8.08	7.41	2.92
5		Resultant	49.26	14.20	12.90	7.71	3.72
R		Radial	37.62	16.69	5.39	4.51	1.24
I		Transverse	20.81	11.98	3.05	2.12	1.37
V	2.0	Vertical	28.26	2.83	1.35	4.88	1.52
6		Resultant	43.17	20.44	5.55	4.90	1.77
R		Radial	39.78	17.82	6.58	2.35	2.26
I		Transverse	17.47	15.77	3.81	2.31	1.40
V	5.0	Vertical	26.01	7.39	9.47	6.88	4.03
7		Resultant	42.22	20.92	10.73	7.05	4.08
R		Radial	24.93	17.82	5.39	5.05	1.98
I		Transverse	15.89	11.11	5.05	3.23	1.37
V	7.0	Vertical	14.87	2.80	8.17	6.32	3.73
8		Resultant	25.59	19.46	8.74	7.76	3.89

Table (T5-8B)

Blaydon, Contract (1)

Disc no	Date	File name
DATA-9	04.12.1986	RIV
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	13m
Hammer		
Frequency	Model	Energy
27.5Hz	Vibrodriver (PTC 25)	6.9kJ/cycle

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3.0m	B 6.0m	C 8.0m	D 14.0m	E 20.0m
R		Radial	13.50	17.82	4.11	6.31	3.64
I		Transverse	7.71	13.74	5.15	3.88	2.03
V	8.0	Vertical	12.32	7.22	9.97	10.23	5.64
9		Resultant	15.22	22.53	11.01	11.57	5.70
R		Radial	18.27	11.89	3.29	5.41	4.20
I		Transverse	15.05	9.01	6.86	2.31	1.54
V	10.0	Vertical	12.42	4.59	10.69	9.14	4.03
10		Resultant	18.37	12.58	12.65	9.65	5.22
R		Radial	35.37	17.82	5.85	4.69	2.63
I		Transverse	26.76	6.29	7.62	1.20	1.72
V	11.0	Vertical	19.95	5.21	9.70	8.70	3.43
11		Resultant	38.79	18.89	12.95	9.53	4.03

Table (T5-9A)

Blaydon, Contract (1)

Disc no	Date	File name
DATA-11	05.12.1986	DIS
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	27m
Hammer		
Blow rate	Model	Energy/blow
47 bl/min.	Diesel-hammer (BSP 50c)	61kJ/bl.

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3.8m	B 6.0m	C 8.0m	D 14.0m	E 20.0m
D		Radial	6.30	8.39	9.87	8.12	9.36
I		Transverse	11.61	2.23	3.81	2.77	2.26
S	22.25	Vertical	4.89	1.94	3.14	3.22	5.94
4		Resultant	12.34	8.59	10.71	8.14	9.59
D		Radial	5.04	5.07	1.28	1.98	3.92
I		Transverse	5.85	1.26	1.24	1.66	1.67
S	22.28	Vertical	2.25	0.97	0.81	1.51	5.44
5		Resultant	7.72	5.22	1.50	2.22	5.60
D		Radial	6.03	8.77	10.24	8.30	9.73
I		Transverse	11.71	2.48	3.91	2.77	2.38
S	22.30	Vertical	4.01	2.31	3.50	3.49	6.04
6		Resultant	12.12	9.04	11.13	8.31	9.99
D		Radial	6.57	8.75	9.96	8.30	9.82
I		Transverse	11.89	2.29	3.43	2.86	2.47
S	22.35	Vertical	4.79	2.15	3.23	3.59	5.84
7		Resultant	12.28	8.77	10.66	8.33	10.11
D		Radial	5.85	8.29	10.05	8.03	9.36
I		Transverse	12.73	1.99	3.43	2.68	5.64
S	22.50	Vertical	4.21	2.21	3.23	4.04	5.64
8		Resultant	13.01	8.48	10.68	8.04	9.66

Table (T5-9B)

Blaydon, Contract (1)

Disc no	Date	File name
DATA-11	05.12.1986	DIS
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	27m
Hammer		
Blow rate	Model	Energy/blow
47 bl/min.	Diesel-hammer (BSP 50c)	61kJ/bl.

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3.8m	B 6.0m	C 8.0m	D 14.0m	E 20.0m
D		Radial	6.57	9.01	9.32	10.37	6.41
I		Transverse	12.91	2.25	6.77	5.26	4.71
S	22.65	Vertical	4.50	2.32	2.78	3.79	3.23
9		Resultant	13.41	9.06	11.47	11.00	6.63
D		Radial	6.39	9.09	9.69	10.64	6.50
I		Transverse	13.19	2.41	7.72	5.45	4.94
S	22.75	Vertical	4.01	2.27	2.69	4.06	3.23
10		Resultant	13.62	9.68	11.77	10.85	6.76
D		Radial	4.86	9.68	9.69	10.64	6.50
I		Transverse	12.26	2.41	7.72	5.43	5.56
S	23.00	Vertical	4.01	2.27	2.69	4.06	3.23
11		Resultant	12.56	9.80	12.30	10.96	6.74
D		Radial	1.35	2.31	1.19	2.07	2.07
I		Transverse	1.86	1.32	2.00	1.38	1.31
S	23.10	Vertical	1.37	0.83	1.26	1.60	2.12
12		Resultant	2.08	2.65	2.02	2.47	2.97
D		Radial	3.96	9.37	9.60	10.64	6.50
I		Transverse	12.82	2.19	7.62	5.63	5.38
S	23.25	Vertical	4.11	2.27	2.78	4.15	3.13
13		Resultant	12.82	9.48	12.26	10.80	6.80

Table (T5-10A)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-K	24.05.1988	BFV
	Pile	
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	12m
	Hammer	
Frequecy	Model	Energy
27.5Hz	Vibrodriver (PTC 50H)	10.7 kJ/cycle

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	Pile no.	Geophone-set Stand-off	A 2m	B 5m	C 8m	D 15m	E 20m
B			Radial	1.89	1.46	1.10	1.17	—
F			Transverse	0.56	1.04	0.92	0.64	0.36
V	7.0	1	Vertical	1.27	1.35	2.11	2.09	1.00
1			Resultant	2.03	1.97	2.18	2.10	1.02
B			Radial	1.89	2.19	1.72	1.08	—
F			Transverse	1.30	1.24	0.47	0.92	0.45
V	8.6	1	Vertical	1.56	0.81	1.58	1.82	1.00
3			Resultant	2.07	2.47	2.02	1.95	1.02
B			Radial	1.53	1.46	1.16	1.08	—
F			Transverse	0.84	1.14	0.33	1.02	0.45
V	9.2	1	Vertical	2.15	2.06	2.51	2.09	1.50
4			Resultant	2.45	2.46	2.54	2.21	1.53
B			Radial	1.62	1.01	0.85	0.81	—
F			Transverse	0.84	0.86	0.29	0.55	0.45
V	7.5	2	Vertical	1.47	0.36	0.75	1.18	0.90
5			Resultant	1.66	1.07	0.87	1.24	0.99
B			Radial	1.44	1.01	0.94	0.99	—
F			Transverse	0.56	0.76	0.25	0.65	0.45
V	8.0	2	Vertical	1.47	0.45	0.41	1.18	0.90
6			Resultant	1.51	1.04	0.93	1.27	0.93

Table (T5-10B)

Blaydon. Contract (2)

Disc no	Date	File name
PDR2-K	24.05.1988	BFV
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	12m
Hammer		
Frequecy	Model	Energy
27.5Hz	Vibrodriver (PTC 50H)	10.7 kJ/cycle

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Pile no.	Geophone-set Stand-off	A 2m	B 5m	C 8m	D 15m	E 20m
BFV 7	9.1	2	Radial	1.71	1.27	1.09	0.99	0.37
			Transverse	0.74	1.05	0.33	0.55	0.45
			Vertical	1.27	0.45	0.64	1.64	1.00
			Resultant	1.75	1.45	1.05	1.73	1.01
BFV 8	11.0	2	Radial	1.89	1.46	1.36	1.08	—
			Transverse	0.84	1.14	0.24	0.65	0.54
			Vertical	1.27	0.54	0.46	1.91	1.21
			Resultant	2.11	1.74	1.36	1.97	1.26
BFV 9	7.3	3	Radial	0.72	0.64	0.37	0.63	—
			Transverse	0.46	0.76	0.15	0.55	0.36
			Vertical	1.66	0.63	0.69	1.18	0.40
			Resultant	1.67	0.88	0.69	1.11	0.48
BFV 10	8.5	3	Radial	1.35	3.38	0.75	0.81	—
			Transverse	0.56	0.76	0.36	0.55	0.45
			Vertical	2.15	1.26	1.46	1.55	1.51
			Resultant	2.20	3.52	1.48	1.34	1.53

Table (T5-11)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-L	24.05.1988	BB
	Pile	
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	17m
	Hammer	
Frequecy	Model	Energy
27.5Hz	Vibrodriver (PTC 50H)	10.7 kJ/cycle

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 4m	B 8m	C 11m	D 17m	E 22m
B		Radial	1.35	1.19	0.86	0.54	0.18
B		Transverse	0.74	0.86	0.43	0.28	0.30
	12.0	Vertical	1.86	0.90	0.78	1.18	1.10
1		Resultant	1.92	1.34	1.66	1.20	1.12
B		Radial	1.44	1.37	1.04	0.64	0.18
B		Transverse	0.65	0.66	0.41	0.46	0.35
	12.9	Vertical	1.76	0.81	0.56	1.37	1.31
3		Resultant	1.83	1.50	1.11	1.38	1.33
B		Radial	1.62	1.19	0.93	0.53	0.27
B		Transverse	0.84	0.76	0.33	0.55	0.36
	15.0	Vertical	1.17	0.72	0.56	1.37	1.51
4		Resultant	1.65	1.55	1.06	1.30	1.52

Table (T5-12A)

Blaydon, Contract (2)

Disc no	Date	File name
DATA-36	05.05.1988	BAH
	Pile	
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	21m
	Hammer	
Blow rate	**Model**	**Energy/blow**
145 bl/min.	Air-hammer (BSP900N)	11.9kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 4m	C 7m	D 12m	E 15m
B		Radial	9.99	6.12	4.36	5.14	7.47
A		Transverse	9.94	6.67	5.64	3.41	5.00
H	14	Vertical	8.70	6.20	1.73	2.87	3.92
1		Resultant	12.98	7.64	7.21	5.89	7.70
B		Radial	9.63	4.33	4.58	5.05	7.47
A		Transverse	10.78	7.24	6.19	6.30	4.91
H	14.2	Vertical	8.90	6.74	1.66	2.27	7.44
2		Resultant	12.78	8.13	7.21	6.51	7.87
B		Radial	10.44	4.52	4.62	5.05	7.28
A		Transverse	9.29	6.39	6.54	5.80	5.09
H	14.6	Vertical	8.70	6.47	1.83	2.27	3.62
3		Resultant	12.14	7.38	7.27	5.98	7.71
B		Radial	8.55	5.00	4.57	5.23	7.74
A		Transverse	10.59	7.05	6.88	5.84	5.09
H	14.8	Vertical	9.19	6.47	1.88	2.27	7.04
4		Resultant	12.85	7.56	7.17	6.51	8.21
B		Radial	9.45	4.71	5.72	5.86	8.39
A		Transverse	13.47	7.91	7.40	5.42	5.18
H	15.3	Vertical	11.05	7.45	0.51	2.73	6.13
5		Resultant	14.81	8.18	7.88	6.70	8.20

Table (T5-12B)

Blaydon, Contract (2)

Disc no	Date	File name
DATA-36	05.05.1988	BAH
	Pile	
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	21m
	Hammer	
Blow rate	Model	Energy/blow
145 bl/min.	Air-hammer (BSP900N)	11.9kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	Geophone-set Stand-off	A 3m	B 6m	C 10m	D 14m	E 17m
B		Radial	6.39	1.25	2.76	1.53	—
A		Transverse	5.30	3.23	1.69	2.27	2.14
H	12	Vertical	11.97	1.53	3.60	1.64	1.00
6		Resultant	13.19	4.97	4.02	2.68	2.55
B		Radial	4.23	1.32	4.05	1.53	—
A		Transverse	3.72	3.43	2.83	2.35	1.79
H	12.5	Vertical	4.40	1.71	2.32	1.46	0.90
7		Resultant	5.65	3.98	4.29	2.89	2.69

Table (T5-13)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-O	28.06.1988	BLA
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	33m
Hammer		
Blow rate	Model	Energy/blow
145 bl/min.	Air-hammer (BSP900N)	11.9kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 4m	B 8m	C 11m	D 17m	E 22
BLA1	28.0	Radial	1.26	—	1.37	1.53	1.20
		Transverse	0.84	0.67	1.14	0.92	0.98
		Vertical	0.68	0.72	1.31	1.46	1.51
		Resultant	1.35	1.39	1.64	1.72	1.72
BLA2	28.2	Radial	1.44	—	1.37	1.80	1.20
		Transverse	0.65	0.57	1.18	0.74	1.07
		Vertical	0.88	0.81	1.28	1.55	1.51
		Resultant	1.75	1.42	1.65	2.02	1.79
BLA3	28.6	Radial	1.35	—	1.05	1.44	0.46
		Transverse	0.56	0.57	1.08	0.65	0.54
		Vertical	0.78	0.63	1.03	1.37	0.90
		Resultant	1.46	1.11	1.55	1.76	1.07
BLA4	29.0	Radial	1.26	—	0.98	1.53	0.65
		Transverse	0.84	0.57	1.23	0.74	0.54
		Vertical	0.68	0.81	1.17	1.46	0.90
		Resultant	1.31	1.10	1.63	1.82	0.97

Table (T5-14A)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-P,Q	20.07.1988	BSA
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (16W)	9.0m
Hammer		
Blow rate	Model	Energy/blow
250 bl/min.	Air-hammer (BSP 600N)	4.1kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 4m	C 8m	D 13m	E 22m
B		Radial	8.55	13.62	5.55	1.80	3.78
S		Transverse	7.25	7.05	2.90	1.11	2.77
A	1.0	Vertical	17.02	9.25	8.22	4.73	5.13
3		Resultant	17.99	15.24	8.44	4.79	6.13
B		Radial	5.76	14.53	5.11	1.80	3.69
S		Transverse	8.36	6.67	5.26	1.38	2.68
A	1.3	Vertical	15.25	9.43	7.72	4.37	3.62
4		Resultant	16.69	15.12	7.95	4.41	4.27
B		Radial	7.65	14.99	6.31	2.07	4.24
S		Transverse	7.34	4.19	2.92	0.92	2.32
A	1.5	Vertical	15.84	9.79	8.13	4.19	3.42
5		Resultant	16.01	15.15	6.52	4.32	4.71
B		Radial	7.74	14.26	4.78	1.71	3.78
S		Transverse	7.52	5.15	2.67	0.74	1.96
A	2.4	Vertical	16.03	9.43	7.01	3.91	3.11
6		Resultant	17.53	14.65	7.73	3.94	4.22
B		Radial	5.22	14.62	4.02	1.80	2.67
S		Transverse	5.67	5.24	3.18	1.93	4.19
A	3.8	Vertical	14.18	7.99	7.18	4.00	3.52
8		Resultant	14.55	15.21	7.77	4.02	4.21

Table (T5-14B)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-Q	20.07.1988	BSA
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (16W)	9.0m
Hammer		
Blow rate	Model	Energy/blow
250 bl/min.	Air-hammer (BSP 600N)	4.1kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 4m	C 8m	D 13m	E 22m
B		Radial	3.78	4.02	4.11	1.44	2.21
S		Transverse	2.97	1.81	1.15	0.74	1.52
A	5.0	Vertical	8.12	5.03	3.68	2.82	2.61
9		Resultant	8.38	6.13	4.30	2.87	2.61
B		Radial	2.97	5.67	2.39	1.17	1.57
S		Transverse	2.69	2.86	1.21	0.55	0.98
A	5.9	Vertical	6.06	3.59	2.54	2.00	1.60
11		Resultant	6.29	6.04	3.11	2.07	1.89
B		Radial	3.24	5.39	3.49	1.62	1.84
S		Transverse	2.97	2.48	0.94	0.74	1.07
A	6.7	Vertical	8.02	4.49	3.47	3.09	2.41
12		Resultant	8.09	5.87	4.81	3.12	2.44
B		Radial	4.86	9.87	4.08	1.26	2.03
S		Transverse	3.15	3.52	2.41	0.83	1.52
A	7.2	Vertical	11.15	6.55	4.95	3.00	2.41
14		Resultant	11.73	10.46	5.55	3.04	2.57

Table (T5-15)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-G	07.05.1988	BHH
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	23m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 4.0m	C 9.0m	D 15.0m	E 20.0m
B		Radial	7.20	11.33	4.76	5.59	8.30
H		Transverse	4.18	7.34	4.10	3.23	5.54
H	19.0	Vertical	14.67	7.09	5.83	5.28	4.12
3		Resultant	15.33	11.44	7.01	6.31	9.34
B		Radial	8.91	10.97	4.78	5.23	6.36
H		Transverse	5.20	3.91	4.37	4.52	7.05
H	20.2	Vertical	13.79	6.74	6.12	5.10	3.22
4		Resultant	13.99	11.44	7.60	6.64	7.51
B		Radial	9.09	10.97	4.85	5.23	6.45
H		Transverse	5.02	3.91	4.58	4.89	6.43
H	20.8	Vertical	13.30	6.56	6.11	5.37	3.32
5		Resultant	13.44	11.95	7.72	6.70	7.07
B		Radial	7.29	11.15	4.92	4.96	6.64
H		Transverse	4.92	3.81	3.98	4.52	7.05
H	21.0	Vertical	13.79	6.29	6.03	5.10	3.12
6		Resultant	13.97	12.06	7.26	6.42	7.57
B		Radial	6.66	12.61	5.89	4.78	8.67
H		Transverse	5.11	5.24	4.05	4.25	6.97
H	21.5	Vertical	13.99	5.48	6.00	4.73	2.91
8		Resultant	14.36	13.46	7.73	6.24	8.73

Table (T5-16A)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-G	12.05.1988	BLH
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	23m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 15.0m	E 20.0m
B		Radial	6.03	5.58	1.63	0.72	0.74
L		Transverse	11.98	4.10	0.37	0.28	0.27
H	9.5	Vertical	15.65	4.94	1.66	0.82	0.80
1		Resultant	20.61	8.50	2.36	1.13	1.12
B		Radial	9.72	11.33	8.12	2.07	1.38
L		Transverse	6.50	12.58	7.82	1.66	0.71
H	10.0	Vertical	20.05	13.83	6.41	5.19	3.02
2		Resultant	23.21	21.86	12.97	5.83	3.39
B		Radial	11.34	15.26	15.76	5.32	1.29
L		Transverse	8.83	8.20	10.68	3.14	1.25
H	11.5	Vertical	18.58	12.66	9.12	6.37	3.62
3		Resultant	23.49	21.46	21.11	8.87	4.04
B		Radial	12.78	13.16	14.32	5.50	1.57
L		Transverse	5.11	8.20	8.21	2.77	1.43
H	12.5	Vertical	18.19	11.31	8.28	6.19	4.12
4		Resultant	22.81	19.19	18.47	8.73	4.63
B		Radial	7.65	15.54	13.61	9.65	2.58
L		Transverse	5.67	9.34	7.74	3.14	1.88
H	13.3	Vertical	15.16	11.58	8.24	6.92	5.03
5		Resultant	17.90	21.51	17.69	12.28	5.96

Table (T5-16B)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-G	12.05.1988	BLH
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	23m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 15.0m	E 20.0m
B		Radial	6.39	15.63	13.25	10.10	3.04
L		Transverse	5.11	9.24	7.44	3.42	2.05
H	15.0	Vertical	13.99	11.76	8.09	7.64	4.52
6		Resultant	16.20	21.63	17.21	13.12	5.82
B		Radial	5.22	17.18	15.49	7.31	2.40
L		Transverse	6.87	12.87	7.60	2.31	1.96
H	17.0	Vertical	18.29	11.23	6.84	5.91	4.22
7		Resultant	20.22	24.22	18.56	9.68	5.23
B		Radial	5.13	16.36	15.32	8.39	2.95
L		Transverse	3.90	8.77	6.35	2.95	1.96
H	18.0	Vertical	13.11	11.94	6.85	6.64	5.23
8		Resultant	14.61	22.07	17.94	11.09	6.32
B		Radial	5.67	15.90	15.73	9.02	3.13
L		Transverse	3.25	8.67	6.56	2.68	2.23
H	18.5	Vertical	13.50	12.30	6.81	7.01	5.53
9		Resultant	14.99	21.89	18.35	11.73	6.73
B		Radial	5.13	15.17	15.72	9.65	3.41
L		Transverse	4.37	7.91	6.39	2.77	2.50
H	19.2	Vertical	15.26	12.57	7.22	7.37	5.73
10		Resultant	16.68	21.23	18.44	12.45	7.12

Table (T5-16C)

Blaydon. Contract (2)

Disc no	Date	File name
PDR2-G	12.05.1988	BLH
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	23m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 15.0m	E 20.0m
B		Radial	4.86	14.53	15.39	9.83	3.60
L		Transverse	3.81	7.91	6.97	3.05	2.86
H	20.0	Vertical	15.55	13.83	7.96	7.37	5.83
11		Resultant	16.73	21.56	18.68	12.66	7.42
B		Radial	5.04	14.08	15.35	8.84	3.04
L		Transverse	3.99	7.05	8.05	2.40	2.95
H	21.0	Vertical	14.96	13.47	8.15	6.64	5.63
12		Resultant	16.28	20.72	19.15	11.31	7.05
B		Radial	4.50	15.26	15.64	8.93	3.04
L		Transverse	5.57	8.58	7.80	2.68	2.23
H	21.5	Vertical	13.79	13.20	8.19	6.46	5.23
13		Resultant	15.54	21.92	19.30	11.37	6.44

Table (T5-17A)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-H	12.05.1988	BL
Pile		
Type	Dimensions	Length
H-pile	$356 \times 368 \times 152$kg/m	21m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 15.0m	E 20.0m
B		Radial	2.70	1.55	0.30	0.72	1.11
L		Transverse	1.39	0.86	0.47	0.55	0.45
	7.0	Vertical	3.42	1.71	0.02	1.27	1.00
1		Resultant					
B		Radial	2.25	1.55	0.24	0.81	1.01
L		Transverse	1.21	0.76	0.40	0.74	0.36
	8.0	Vertical	3.03	1.53	0.02	1.09	1.00
2		Resultant	3.96	2.31	0.47	1.55	1.45
B		Radial	14.85	14.81	13.61	7.58	9.77
L		Transverse	6.22	3.81	5.60	4.80	6.88
	8.5	Vertical	25.04	8.80	6.59	6.28	5.33
3		Resultant	29.77	17.64	16.12	10.95	13.04
B		Radial	14.31	13.44	13.25	7.49	9.87
L		Transverse	6.69	3.43	4.31	5.26	6.34
	9.2	Vertical	23.08	7.81	6.36	5.82	5.03
4		Resultant	27.97	15.92	15.32	10.85	12.76
B		Radial	6.03	5.58	1.63	0.72	0.74
L		Transverse	11.98	4.10	0.37	0.28	0.27
	9.5	Vertical	15.65	4.94	1.66	0.82	0.80
5		Resultant	20.61	8.50	2.36	1.13	1.12

Table (T5-17B)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-H	12.05.1988	BL
	Pile	
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	21m
	Hammer	
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

		Peak Particle Velocity Measurements ($mm.s^{-1}$)					
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 15.0m	E 20.0m
BL 6	10.0	Radial	9.72	11.33	8.12	2.07	1.38
		Transverse	6.50	12.58	7.82	1.66	0.71
		Vertical	20.05	13.83	6.41	5.19	3.02
		Resultant	23.21	21.86	12.97	5.83	3.39
BL 7	11.5	Radial	11.34	15.26	15.76	5.32	1.29
		Transverse	8.83	8.20	10.68	3.14	1.25
		Vertical	18.58	12.66	9.12	6.37	3.62
		Resultant	23.49	21.46	21.11	8.87	4.04
BL 8	12.5	Radial	12.78	13.16	14.32	5.50	1.57
		Transverse	5.11	8.20	8.21	2.77	1.43
		Vertical	18.19	11.31	8.28	6.19	4.12
		Resultant	22.81	19.19	18.47	8.73	4.63
BL 9	13.3	Radial	7.65	15.54	13.61	9.65	2.58
		Transverse	5.67	9.34	7.74	3.14	1.88
		Vertical	15.16	11.58	8.24	6.92	5.03
		Resultant	17.90	21.51	17.69	12.28	5.96
BL 10	15.0	Radial	6.39	15.63	13.25	10.10	3.04
		Transverse	5.11	9.24	7.44	3.42	2.05
		Vertical	13.99	11.76	8.09	7.64	4.52
		Resultant	16.20	21.63	17.21	13.12	5.82

Table (T5-18)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-N	28.06.1988	BLN
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	21m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP357)	800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 4m	B 8m	D 17m	E 27m	C 37m
B		Radial	10.08	10.79	13.83	4.24	3.26
L		Transverse	4.55	2.29	2.32	2.95	0.94
N	19.5	Vertical	25.92	9.34	10.95	2.73	1.21
1		Resultant	26.87	12.13	14.99	4.67	3.46
B		Radial	9.36	11.15	14.48	4.69	3.40
L		Transverse	3.53	2.57	2.68	2.86	1.02
N	19.8	Vertical	26.80	8.26	11.06	2.55	1.29
2		Resultant	27.47	12.13	15.47	4.97	3.62
B		Radial	8.19	12.34	15.31	4.51	2.89
L		Transverse	3.44	2.48	2.77	2.58	1.14
N	20.0	Vertical	24.06	8.26	11.46	2.27	1.26
3		Resultant	24.67	12.77	16.41	4.62	3.04
B		Radial	6.30	12.61	16.23	5.68	2.70
L		Transverse	3.99	2.67	3.30	2.86	1.06
N	21.4	Vertical	24.45	8.71	11.46	2.09	1.42
4		Resultant	24.48	12.77	17.31	5.96	2.92

Table (T5-19)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-O	28.06.1988	BLY
	Pile	
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	32m
	Hammer	
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 4.0m	B 8.0m	C 11.0m	D 17.0m	E 22.0m
B		Radial	3.69	—	3.48	3.25	2.12
L		Transverse	5.11	3.24	4.73	2.58	2.95
Y	29.0	Vertical	5.97	4.31	3.48	3.00	2.81
5		Resultant	7.27	4.85	5.17	3.75	3.59
B		Radial	3.69	—	4.198	3.07	1.94
L		Transverse	5.11	3.14	4.85	2.86	2.95
Y	29.2	Vertical	6.26	4.40	3.46	2.91	2.81
6		Resultant	7.86	4.92	5.53	3.74	3.57
B		Radial	3.42	4.30	4.09	2.98	1.75
L		Transverse	4.92	3.05	4.88	2.77	3.04
Y	29.5	Vertical	5.67	4.94	4.02	3.00	2.91
7		Resultant	6.83	5.73	5.72	3.92	3.62

Table (T5-20)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-P	20.07.1988	BRH
Pile		
Type	Dimensions	Length
H-pile	$356 \times 368 \times 152kg/m$	33m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 4.0m	C 8.0m	D 13.0m	E 22.0m
BRH1	30.0	Radial	8.38	12.16	5.33	4.96	2.31
		Transverse	2.23	4.57	3.00	2.03	1.43
		Vertical	3.62	4.13	1.90	3.28	1.31
		Resultant	7.50	12.80	5.35	5.27	2.52
BRH2	30.2	Radial	7.11	5.76	5.46	5.23	2.21
		Transverse	2.42	2.19	2.52	2.12	1.34
		Vertical	3.42	4.04	1.78	3.09	1.21
		Resultant	7.27	5.08	5.47	5.51	2.40
BRH3	30.6	Radial	7.29	5.94	5.66	5.50	2.21
		Transverse	2.79	2.00	2.46	2.03	1.52
		Vertical	3.52	3.86	1.84	3.00	1.31
		Resultant	7.61	6.04	5.67	5.74	2.37
BRH4	32.8	Radial	6.93	6.31	5.76	6.95	2.31
		Transverse	2.42	1.14	4.76	2.77	2.41
		Vertical	3.03	3.77	1.75	2.27	1.41
		Resultant	7.48	6.34	5.76	6.97	2.85
BRH5	33.0	Radial	6.66	5.85	5.78	6.76	2.31
		Transverse	2.42	1.24	4.26	4.43	2.41
		Vertical	3.23	3.77	1.80	2.64	1.61
		Resultant	7.45	5.94	5.81	6.89	2.78

Table (T5-21)

Blaydon, Contract (2)

Disc no	Date	File name
PDR2-T	10.08.1988	BHC
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	35m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP357)	800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3m	B 5.5m	C 8.2m	D 14m	E 18
B		Radial	1.53	4.66	1.96	2.98	1.75
H		Transverse	2.42	3.14	1.44	1.85	2.68
C	15.0	Vertical	3.52	2.87	2.65	2.18	2.31
1		Resultant	3.84	5.23	2.99	3.02	3.59
B		Radial	9.99	11.15	6.20	3.79	2.77
H		Transverse	14.86	6.39	7.00	2.58	2.41
C	19.0	Vertical	10.17	8.08	6.19	2.73	2.01
2		Resultant	15.21	13.96	9.35	4.15	3.20
B		Radial	3.24	11.42	4.62	2.98	2.12
H		Transverse	4.37	4.96	3.67	1.66	2.32
C	21.0	Vertical	9.58	7.36	4.87	2.64	2.41
3		Resultant	10.71	13.84	6.56	3.16	3.07
B		Radial	1.53	3.11	1.20	2.07	0.65
H		Transverse	2.32	2.48	0.99	1.94	0.45
C	26.5	Vertical	2.84	2.25	2.19	1.09	1.50
4		Resultant	3.20	3.42	2.21	2.29	1.51
B		Radial	1.44	2.83	1.64	1.71	0.55
H		Transverse	1.58	2.19	0.95	1.29	0.36
C	33.0	Vertical	2.74	1.98	1.74	1.09	0.80
7		Resultant	2.87	3.06	1.81	1.87	0.85

Table (T5-22)

Blast Vibration Measurements

Blaydon, (North Bank River Tyne)

(25.08.1988)

30kg explosive in 6 holes			
File no.	Velocity (mm/s)	Stand-off 400m	408m
B	Radial	1.26	0.84
L	Transverse	1.11	0.69
S	Vertical	1.76	1.90
1	Resultant	2.21	2.10

Table (T5-23)

Blast Vibration Measurements

Blaydon, (South Bank River Tyne)

(30.08.1988)

7 holes(60mm), 5kg explosive in each Depth of explosive = 14.7m from the ground level					
Peak Particle Velocity $mm.s^{-1}$					
File no.	Geophone-set Stand-off	A 32m	B 40m	D 45m	E 52m
B	Radial	34.67	17.86	17.82	8.73
L	Transverse	30.18	—	16.98	8.18
S	Vertical	27.94	14.20	18.22	11.54
2	Resultant	38.69	18.53	24.87	14.05

Table (T5-24A)

Blaydon, Contract (3) Pile 1

Disc no	Date	File name
PDR2-b,c	25.11.1988	BDH
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	23m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 7.0m*	C 12.0m	D 15.0m	E 18.0m
B		Radial	14.20	0.63	0.11	0.46	0.72
D		Transverse	35.45	0.28	0.09	0.48	0.28
H	1.00	Vertical	17.79	0.64	0.44	0.54	0.39
1		Resultant	35.50	0.73	0.44	0.70	0.73
B		Radial	45.64	16.24	3.97	4.57	5.22
D		Transverse	38.93	7.48	3.24	2.95	1.21
H	2.20	Vertical	39.19	10.92	9.30	7.09	6.45
2		Resultant	66.99	18.41	9.34	7.30	7.13
B		Radial	42.41	15.51	2.17	4.30	5.49
D		Transverse	55.01	7.94	3.31	2.95	1.30
H	3.00	Vertical	50.15	10.28	6.93	5.93	5.48
3		Resultant	76.81	18.06	7.10	6.31	5.92
B		Radial	14.94	15.69	3.08	5.05	3.42
D		Transverse	28.93	7.94	3.90	2.19	1.67
H	6.00	Vertical	22.51	7.64	5.74	4.76	4.11
4		Resultant	37.04	16.92	6.35	5.34	4.62
B		Radial	19.92	7.85	3.71	4.30	3.78
D		Transverse	20.00	5.72	3.79	2.86	1.30
H	9.00	Vertical	16.68	7.01	4.89	3.86	4.21
5		Resultant	25.33	9.67	5.41	4.60	5.48

Table (T5-24B)

Blaydon, Contract (3) Pile 1

Disc no	Date	File name
PDR2-b,c	25.11.1988	BDH
	Pile	
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	23m
	Hammer	
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

			Peak Particle Velocity Measurements ($mm.s^{-1}$)				
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 7.0m*	C 12.0m	D 15.0m	E 18.0m
B		Radial	12.26	12.09	4.97	5.12	3.33
D		Transverse	25.09	10.61	3.63	2.57	1.30
H	11.0	Vertical	18.39	13.74	8.85	5.66	5.77
6		Resultant	31.77	14.88	9.37	5.81	6.24
B		Radial	43.33	14.07	5.12	4.48	2.52
D		Transverse	71.80	5.26	4.29	4.10	2.04
H	13.0	Vertical	31.86	12.19	12.13	6.91	7.53
7		Resultant	79.03	15.77	12.53	7.00	7.72
B		Radial	26.65	9.20	2.94	3.93	2.97
D		Transverse	40.54	5.54	2.47	3.81	1.49
H	15.0	Vertical	32.06	11.47	9.56	5.66	5.87
8		Resultant	46.49	12.01	9.75	5.74	6.36
B		Radial	17.98	10.10	3.40	2.83	2.07
D		Transverse	30.27	5.81	2.65	3.34	1.67
H	16.0	Vertical	10.35	10.65	8.78	5.48	5.48
9		Resultant	33.46	12.02	8.88	5.51	5.69
B		Radial	29.32	10.73	2.22	2.28	1.62
D		Transverse	36.88	5.54	2.61	2.95	2.14
H	17.0	Vertical	12.66	8.83	7.53	5.12	5.28
10		Resultant	42.40	11.65	7.61	5.26	5.31

(*) this set of geophones were set on the ground surface above the gas pipe location, see figure (5.32)

Table (T5-25A)

Blaydon, Contract (3) Pile 2

Disc no	Date	File name
PDR2-d	25.11.1988	BDH
	Pile	
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	23m
	Hammer	
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3.0m	B 6.0m	C 10.0m	D 15.0m	E 16.0m*
B		Radial	3.24	2.56	1.47	2.07	0.92
D		Transverse	1.86	2.86	0.99	0.83	0.80
H	5.00	Vertical	4.79	3.05	2.98	1.82	1.21
11		Resultant	5.10	3.44	3.04	2.23	1.51
B		Radial	4.59	2.74	1.58	2.35	0.74
D		Transverse	2.51	5.15	0.86	1.02	1.16
H	7.00	Vertical	6.85	4.13	4.25	2.73	1.21
12		Resultant	7.57	5.49	4.24	3.05	1.34
B		Radial	5.94	4.48	2.79	3.70	1.11
D		Transverse	3.34	5.05	2.36	4.71	1.61
H	8.50	Vertical	7.24	5.75	5.61	4.37	2.01
13		Resultant	8.44	7.67	5.65	5.45	2.63
B		Radial	5.22	4.84	2.42	2.80	0.92
D		Transverse	2.04	3.24	1.99	3.51	2.32
H	10.0	Vertical	7.04	5.03	4.29	4.19	1.81
14		Resultant	7.27	5.41	4.35	4.77	2.32
B		Radial	5.31	5.21	3.97	3.88	1.11
D		Transverse	2.04	2.57	1.73	4.71	2.41
H	12.0	Vertical	7.43	5.30	5.14	4.73	2.11
15		Resultant	7.46	6.02	5.18	5.50	2.67

Table (T5-25B)

Blaydon, Contract (3) Pile 2

Disc no	Date	File name
PDR2-d	25.11.1988	BDH
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	23m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3.0m	B 6.0m	C 10.0m	D 15.0m	E 16.0m*
B		Radial	5.40	8.23	4.78	5.50	1.29
D		Transverse	3.07	6.00	2.31	4.43	2.50
H	15.0	Vertical	7.34	4.76	7.33	5.91	3.32
16		Resultant	7.58	10.15	8.33	8.89	3.86
B		Radial	6.12	9.87	4.78	6.67	2.12
D		Transverse	2.23	2.86	1.56	4.15	2.68
H	17.0	Vertical	8.31	5.75	8.30	6.73	3.82
17		Resultant	8.52	10.57	9.33	10.15	4.05

* This geophone-set was placed on the gas pipe some 2m below the ground surface.

Table (T5-26A)

(Blaydon, Contract 3)

Disc no	Date	File name
PDR2-o	14.03.1989	GHH
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	17m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP357)	400-1000mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	Drop (mm)	Geophone-set Stand-off	E 2m	D 9m	C 15m⊘	B 17m⊘	A 21m
G			Radial	21.76	18.94	2.48	2.65	2.88
H			Transverse	39.29	10.52	2.21	1.43	0.84
H	3.7	1200	Vertical	42.91	13.65	9.23	7.00	4.49
1			Resultant	51.42	20.80	9.27	7.04	4.61
G			Radial	6.17	6.67	1.14	1.55	1.26
H			Transverse	18.66	2.58	1.49	0.86	0.65
H	5.0	600	Vertical	13.06	5.73	3.14	2.69	2.05
2			Resultant	22.25	7.26	3.18	2.73	2.10
G			Radial	9.59	7.67	0.89	1.56	1.17
H			Transverse	17.15	2.12	0.65	0.86	0.46
H	9.2	400	Vertical	11.06	8.19	3.93	2.70	2.05
3			Resultant	20.87	9.03	3.91	2.71	2.15
G			Radial	12.45	6.04	4.05	2.19	1.53
H			Transverse	14.47	5.45	1.29	1.14	0.56
H	9.8	400	Vertical	13.87	9.46	4.95	3.68	2.93
4			Resultant	19.45	11.08	6.16	3.74	2.95
G			Radial	9.31	9.56	3.49	2.56	1.80
H			Transverse	12.06	3.88	0.72	1.24	0.93
H	11.2	400	Vertical	9.95	8.74	7.72	6.91	4.30
5			Resultant	15.56	9.98	7.76	6.97	4.49

Table (T5-26B)

(Blaydon, Contract 3)

Disc no	Date	File name
PDR2-p	14.03.1989	GHH
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	17m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP357)	400-1000mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	drop (mm)	Geophone-set Stand-off	E 2m	D 9m	C 15m⊘	B 17m⊘	A 21m
G			Radial	7.19	4.78	2.61	1.64	1.44
H			Transverse	19.02	3.97	1.15	0.95	0.56
H	12.0	400	Vertical	10.65	6.46	3.72	3.41	2.35
6			Resultant	20.36	6.65	3.96	3.50	2.38
G			Radial	9.22	7.58	3.41	1.74	1.53
H			Transverse	17.23	4.52	1.28	1.04	0.84
H	13.5	1000	Vertical	9.85	6.00	5.58	5.20	2.83
7			Resultant	17.50	8.48	6.13	5.21	2.91

⊘ The line of the gas pipes run between these two sets of geophones (see figure (5.36)).

Table (T5-27)

Blaydon, Contract (3)

Disc no	Date	File name
PDR2-R.S	21.03.1989	MHH
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	16.5m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Drop (mm)	Geophone-set Stand-off	A 3m	B 9m	C 12m	D 17m	E 21m
M			Radial	4.06	6.86	6.58	2.70	0.83
H			Transverse	2.40	3.03	1.72	1.11	1.16
H	11.2	400	Vertical	3.82	5.56	5.93	6.65	3.41
7			Resultant	4.69	7.32	6.89	7.04	3.42
M			Radial	3.79	7.12	6.76	2.61	0.92
H			Transverse	2.13	2.46	2.00	1.02	1.34
H	11.8	400	Vertical	4.19	5.42	5.47	6.84	0.50
8			Resultant	4.34	7.65	7.11	7.13	1.54
M			Radial	4.87	7.76	6.39	2.34	0.92
H			Transverse	1.75	2.67	2.09	1.02	1.33
H	12.8	400	Vertical	4.19	5.64	5.57	7.24	3.81
9			Resultant	5.36	8.36	7.03	7.51	3.82
M			Radial	4.69	7.06	6.31	2.25	1.01
H			Transverse	2.31	2.42	2.86	1.02	1.34
H	13.2	400	Vertical	3.73	5.42	6.37	6.84	3.41
10			Resultant	5.08	7.57	6.77	7.16	3.45

Table (T5-28)

Blast Vibration Measurement

Darlington, Cleveland Forge Site

Messrs Stonegrave Aggregate

Disc	Date	Time	File
PDR2-t	22.03.1989	15.10	dbv2
Type	Holes no.	Charge per hole	Depth
Gelex explosive	25	3-4 oz	1.0m

Geophone-set Stand-off	A 13m	B 20m	C 23m	D 32m	E 35m
Particle Velocity ($mm.s^{-1}$)					
Radial	28.95	10.07	18.72	9.68	6.95
Transverse	39.97	9.75	8.83	36.43	5.05
Vertical	40.22	18.23	17.21	—	8.08
Resultant	50.03	20.88	19.15	36.66	9.09
Particle Acceleration ($mm.s^{-2}$)					
Radial	3213	880	1256	973	495
Transverse	4339	939	658	2666	350
Vertical	4487	1872	1589	—	542
Resultant	5516	2008	1609	2671	664
Particle Displacement (mm)					
Radial	0.269	0.400	0.263	0.135	0.098
Transverse	0.295	0.153	0.165	0.432	0.086
Vertical	0.401	0.249	0.204	—	0.134
Resultant	0.494	0.405	0.293	0.450	0.155

Table (T5-29)

Edinburgh, Dundas street

Disc no	Date	File name
DATA-18	02.12.1987	ESH
Pile		
Type	Dimensions	Length
Sheet-pile	Frodingham (4N)	9.0m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 9.0m	D 14.0m	E 18.0m
E		Radial	1.53	1.19	0.32	0.50	0.40
S		Transverse	1.67	0.76	0.19	—	0.54
H		Vertical	2.64	1.38	0.46	0.50	0.58
2	3.5	Resultant	2.86	1.76	0.47	0.52	0.64
E		Radial	15.03	6.31	0.68	0.68	0.62
S		Transverse	7.25	2.57	0.47	—	0.54
H		Vertical	10.46	3.83	2.80	1.59	0.88
3	4.3	Resultant	19.00	6.36	2.82	1.61	0.90
E		Radial	1.80	1.19	0.33	0.32	0.43
S		Transverse	1.67	0.86	0.24	—	0.54
H		Vertical	3.42	1.29	0.43	0.50	0.38
4	5.0	Resultant	3.76	1.58	0.46	0.52	0.56
E		Radial	22.23	9.87	0.64	0.50	0.58
S		Transverse	3.72	7.15	0.56	—	0.63
H		Vertical	19.76	4.53	1.62	1.23	0.48
5	5.2	Resultant	28.44	11.09	1.64	1.36	0.73
E		Radial	10.62	4.48	1.34	0.86	0.53
S		Transverse	7.71	4.96	0.99	—	0.63
H	5.7	Vertical	21.81	4.80	1.65	1.97	0.86
6		Resultant	25.23	6.08	1.65	1.97	0.86

Table (T5-30A)

Great Yarmouth

Disc no	Date	File name
PDR2-I	03.03.1989	YTV
Pile		
Type	Dimensions	Length
Tubular	Diameter=1200mm	21m
Hammer		
Frequency	Model	Energy/cycle
40Hz	Vibrodriver (PTC RH23HFI)	5.6kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	D 7.0m	B 13.0m	A 15.0m	C 18.0m	E 20.0m
Y		Radial	1.08	1.37	1.26	0.54	1.19
T		Transverse	1.11	0.67	0.83	1.19	0.62
V	4.5	Vertical	0.46	0.81	0.98	0.59	1.10
1		Resultant	1.35	1.48	1.43	1.25	1.23
Y		Radial	1.08	1.55	1.35	0.54	1.11
T		Transverse	1.01	0.67	0.84	1.42	0.71
V	5.2	Vertical	0.45	0.81	0.98	0.59	1.00
2		Resultant	1.34	1.64	1.54	1.44	1.14
Y		Radial	1.26	1.55	1.26	0.55	1.11
T		Transverse	1.01	0.67	0.84	1.54	0.63
V	5.8	Vertical	0.64	0.55	0.88	0.67	1.00
3		Resultant	1.48	1.65	1.30	1.51	1.11
Y		Radial	1.35	1.00	1.44	1.57	1.56
T		Transverse	1.38	1.52	1.76	1.27	0.89
V	6.1	Vertical	0.64	1.62	1.37	0.19	1.71
5		Resultant	1.74	1.99	2.34	1.67	1.77
Y		Radial	1.35	1.01	1.80	2.17	1.57
T		Transverse	1.57	1.62	1.86	1.11	0.80
V	10.5	Vertical	0.73	1.62	1.27	0.28	1.81
6		Resultant	1.85	2.13	2.51	2.23	1.83

Table (T5-30B)

Great Yarmouth

Disc no	Date	File name
PDR2-I	03.03.1989	YTV
Pile		
Type	Dimensions	Length
Tubular	Diameter=1200mm	21m
Hammer		
Frequency	Model	Energy/cycle
40Hz	Vibrodriver (PTC RH23HFI)	5.6kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	D 7.0m	B 13.0m	A 15.0m	C 18.0m	E 20.0m
YTV 8	12.4	Radial	0.99	2.28	1.35	2.49	1.57
		Transverse	1.47	3.33	1.48	1.71	0.62
		Vertical	0.91	1.71	2.05	0.97	1.40
		Resultant	1.74	2.83	2.51	2.94	1.56
YTV 9	13.0	Radial	0.99	2.37	1.08	2.72	1.56
		Transverse	1.57	3.34	1.49	1.51	0.63
		Vertical	0.82	1.71	2.05	1.27	1.41
		Resultant	1.81	2.86	2.35	3.07	1.66
YTV 10	13.5	Radial	0.99	2.56	0.99	2.82	1.29
		Transverse	1.66	3.43	1.39	1.55	0.45
		Vertical	0.91	1.62	2.25	1.25	1.31
		Resultant	1.85	4.11	2.62	3.27	1.35
YTV 12	14.7	Radial	0.91	2.74	0.90	2.35	1.29
		Transverse	1.48	3.34	1.39	1.35	0.54
		Vertical	0.82	1.62	2.24	1.18	1.11
		Resultant	1.64	4.07	2.61	2.74	1.34
YTV 13	15.2	Radial	0.99	2.38	0.99	3.17	1.57
		Transverse	1.19	3.15	0.83	1.57	0.53
		Vertical	0.45	1.52	2.05	1.33	1.71
		Resultant	1.40	3.69	2.33	3.47	1.94

Table (T5-31A)

Grimsby, Trial Piling

Disc no	Date	File name
DATA17	15.04.1987	SDG
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (25W)	15m
Hammer		
Weight	Model	Max.Energy
1500kg	Diesel-hammer (BSP B15)	37.2kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Pile no.	Geophone-set Stand-off	E 4.0m	D 6.0m	C 9.5m	B 11.0m	A 13.0m
SDG 1	11.0	1	Radial	9.59	6.13	8.55	7.36	10.04
			Transverse	3.38	3.55	7.03	3.61	5.76
			Vertical	10.25	7.27	5.22	6.18	9.50
			Resultant	10.87	8.11	10.96	7.82	14.29
SDG 2	13.5	1	Radial	10.70	9.47	10.15	10.01	10.31
			Transverse	3.91	3.55	5.11	5.71	4.27
			Vertical	9.65	9.45	5.58	4.74	9.11
			Resultant	11.11	10.36	11.07	10.05	13.88
SDG 3	14.0	1	Radial	9.40	8.66	10.32	10.83	11.66
			Transverse	2.84	2.35	5.91	5.99	3.99
			Vertical	8.94	9.09	6.89	7.73	9.99
			Resultant	9.64	9.78	11.79	11.42	14.76
SDG 4	12.0	2+3	Radial	5.44	3.25	4.08	3.06	7.61
			Transverse	2.43	2.17	2.97	2.58	3.25
			Vertical	4.42	4.65	9.22	4.65	7.23
			Resultant	6.30	5.46	9.36	5.67	10.34
SDG 5	12.5	2+3	Radial	13.18	12.99	13.49	11.29	11.75
			Transverse	7.25	4.48	8.54	5.61	5.48
			Vertical	13.37	10.73	10.47	6.62	10.18
			Resultant	16.62	16.07	15.47	12.42	15.50

Table (T5-31B)

Grimsby, Trial Piling

Disc no	Date	File name
DATA17	15.04.1987	SDG
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (25W)	15m
Hammer		
Weight	Model	Max.Energy
1500kg	Diesel-hammer (BSP B15)	37.2kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Pile no.	Geophone-set Stand-off	E 4.0m	D 6.0m	C 9.5m	B 11.0m	A 13.0m
S			Radial	12.17	12.72	14.07	12.11	12.29
D			Transverse	6.72	4.29	9.00	5.23	5.57
G	13.0	2+3	Vertical	12.66	10.27	10.14	6.44	9.59
6			Resultant	13.57	15.59	16.30	13.20	15.64
S			Radial	11.62	12.00	13.98	11.84	12.02
D			Transverse	5.64	4.66	9.91	5.14	5.20
G	13.3	2+3	Vertical	12.16	10.55	10.25	6.44	9.30
7			Resultant	13.52	14.52	16.84	12.89	15.24
S			Radial	14.29	10.28	10.48	9.73	9.59
D			Transverse	4.75	4.75	7.12	4.16	3.44
G	11.0	4+5	Vertical	10.55	11.18	9.82	5.64	8.71
8			Resultant	15.06	12.19	12.57	10.53	12.85
S			Radial	15.49	10.82	11.61	10.47	10.58
D			Transverse	4.30	4.20	8.39	4.66	3.81
G	11.5	4+5	Vertical	11.66	11.27	9.81	6.00	9.20
9			Resultant	16.13	12.98	14.30	11.44	13.91
S			Radial	14.01	9.83	10.83	10.28	9.86
D			Transverse	3.68	3.18	8.93	4.18	3.44
G	12.5	4+5	Vertical	10.65	10.27	9.03	5.73	8.03
10			Resultant	14.54	11.19	14.19	11.04	12.72

Table (T5-31C)

Grimsby, Trial Piling

Disc no	Date	File name
DATA17	15.04.1987	SDG
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (25W)	15m
Hammer		
Weight	Model	Max.Energy
1500kg	Diesel-hammer (BSP B15)	37.2kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	Pile no.	Geophone-set Stand-off	E 4.0m	D 6.0m	C 9.5m	B 11.0m	A 13.0m
S			Radial	12.82	9.74	10.91	10.47	10.13
D			Transverse	3.86	2.91	9.17	4.47	3.99
G	13.0	4+5	Vertical	10.55	9.91	8.89	5.55	7.03
11			Resultant	13.42	10.92	14.33	11.36	12.75
S			Radial	10.70	9.11	11.53	10.92	10.66
D			Transverse	3.50	2.35	9.42	4.09	3.99
G	13.5	4+5	Vertical	10.05	9.85	8.70	5.37	7.64
12			Resultant	11.20	10.14	15.10	11.57	13.05
S			Radial	9.68	7.94	11.05	10.56	10.31
D			Transverse	3.14	2.26	8.85	3.71	4.09
G	14.0	4+5	Vertical	8.74	8.91	8.53	5.01	7.33
13			Resultant	10.12	9.11	14.40	11.18	12.49

Table (T5-32A)

Grimsby, Main Piling, (PDR1)

Disc no	Date	File name
DATA-22	18.06.1987	GRD
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (25W)	16.0m
Hammer		
Weight	Model	Max.Energy
1500kg	Diesel-hammer (BSP B15)	37.2kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	pile no.	Geophone-set Stand-off	A 5.0m	B 8.0m	C 11.5m	D 15.0m	E 20.0m
GRD1	11.0	5+6	Radial	18.99	13.34	1.78	3.83	2.46
			Transverse	3.90	3.57	2.87	0.46	0.63
			Vertical	11.74	—	2.05	2.23	1.73
			Resultant	19.28	13.48	3.05	3.78	3.00
GRD2	11.2	5+6	Radial	19.25	14.08	1.78	3.83	2.55
			Transverse	4.37	3.53	3.16	0.46	0.71
			Vertical	11.83	—	2.09	2.32	1.73
			Resultant	19.53	15.20	3.32	3.87	3.08
GRD3	11.6	5+6	Radial	19.35	15.08	1.69	3.82	2.55
			Transverse	3.99	3.43	3.22	0.46	0.89
			Vertical	11.83	—	2.10	2.23	1.63
			Resultant	19.61	15.19	3.40	3.90	3.02
GRD4	12.0	5+6	Radial	19.98	14.44	2.07	4.01	2.74
			Transverse	3.72	3.24	2.99	0.46	0.63
			Vertical	11.64	—	2.12	2.14	1.73
			Resultant	20.54	14.54	3.15	4.11	3.18
GRD5	12.2	5+6	Radial	20.43	15.81	2.04	4.37	2.92
			Transverse	3.53	3.81	3.89	0.46	0.89
			Vertical	12.03	—	2.24	2.23	1.83
			Resultant	20.75	16.08	4.06	4.42	3.44

Table (T5-32B)

Grimsby, Main Piling, (PDR1)

Disc no	Date	File name
DATA-22	18.06.1987	GRD
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (25W)	16.0m
Hammer		
Weight	Model	Max.Energy
1500kg	Diesel-hammer (BSP B15)	37.2kJ

Peak Particle Velocity Measurements

($mm.s^{-1}$)

File no.	Depth (m)	pile no.	Geophone-set Stand-off	A 5.0m	B 8.0m	C 11.5m	D 15.0m	E 20.0m
GRD 6	12.4	5+6	Radial	19.26	14.99	5.47	4.28	2.83
			Transverse	3.81	4.29	1.69	0.37	0.63
			Vertical	11.74	—	2.52	2.14	1.73
			Resultant	19.58	15.28	5.63	4.35	3.36
GRD 7	12.5	3+4	Radial	19.56	17.55	5.52	4.37	3.11
			Transverse	3.81	4.86	1.71	0.46	0.71
			Vertical	10.76	—	2.33	1.96	1.73
			Resultant	19.88	17.72	5.67	4.40	3.52
GRD 8	12.7	5+6	Radial	6.30	12.80	4.47	4.01	4.58
			Transverse	3.16	2.48	1.65	0.56	1.79
			Vertical	9.00	8.17	1.88	1.32	1.63
			Resultant	11.12	12.97	4.59	4.03	5.12
GRD 9	12.8	3+4	Radial	6.39	12.70	4.32	4.01	
			Transverse	3.16	2.95	1.68	0.65	
			Vertical	8.80	8.62	2.09	1.41	
			Resultant	11.09	12.86	4.52	4.05	

Table (T5-33)

Grimsby, Main Piling, (PDR2)

Disc no	Date	File name
DATA-23	18.06.1987	GRS
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (25W)	16.0m
Hammer		
Weight	Model	Max.Energy
1500kg	Diesel-hammer (BSP B15)	37.2kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	pile no.	Geophone-set Stand-off	A 5.0m	B 8.0m	C 11.5m	D 15.0m	E 20.0m
GRS1	12.8	3+4	Radial	12.96	17.91	6.04	5.01	4.52
			Transverse	4.92	4.38	1.89	0.52	0.63
			Vertical	12.42	7.09	0.06	1.68	1.73
			Resultant	15.96	18.12	6.27	5.01	4.83
GRS2	13.0	3+4	Radial	11.43	17.46	6.18	5.01	4.33
			Transverse	4.37	3.91	1.84	0.52	0.63
			Vertical	11.44	7.27	2.83	1.50	1.33
			Resultant	14.70	17.59	6.43	5.02	4.49
GRS4	13.4	5+6	Radial	10.80	14.62	6.36	5.01	5.07
			Transverse	4.46	3.62	1.62	0.59	1.70
			Vertical	10.76	6.91	2.41	1.50	1.33
			Resultant	13.76	14.70	6.59	5.03	5.47
GRS5	13.5	5+6	Radial	10.17	15.90	6.04	5.10	5.07
			Transverse	4.27	3.43	1.74	0.52	1.88
			Vertical	10.56	6.11	2.26	1.68	1.53
			Resultant	13.07	16.01	6.32	5.13	5.53
GRS6	11.0	7+8	Radial	17.28	13.07	4.07	3.83	3.78
			Transverse	5.95	2.95	1.25	0.42	0.71
			Vertical	16.04	8.53	3.70	2.69	2.33
			Resultant	22.16	13.63	4.75	3.87	4.16

Table (T5-34)

Immingham

Disc no	Date	File name
PDR2-A	28.01.1988	IDP
Pile		
Type	Dimensions	Length
Tube-pile	1620mm diameter, 16mm thickness	20m
Hammer		
Weight	Model	Max.Energy
3500kg	Hydraulic-hammer (IHC S-70)	70kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 15m	B 18m	C 21m	D 29m	E 33m
I		Radial	1.80	0.82	1.12	1.35	0.55
D		Transverse	0.74	0.67	0.16	0.35	0.36
P	14.0m	Vertical	0.59	0.45	0.89	0.36	0.50
2		Resultant	1.89	1.01	1.13	1.36	0.63
I		Radial	2.25	1.19	1.31	1.62	0.55
D		Transverse	0.74	0.57	0.18	0.27	0.71
P	14.5m	Vertical	0.78	0.81	0.91	0.46	0.61
4		Resultant	2.27	1.29	1.31	1.67	0.77
I		Radial	2.43	1.55	1.47	1.48	0.56
D		Transverse	0.65	0.66	0.21	0.27	0.26
P	16.0m	Vertical	0.68	0.72	1.04	0.64	0.60
6		Resultant	2.44	1.65	1.51	1.49	0.71

Table (T5-35A)

Keighley, River Worth

Disc no	Date	File name
DATA-12	02.03.1987	KGL
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 126kg/m	32m
Hammer		
Weight	Model	Drop height
3000kg	Hydraulic-hammer (BSP357)	800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	pile-set blows/mm	Geophone-set Stand-off	A 4m	B 7m	C 11m	D 15m	E 20m
KGL4	15.0	14/25	Radial	8.10	5.30	6.33	7.76	7.51
			Transverse	1.77	2.57	1.65	2.40	3.60
			Vertical	3.62	3.95	3.13	6.33	8.05
			Resultant	8.49	5.75	6.46	8.99	9.45
KGL5	16.5	20/25	Radial	7.74	4.84	8.09	6.67	7.33
			Transverse	1.86	2.95	1.79	1.75	3.06
			Vertical	3.13	3.14	3.16	4.88	6.94
			Resultant	7.80	5.17	8.23	6.95	8.08
KGL6	17.5	23/25	Radial	12.51	7.86	9.87	8.75	6.87
			Transverse	3.81	2.48	2.89	2.86	2.92
			Vertical	6.16	5.30	4.56	7.41	5.84
			Resultant	13.72	7.96	10.44	9.57	7.21
KGL7	19.0	28/25	Radial	7.47	4.84	8.86	7.94	8.44
			Transverse	3.16	2.57	2.31	3.23	2.92
			Vertical	2.05	2.42	3.63	6.77	5.14
			Resultant	7.54	5.32	9.02	9.26	8.45
KGL8	20.0	28/25	Radial	5.76	3.56	7.60	6.95	8.16
			Transverse	2.60	2.19	1.71	3.32	2.21
			Vertical	2.44	1.86	2.59	6.68	4.43
			Resultant	5.97	4.13	7.70	9.51	8.18

Table (T5-35B

Keighley, River Worth

Disc no	Date	File name
DATA-12	02.03.1987	KGL
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 126kg/m	32m
Hammer		
Weight	Model	Drop height
3000kg	Hydraulic-hammer (BSP357)	800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Pile-set blows/mm	Geophone-set Stand-off	A 4m	B 7m	C 11m	D 15m	E 20m
K			Radial	5.13	2.92	4.84	8.75	8.07
G			Transverse	6.33	3.81	1.37	2.58	3.15
L	22.5	30/25	Vertical	2.84	1.86	2.01	6.86	2.92
9			Resultant	7.13	3.88	5.22	11.25	8.19
K			Radial	4.77	2.38	5.63	11.09	8.53
G			Transverse	2.42	2.57	1.58	4.71	5.34
L	26.0	33/25	Vertical	1.27	2.07	1.72	7.23	3.51
10			Resultant	4.99	3.61	5.74	13.67	8.82
K			Radial	5.31	4.60	5.94	10.19	7.98
G			Transverse	2.51	2.67	2.05	4.98	6.01
L	27.0	33/25	Vertical	1.56	2.60	1.57	6.77	3.81
11			Resultant	5.89	4.30	6.07	12.42	8.22
K			Radial	5.13	4.60	6.91	7.94	6.59
G			Transverse	2.69	4.38	2.28	3.42	5.30
L	29.5	35/25	Vertical	1.88	1.98	1.39	5.13	2.72
12			Resultant	5.79	5.80	6.93	9.46	6.62
K			Radial	5.58	4.30	6.51	6.58	5.02
G			Transverse	5.11	4.19	2.29	3.51	4.13
L	30.0	40/25	Vertical	2.15	1.89	1.19	4.59	2.52
13			Resultant	6.14	5.46	6.52	8.02	5.22

Table (T5-36A)

Keighley, River Worth (Pile-7)

Disc no	Date	File name
DATA-13	02.03.1987	ELY
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 126kg/m	32m
Hammer		
Weight	Model	Drop height
3000kg	Hydraulic-hammer (BSP 357)	800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Pile-set blows/mm	Geophone-set Stand-off	A 4.0m	B 7.0m	C 10.0m	D 15.0m	E 20.0m
E			Radial	10.35	10.51	10.95	9.92	8.99
L			Transverse	7.43	3.91	4.22	2.79	1.40
Y	20.5	24/25	Vertical	3.62	1.98	3.54	4.15	4.43
4			Resultant	10.78	10.98	11.26	10.04	9.78
E			Radial	9.99	9.32	12.89	9.56	8.99
L			Transverse	8.27	2.86	3.98	2.49	1.67
Y	21.5	26/25	Vertical	3.62	2.07	4.05	3.42	3.93
5			Resultant	10.88	9.65	13.61	9.59	9.66
E			Radial	7.38	6.95	10.88	7.31	8.53
L			Transverse	7.15	4.00	3.05	2.12	2.44
Y	23.0	28/25	Vertical	3.03	1.62	4.13	2.06	3.73
6			Resultant	7.95	7.68	11.32	7.42	9.33
E			Radial	7.65	4.57	14.12	7.40	8.71
L			Transverse	4.64	3.14	3.36	1.66	2.56
Y	25.0	35/25	Vertical	1.96	1.17	3.48	1.60	3.63
7			Resultant	7.84	4.90	14.48	7.53	9.46
E			Radial	6.30	4.30	8.65	5.14	5.76
L			Transverse	3.81	3.05	2.80	1.75	4.97
Y	27.0	35/25	Vertical	4.60	2.42	2.19	2.22	3.03
8			Resultant	6.99	4.79	8.82	5.27	6.45

Table (T5-36B)

Keighley, River Worth (Pile-7)

Disc no	Date	File name
DATA-13	02.03.1987	ELY
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 126kg/m	32m
Hammer		
Weight	Model	Drop height
3000kg	Hydraulic-hammer (BSP 357)	800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Pile-set blows/mm	Geophone-set Stand-off	A 4.0m	B 7.0m	C 10.0m	D 15.0m	E 20.0m
E			Radial	5.49	5.67	8.70	6.49	4.75
L			Transverse	3.53	4.00	3.14	2.95	4.94
Y	29.8	50/25	Vertical	2.25	1.08	3.24	1.58	2.32
9			Resultant	6.21	6.76	8.81	6.76	5.54
E			Radial	5.76	4.94	9.28	6.95	4.47
L			Transverse	3.53	3.05	3.62	2.95	5.12
Y	30.0	70/25	Vertical	2.15	1.26	3.43	1.51	2.12
10			Resultant	6.45	5.82	9.37	7.15	5.62

Table (T5-37A)

Keighley, River Worth

Disc no	Date	File name
DATA-14	02.04.1987	KRW
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 126kg/m	32m
Hammer		
Weight	Model	Drop height
3000kg	Hydraulic-hammer (BSP 357)	800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Plie-set blows/mm	Geophone-set Stand-off	A 3.0m	B 6.0m	C 10.0m	D 16.0m	E 20.0m
KRW 1	25.0	29/25	Radial	5.85	5.58	2.89	8.27	7.04
			Transverse	10.13	3.80	3.57	2.60	4.89
			Vertical	18.56	4.68	2.13	2.49	2.70
			Resultant	18.99	5.61	3.99	8.59	7.88
KRW 2	26.0	32/25	Radial	5.40	5.76	3.24	8.54	6.77
			Transverse	3.90	2.47	4.05	2.42	4.98
			Vertical	5.89	4.05	2.02	2.22	2.50
			Resultant	6.96	5.77	4.55	8.85	7.73
KRW 3	26.5	39/25	Radial	12.24	3.84	2.65	7.01	5.50
			Transverse	4.64	2.20	2.75	2.29	4.45
			Vertical	7.16	2.93	1.73	1.87	2.30
			Resultant	12.29	3.87	3.27	7.25	6.25
KRW 4	27.0	48/25	Radial	13.59	3.84	2.27	5.66	4.83
			Transverse	9.66	2.66	2.33	2.29	3.29
			Vertical	13.87	2.98	1.79	1.58	1.70
			Resultant	14.23	3.86	2.97	5.87	5.23
KRW 5	28.0	80/25	Radial	11.79	4.11	2.88	4.30	3.36
			Transverse	12.91	5.52	4.44	1.92	2.25
			Vertical	28.73	3.64	1.50	1.33	0.91
			Resultant	28.95	6.00	4.53	4.48	3.56

Table (T5-37B)

Keighley, River Worth

Disc no	Date	File name
DATA-14	02.04.1987	KRW
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 126kg/m	32m
Hammer		
Weight	Model	Drop height
3000kg	Hydraulic-hammer (BSP 357)	800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Pile-set blows/mm	Geophone-set Stand-off	A 3.0m	B 6.0m	C 10.0m	D 16.0m	E 20.0m
KRW6	28.5	125/25	Radial	10.17	5.30	3.28	4.66	3.26
			Transverse	16.72	5.99	5.74	1.74	2.07
			Vertical	41.46	3.91	1.08	1.69	0.91
			Resultant	42.07	6.45	5.75	4.74	3.69
KRW7	28.8	25/5	Radial	16.38	4.94	3.27	4.66	3.63
			Transverse	18.89	5.61	5.76	1.92	2.34
			Vertical	39.79	3.91	1.04	1.51	0.99
			Resultant	40.10	5.96	5.76	4.93	3.99
KRW8	29.5	27/5	Radial	7.47	4.84	3.28	4.57	3.26
			Transverse	16.26	4.47	5.92	1.64	2.25
			Vertical	29.03	2.84	0.89	1.51	0.81
			Resultant	29.49	4.86	5.92	4.66	3.74
KRW9	30.3	32/5	Radial	7.65	4.48	3.28	4.57	2.99
			Transverse	17.65	2.56	5.81	1.59	2.16
			Vertical	6.53	1.73	0.75	1.42	0.91
			Resultant	19.18	5.44	6.71	5.04	3.80

Table (T5-38A)

Keighley, River Worth

Disc no	Date	File name
DATA-18	28.04.1987	KVS
Pile		
Type	Dimensions	Length
Sheet-pile	Frodingham (3N)	9.0m
Hammer		
Frequency	Model	Energy
28Hz	Vibrodriver (Muller MS25H)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 12.0m	E 16.0m
K		Radial	23.67	26.96	4.09	4.06	2.90
V		Transverse	27.41	27.92	8.58	3.23	1.37
S	4.5	Vertical	25.13	18.23	10.05	5.97	3.93
1		Resultant	36.70	35.91	10.43	6.71	4.57
K		Radial	22.32	2.65	11.07	3.52	1.43
V		Transverse	19.23	2.38	4.11	1.94	1.54
S	4.8	Vertical	6.16	8.08	6.69	3.88	2.32
2		Resultant	27.59	8.73	7.60	4.95	2.42
K		Radial	22.41	2.83	11.07	4.06	1.52
V		Transverse	28.23	2.57	4.64	2.12	1.72
S	5.0	Vertical	6.75	8.26	7.20	4.24	2.32
3		Resultant	34.03	8.92	12.44	5.55	2.46
K		Radial	18.45	3.02	11.78	3.70	1.34
V		Transverse	21.46	3.05	5.19	1.94	1.46
S	5.2	Vertical	9.58	6.91	6.49	4.06	2.12
4		Resultant	27.63	7.75	12.65	5.27	2.30
K		Radial	7.56	2.65	6.39	3.25	1.15
V		Transverse	8.64	3.05	3.86	1.94	1.46
S	5.6	Vertical	12.32	5.48	5.46	3.88	2.12
5		Resultant	13.56	6.51	7.89	5.05	2.32

Table (T5-38B)

Keighley, River Worth

Disc no	Date	File name
DATA-18	28.04.1987	KVS
	Pile	
Type	Dimensions	Length
Sheet-pile	Frodingham (3N)	9.0m
	Hammer	
Frequency	Model	Energy
28Hz	Vibrodriver (Muller MS25H)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 12.0m	E 16.0m
K		Radial	7.02	2.65	6.44	2.80	1.15
V		Transverse	6.87	3.14	4.32	1.75	1.37
S	6.0	Vertical	14.47	6.02	4.98	3.51	2.02
6		Resultant	16.18	6.47	8.04	4.53	2.22
K		Radial	14.58	3.02	3.81	2.80	1.34
V		Transverse	19.23	3.34	3.85	1.85	1.28
S	6.2	Vertical	16.82	8.08	5.75	3.60	2.32
7		Resultant	24.45	8.38	6.85	4.48	2.47
K		Radial	15.84	4.02	2.36	3.52	2.44
V		Transverse	19.51	6.29	6.07	1.75	1.72
S	6.5	Vertical	17.11	9.70	7.85	4.97	2.52
8		Resultant	25.18	11.09	8.22	5.99	2.77

Table (T5-39A)

Keighley, River Worth

Disc no	Date	File name
DATA-19	28.04.1987	KHH
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 126kg/m	32m
Hammer		
Weight	Model	Drop height
3000kg	Hydraulic-hammer (BSP 357)	800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Pile-set blows/mm	Geophone-set Stand-off	A 2.0m	B 5.0m	C 9.0m	D 13.0m	E 18.0m
K			Radial	9.90	7.59	9.37	17.00	10.30
H			Transverse	11.52	5.34	3.48	8.12	1.79
H	16.0	55/100	Vertical	7.14	3.59	4.89	4.78	2.73
1			Resultant	12.47	8.58	9.40	18.78	10.64
K			Radial	8.73	6.22	10.55	14.75	10.02
H			Transverse	6.32	5.05	2.67	5.81	1.79
H	17.0		Vertical	7.34	3.32	3.95	4.69	2.43
2			Resultant	9.41	7.32	10.68	16.01	10.29
K			Radial	5.49	5.58	6.56	9.97	8.30
H			Transverse	4.27	5.72	3.19	4.71	1.79
H	18.5	80/100	Vertical	4.30	1.98	2.83	3.78	1.89
3			Resultant	6.32	5.99	7.16	10.95	8.43
K			Radial	6.21	6.12	7.25	9.43	9.19
H			Transverse	3.81	5.15	4.00	3.60	2.05
H	20.0		Vertical	3.81	2.07	2.71	4.14	1.59
4			Resultant	6.82	6.19	7.74	10.22	9.25
K			Radial	10.08	7.04	7.33	10.51	9.93
H			Transverse	7.71	5.43	4.08	3.42	2.14
H	21.0	50/50	Vertical	6.85	2.60	2.78	4.96	1.69
5			Resultant	10.74	7.19	7.82	11.26	10.22

Table (T5-39B)

Keighley, River Worth

Disc no	Date	File name
DATA-19	28.04.1987	KHH
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 126kg/m	32m
Hammer		
Weight	Model	Drop height
3000kg	Hydraulic-hammer (BSP 357)	800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Pile-set blows/mm	Geophone-set Stand-off	A 2.0m	B 5.0m	C 9.0m	D 13.0m	E 18.0m
KHH 6	22.0		Radial	6.75	5.03	6.46	9.25	9.10
			Transverse	7.15	4.76	2.81	2.86	2.23
			Vertical	4.21	1.80	2.07	4.69	1.69
			Resultant	8.51	5.26	6.52	9.96	9.19
KHH 7	23.0	65/50	Radial	4.41	4.06	6.15	7.98	8.82
			Transverse	12.54	6.58	3.01	2.03	2.14
			Vertical	4.14	2.24	1.98	4.14	1.69
			Resultant	12.93	7.20	6.65	8.63	8.89
KHH 8	24.0	65/50	Radial	4.59	4.30	7.21	8.61	8.82
			Transverse	11.15	5.53	2.59	3.32	2.59
			Vertical	4.79	1.98	2.49	3.59	1.69
			Resultant	12.22	6.09	7.32	9.32	9.96
KHH 9	25.0	40/50	Radial	5.04	3.93	7.66	8.52	8.45
			Transverse	8.83	4.96	2.66	3.23	3.13
			Vertical	9.00	2.69	2.81	3.23	1.79
			Resultant	9.95	5.56	7.74	9.28	8.62
KHH 10	17.0	75/50	Radial	9.18	8.32	10.08	10.78	7.99
			Transverse	3.72	6.77	3.35	3.69	1.70
			Vertical	3.52	3.05	4.54	4.14	2.63
			Resultant	9.65	10.05	10.78	10.61	8.16

Table (T5-40A)

Keighley, River Aire (Pile B)

Disc no	Date	File name
DATA-20	18.05.1987	KVH
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 134kg/m	16.0m
Hammer		
Frequency	Model	Energy
28Hz	Vibrodriver (Muller MS25H)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3.0m	B 5.0m	C 7.0m	D 9.0m	E 13.0m
K		Radial	8.91	7.75	6.49	4.65	—
V		Transverse	4.37	2.97	2.76	2.95	1.43
H	5.0	Vertical	6.85	4.96	2.87	2.41	2.93
1		Resultant	10.59	8.19	6.99	4.86	2.90
K		Radial	4.05	6.93	2.74	2.48	—
V		Transverse	6.22	8.81	1.62	4.15	0.89
H	11.0	Vertical	3.91	2.26	2.78	1.77	1.79
2		Resultant	7.57	8.91	3.83	4.39	1.80
K		Radial	5.49	6.06	4.48	3.92	—
V		Transverse	5.39	5.24	3.34	4.15	2.50
H	13.0	Vertical	4.11	3.91	2.16	3.55	1.69
3		Resultant	7.88	6.83	4.76	4.55	2.70

Table (T5-40B)

Keighley, River Aire **(Pile A)**

Disc no	Date	File name
DATA-20	18.05.1987	KVH
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 134kg/m	16.0m
Hammer		
Frequency	Model	Energy
28Hz	Vibrodriver (Muller MS25H)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3.0m	B 5.0m	C 7.0m	D 9.0m	E 13.0m
K		Radial	10.98	6.20	3.11	3.47	—
V		Transverse	2.14	7.55	6.48	4.71	1.79
H	5.0	Vertical	15.94	8.85	5.48	5.32	3.90
4		Resultant	17.05	10.62	7.76	6.57	4.00
K		Radial	4.68	5.15	2.01	3.29	—
V		Transverse	9.20	5.02	3.72	3.51	1.79
H	11.0	Vertical	11.74	4.09	2.96	2.41	2.93
5		Resultant	14.73	8.18	4.20	4.58	3.00
K		Radial	8.64	18.56	9.32	5.91	—
V		Transverse	6.60	16.12	5.62	2.12	6.61
H	13.0	Vertical	6.06	6.60	2.33	2.14	5.41
6		Resultant	10.23	19.57	10.03	6.63	7.70

Table (T5-41A)

Keighley, River Aire (Pile 1)

Disc no	Date	File name
DATA-21	21.05.1987	KDH
Pile		
Type	Dimensions	Length
H-pile	$356 \times 368 \times 134$kg/m	32m
Hammer		
Weight	Model	Drop height
4000kg	Diesel-hammer (BSP 50c)	800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 7.0m	D 11.0m	E 15.0m
K		Radial	11.61	8.32	12.36	17.99	10.94
D		Transverse	6.32	7.24	10.70	3.78	1.43
H	14.0	Vertical	8.31	7.63	4.59	4.69	2.03
1		Resultant	12.83	10.08	15.79	18.22	11.01
K		Radial	11.61	9.41	13.72	19.35	11.96
D		Transverse	6.78	5.81	11.35	3.97	1.44
H	14.5	Vertical	8.90	7.72	4.61	5.23	2.19
2		Resultant	13.03	12.77	16.86	19.61	12.08
K		Radial	8.82	13.89	12.55	19.08	11.87
D		Transverse	6.78	4.00	9.54	3.51	1.88
H	15.0	Vertical	9.00	5.84	4.01	5.41	2.29
4		Resultant	11.10	15.39	15.38	19.34	11.96

Table (T5-41B)

Keighley, River Aire (Pile 2)

Disc no	Date	File name
DATA-21	21.05.1987	KDH
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 134kg/m	32m
Hammer		
Weight	Model	Drop height
4000kg	Diesel-hammer (BSP 50c)	800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 4.0m	C 4.5m	D 6.0m	E 9.0m
K		Radial	4.23	4.20	7.66	10.15	5.28
D		Transverse	4.83	2.48	4.20	5.17	2.41
H	18.0	Vertical	10.86	5.48	4.06	3.05	2.19
6		Resultant	10.88	5.87	7.69	10.52	5.40
K		Radial	4.59	4.66	7.38	10.51	4.95
D		Transverse	4.64	2.86	3.92	4.71	2.23
H	18.5	Vertical	10.56	5.21	3.89	2.68	2.69
7		Resultant	10.66	5.58	7.41	10.71	5.15
K		Radial	5.31	4.94	6.18	8.34	5.38
D		Transverse	4.89	3.72	2.56	4.52	2.41
H	20.0	Vertical	8.70	3.86	3.77	2.23	2.19
8		Resultant	9.15	5.36	6.24	8.41	5.53

Table (T5-41C)

Keighley, River Aire (Pile 2)

Disc no	Date	File name
DATA-21	21.05.1987	KDH
	Pile	
Type	Dimensions	Length
H-pile	356 × 368 × 134kg/m	32m
	Hammer	
Weight	Model	Drop height
4000kg	Diesel-hammer (BSP 50c)	800mm

		Peak Particle Velocity Measurements ($mm.s^{-1}$)					
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 4.0m	C 5.0m	D 9.0m	E 11.0m
K		Radial	6.12	6.12	5.56	3.99	8.52
D		Transverse	5.57	4.29	3.12	3.84	3.69
H	20.0	Vertical	6.94	2.69	1.89	1.83	3.69
9		Resultant	7.96	6.86	5.69	4.45	9.88
K		Radial	7.02	5.21	3.34	3.75	7.17
D		Transverse	5.67	5.15	2.97	4.82	3.05
H	22.4	Vertical	6.45	3.05	1.93	1.79	2.59
10		Resultant	8.05	6.82	3.87	5.29	8.18
K		Radial	6.66	5.12	3.04	3.84	7.08
D		Transverse	5.30	5.34	2.88	4.82	2.96
H	22.6	Vertical	6.65	3.41	2.01	1.79	2.68
11		Resultant	7.66	6.90	3.50	5.20	8.06
K		Radial	6.75	4.94	2.85	4.77	6.99
D		Transverse	8.27	5.53	3.51	3.93	2.68
H	23.0	Vertical	8.61	3.41	1.86	1.99	2.59
12		Resultant	9.48	6.65	4.50	4.84	7.86
K		Radial	5.76	4.66	2.85	4.95	5.10
D		Transverse	7.52	4.67	4.50	4.55	1.38
H	24.3	Vertical	9.49	2.87	2.35	2.29	1.77
13		Resultant	10.19	5.56	4.63	5.69	5.49

Table (T5-42A

Newark Relief Road, [Pile 1]

Disc no	Date	File name
PDR2-U	26.09.1988	NDH
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 126kg/m	12m
Hammer		
Weight	Model	Drop height
5000kg	Drop-hammer (BANUT)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 5m	C 9m	D 14m	E 18m
N		Radial	12.87	7.95	5.19	3.43	2.77
D		Transverse	7.43	4.29	4.73	1.48	0.89
H	1.5	Vertical	11.64	6.74	5.14	2.37	1.00
1		Resultant	16.19	9.52	6.50	4.33	2.84
N		Radial	19.44	9.96	4.39	4.51	3.87
D		Transverse	5.48	3.24	2.98	1.75	1.25
H	2.8	Vertical	9.58	7.81	4.26	2.64	1.61
2		Resultant	19.84	10.43	4.91	4.69	3.94
N		Radial	22.95	8.04	3.19	3.16	1.94
D		Transverse	6.22	3.05	3.03	1.66	0.98
H	4.0	Vertical	11.05	5.93	3.35	1.55	1.00
3		Resultant	23.77	9.66	4.34	3.52	2.01
N		Radial	16.83	4.75	2.98	2.71	2.49
D		Transverse	5.20	4.19	3.47	1.48	0.63
H	6.0	Vertical	6.45	5.12	2.96	1.82	0.90
4		Resultant	17.91	6.01	4.16	3.15	2.52
N		Radial	13.95	6.95	2.94	2.62	1.48
D		Transverse	7.52	4.96	4.37	1.29	0.63
H	8.1	Vertical	9.78	4.31	2.87	1.55	0.70
5		Resultant	14.04	8.19	4.41	2.81	1.52

Table (T5-42B

Newark Relief Road, [Pile 1]

Disc no	Date	File name
PDR2-U	26.09.1988	NDH
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 126kg/m	12m
Hammer		
Weight	Model	Drop height
5000kg	Drop-hammer (BANUT)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 5m	C 9m	D 14m	E 18m
N		Radial	18.09	12.80	2.81	1.89	1.84
D		Transverse	5.02	6.10	2.40	1.38	0.80
H	9.0	Vertical	7.73	5.48	2.04	1.46	1.11
6		Resultant	18.74	13.79	3.07	2.14	1.92
N		Radial	16.47	11.52	3.10	1.35	1.84
D		Transverse	6.41	5.24	2.26	1.48	0.80
H	10.0	Vertical	5.87	4.76	2.14	1.46	0.70
7		Resultant	16.67	12.60	3.20	1.88	1.87
N		Radial	19.08	10.51	2.93	2.89	1.48
D		Transverse	6.97	6.86	2.90	1.66	1.07
H	10.5	Vertical	6.45	5.48	3.44	1.55	0.80
8		Resultant	19.37	11.86	4.32	2.93	1.54
N		Radial	15.03	13.31	8.51	3.43	2.67
D		Transverse	7.06	7.72	3.82	2.40	2.41
H	11.0	Vertical	8.12	5.66	3.76	1.91	3.02
9		Resultant	15.28	14.69	8.99	4.00	3.54

Table (T5-43A)

Newark Relief Road, [Pile, 2]

Disc no	Date	File name
PDR2-V,W	26.09.1988	WDH
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 110kg/m	12m
Hammer		
Weight	Model	Drop height
4000kg	Drop-hammer (BANUT)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 5m	C 9m	D 14m	E 18m
WDH1	1.0	Radial	2.97	1.92	0.90	0.45	0.65
		Transverse	1.02	0.86	0.22	0.46	0.36
		Vertical	1.66	1.44	1.04	0.55	0.70
		Resultant	3.34	2.09	1.18	0.71	0.82
WDH2	1.2	Radial	2.79	1.55	0.75	0.54	0.55
		Transverse	1.30	0.95	0.41	0.46	0.27
		Vertical	1.66	1.35	0.91	0.45	0.50
		Resultant	3.09	1.86	1.06	0.64	0.75
WDH3	2.2	Radial	34.20	17.27	11.01	2.71	4.33
		Transverse	15.14	12.29	4.04	4.71	2.05
		Vertical	15.75	11.31	7.51	4.00	4.52
		Resultant	34.30	21.14	11.22	5.02	4.95
WDH4	2.8	Radial	1.98	0.91	0.73	0.36	0.55
		Transverse	0.84	0.86	0.33	0.37	0.27
		Vertical	1.08	0.81	0.36	0.27	0.40
		Resultant	1.99	1.13	0.79	0.46	0.55
WDH5	3.4	Radial	26.19	15.45	7.94	3.07	3.23
		Transverse	10.22	10.39	4.88	4.89	1.96
		Vertical	18.58	10.69	6.97	4.19	4.42
		Resultant	26.65	18.40	9.05	5.46	4.49

Table (T5-43B)

Newark Relief Road, [Pile,2]

Disc no	Date	File name
PDR2-V,W	26.09.1988	WDH
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 110kg/m	12m
Hammer		
Weight	Model	Drop height
4000kg	Drop-hammer (BANUT)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 5m	C 9m	D 14m	E 18m
WDH 6	4.0	Radial	25.65	11.97	6.93	2.62	2.58
		Transverse	9.10	10.20	4.44	2.95	1.34
		Vertical	16.04	13.56	5.82	3.18	3.02
		Resultant	26.21	15.92	8.04	3.76	3.28
WDH 7	5.1	Radial	21.87	12.98	6.61	2.53	3.87
		Transverse	6.13	9.72	4.26	3.42	1.61
		Vertical	10.17	12.39	6.41	3.18	4.02
		Resultant	22.53	16.67	9.03	3.98	4.32
WDH 8	6.0	Radial	27.36	14.17	7.60	2.80	3.13
		Transverse	8.36	10.20	2.95	3.51	1.52
		Vertical	10.86	10.06	7.24	2.73	3.32
		Resultant	28.23	17.86	8.22	3.91	3.62
WDH 9	7.0	Radial	23.49	16.27	8.47	2.16	2.03
		Transverse	7.71	8.48	3.99	1.85	1.07
		Vertical	7.43	10.42	5.29	1.91	2.61
		Resultant	23.73	18.09	8.89	2.39	2.97
WDH 10	7.5	Radial	11.97	12.43	7.47	3.70	2.31
		Transverse	9.66	8.01	5.34	3.60	0.89
		Vertical	7.43	7.72	3.68	1.64	1.81
		Resultant	13.13	14.48	8.21	3.86	2.35

Table (T5-43C)

Newark Relief Road, [Pile, 2]

Disc no	Date	File name
PDR2-V,W	26.09.1988	WDH
	Pile	
Type	Dimensions	Length
H-pile	305 × 305 × 110kg/m	12m
	Hammer	
Weight	Model	Drop height
4000kg	Drop-hammer (BANUT)	400-800mm

		Peak Particle Velocity Measurements ($mm.s^{-1}$)					
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 5m	C 9m	D 14m	E 18m
W		Radial	12.78	12.61	7.29	3.70	2.31
D		Transverse	10.96	8.29	5.48	3.78	0.98
H	8.0	Vertical	7.73	7.72	3.72	1.64	1.81
11		Resultant	14.31	14.66	8.87	3.81	2.35
W		Radial	15.21	13.16	7.46	3.88	2.31
D		Transverse	12.17	9.24	6.27	3.69	1.16
H	8.8	Vertical	8.12	8.53	4.32	1.82	1.91
12		Resultant	17.11	15.26	8.20	3.97	2.48
W		Radial	14.67	12.52	7.07	3.61	2.21
D		Transverse	12.08	9.53	6.38	3.60	1.43
H	9.1	Vertical	7.63	7.72	4.02	1.82	2.01
13		Resultant	16.33	14.76	7.59	3.69	2.42
W		Radial	15.48	12.34	6.99	3.52	2.31
D		Transverse	12.82	10.29	6.94	3.51	1.52
H	9.8	Vertical	8.12	7.90	4.45	2.00	1.91
14		Resultant	17.32	14.88	7.69	3.54	2.35

Table (T5-44A)

Newark, Raking Pile (1:4),Pile [A]

Disc no	Date	File name
PDR2-e	16.12.1988	NHD
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 186kg/m	12m
Hammer		
Weight	Model	Drop height
5000kg	Drop-hammer (BANUT400)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	Geophone-set Stand-off	A 4m	B 6m	C 9m	D 15m	E 22m
N		Radial	5.58	11.33	5.58	4.78	2.77
H		Transverse	9.75	4.67	6.04	3.60	3.93
D	11.0	Vertical	6.45	3.59	3.52	2.64	2.11
1		Resultant	10.64	11.82	7.11	4.80	3.98
N		Radial	5.49	11.97	5.86	4.96	2.77
H		Transverse	10.31	4.86	5.76	3.60	4.11
D	11.5	Vertical	6.75	3.68	3.55	2.64	2.01
2		Resultant	11.16	12.51	6.92	5.00	4.14

Table (T5-44B)

Newark, Raking Pile (1:4),`Pile [B]`

Disc no	Date	File name
PDR2-e,f	16.12.1988	NHD
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 186kg/m	12m
Hammer		
Weight	Model	Drop height
5000kg	Drop-hammer (`BANUT400`)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 4m	C 7m	D 13m	E 20m
N		Radial	24.03	7.49	2.45	2.16	1.48
H		Transverse	29.54	5.91	7.97	2.95	1.16
D	3.5	Vertical	16.63	5.48	3.70	2.00	1.00
3		Resultant	33.28	9.42	8.09	3.34	1.75
N		Radial	17.10	15.17	8.61	4.78	1.48
H		Transverse	30.01	9.05	9.39	2.95	2.41
D	6.0	Vertical	26.60	8.44	6.69	2.82	1.00
4		Resultant	31.45	16.77	10.77	5.03	2.45
N		Radial	12.24	15.81	10.15	2.62	1.66
H		Transverse	20.35	12.10	7.80	2.40	1.52
D	7.5	Vertical	28.26	7.36	5.62	2.55	0.90
5		Resultant	31.52	16.67	10.31	3.67	2.45
N		Radial	13.23	12.34	9.24	2.35	1.75
H		Transverse	20.72	8.20	9.13	4.06	1.70
D	9.2	Vertical	18.97	6.47	4.93	2.09	1.00
6		Resultant	23.23	14.81	11.17	4.17	2.01
N		Radial	11.25	11.79	5.45	2.35	1.57
H		Transverse	23.97	10.10	6.05	3.60	2.14
D	10.0	Vertical	17.11	5.84	3.17	1.46	0.90
7		Resultant	25.99	16.47	7.65	4.09	2.26

Table (T5-44C)

Newark, Raking Pile (1:4),Pile [B]

Disc no	Date	File name
PDR2-f	16.12.1988	NHD
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 186kg/m	12m
Hammer		
Weight	Model	Drop height
5000kg	Drop-hammer (BANUT400)	400-800mm

Peak Particle Velocity Measurements $(mm.s^{-1})$							
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 4m	C 7m	D 13m	E 20m
N		Radial	13.50	19.56	6.72	3.07	1.66
H		Transverse	24.15	10.20	5.17	2.22	3.04
D	10.5	Vertical	17.60	6.20	3.52	1.73	1.31
8		Resultant	26.51	22.22	7.89	3.11	3.14
N		Radial	15.66	21.39	7.40	3.88	1.66
H		Transverse	21.65	8.67	8.01	3.05	3.66
D	10.8	Vertical	15.55	6.74	2.97	1.82	1.21
9		Resultant	24.95	23.17	9.52	3.97	3.69
N		Radial	17.46	21.02	8.08	4.69	1.66
H		Transverse	20.16	8.48	9.61	3.51	5.89
D	11.2	Vertical	13.69	5.84	3.66	2.55	1.41
10		Resultant	22.44	22.04	11.07	4.76	5.98
N		Radial	17.37	20.38	8.48	4.69	1.75
H		Transverse	23.13	8.58	10.29	3.51	6.61
D	11.4	Vertical	13.69	5.66	3.86	2.55	1.71
11		Resultant	23.33	21.53	11.84	4.77	6.72
N		Radial	17.19	20.93	8.62	4.87	1.84
H		Transverse	23.97	8.39	11.10	3.88	6.79
D	11.6	Vertical	15.45	5.84	3.85	2.73	1.81
12		Resultant	24.30	22.34	12.75	5.05	6.95

Table (T5-45A)

Newark Relief Road

Disc no	Date	File name
PDR2-g	06.02.1989	NEW
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 110kg/m	18m
Hammer		
Weight	Model	Drop height
5000kg	Drop-hammer (BANUT)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	Geophone-set Stand-off	A 4m	B 7m	C 10m	D 14m	E 22m
N		Radial	12.51	4.20	5.09	1.89	1.01
E		Transverse	2.78	3.33	2.48	1.47	0.71
W	5.0	Vertical	5.18	3.14	2.49	1.27	0.80
1		Resultant	13.55	5.04	5.65	2.06	1.14
N		Radial	10.44	4.94	6.78	1.62	1.19
E		Transverse	6.13	6.19	5.90	2.39	1.16
W	10.0	Vertical	5.18	2.87	2.21	1.18	1.00
2		Resultant	11.04	6.24	8.16	2.48	1.26
N		Radial	13.95	5.48	8.78	2.71	1.19
E		Transverse	4.92	3.81	3.13	1.94	0.71
W	12.0	Vertical	3.52	2.51	1.81	1.27	0.90
3		Resultant	14.09	5.49	8.91	2.96	1.29
N		Radial	19.17	6.12	9.80	2.16	1.19
E		Transverse	5.67	4.38	5.92	2.03	1.52
W	15.0	Vertical	2.23	2.15	1.76	1.27	0.90
4		Resultant	19.90	6.72	10.39	2.43	1.63
N		Radial	22.68	5.85	9.90	3.79	1.19
E		Transverse	4.92	8.00	8.37	2.58	2.41
W	16.5	Vertical	4.40	2.24	1.71	1.45	1.11
5		Resultant	22.85	8.74	10.84	3.82	2.46

Table (T5-45B)

Newark Relief Road

Disc no	Date	File name
PDR2-g	06.02.1989	NEW
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 110kg/m	18m
Hammer		
Weight	Model	Drop height
5000kg	Drop-hammer (BANUT)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 4m	B 7m	C 10m	D 14m	E 22m
N		Radial	21.15	6.21	9.04	5.86	1.20
E		Transverse	7.89	8.67	9.33	2.22	3.75
W	17.0	Vertical	4.79	2.42	2.23	1.55	1.31
6		Resultant	21.25	8.89	11.66	5.92	3.86

Table (T5-46A)

Newark Relief Road, Corner Pile

Disc no	Date	File name
PDR2-h	15.02.1989	NSV
	Pile	
Type	Dimensions	Length
Sheet-pile	Larssen [6]	9.5m
	Hammer	
Frequency	Model	Energy
38.3Hz	Vibrodriver PTC 13H1/1	3.4kJ/cycle

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3m	B 6m	C 8m	D 12m	E 18m
N		Radial	5.85	3.75	2.13	1.53	1.29
S		Transverse	7.43	2.95	1.21	2.22	1.87
V	1.0	Vertical	3.81	3.41	1.91	1.09	1.50
1		Resultant	8.48	5.29	2.52	2.28	2.20
N		Radial	5.13	4.02	0.71	2.43	1.11
S		Transverse	8.56	4.48	1.04	1.75	1.61
V	2.5	Vertical	4.99	2.06	1.62	0.73	1.21
2		Resultant	9.40	5.04	1.97	2.50	1.67
N		Radial	3.42	3.29	1.92	2.79	1.93
S		Transverse	11.06	4.29	2.87	2.12	2.05
V	1.0	Vertical	8.31	3.68	2.61	1.09	1.40
3		Resultant	12.43	5.63	3.27	3.23	2.36
N		Radial	4.68	3.93	1.37	2.62	1.57
S		Transverse	11.33	6.48	1.41	2.77	2.86
V	4.1	Vertical	8.51	4.85	3.14	2.00	1.81
4		Resultant	12.28	7.12	3.18	3.88	3.23
N		Radial	19.35	12.16	2.63	3.43	2.86
S		Transverse	18.21	8.77	7.52	4.52	5.98
V	4.7	Vertical	13.20	6.64	3.59	3.00	2.31
5		Resultant	25.62	12.96	7.82	5.51	6.49

Table (T5-46B)

Newark Relief Road, Single Pile

Disc no	Date	File name
PDR2-h	15.02.1989	NSV
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen [6]	9.5m
Hammer		
Frequency	Model	Energy
38.3Hz	Vibrodriver PTC 13H1/1	3.4kJ/cycle

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3m	D 3m	B 6m	C 8m	E 18m
N		Radial	34.38	23.00	13.43	6.52	4.33
S		Transverse	11.43	32.95	7.72	8.02	3.57
V	1.2	Vertical	18.68	13.65	10.24	7.57	3.82
6		Resultant	37.07	37.28	15.07	9.84	4.35
N		Radial	30.24	15.87	13.80	6.08	2.77
S		Transverse	10.87	20.39	10.29	16.01	6.25
V	3.4	Vertical	19.76	11.19	10.06	7.41	3.72
7		Resultant	30.50	23.15	15.00	18.55	6.78
N		Radial	28.44	14.79	12.98	7.65	4.43
S		Transverse	11.71	27.51	7.53	10.44	3.75
V	4.5	Vertical	18.39	12.56	14.79	6.72	3.16
8		Resultant	31.50	32.05	15.90	11.53	5.19

Table (T5-47)

Newbiggin, Sea Front

Disc no	Date	File name
DATA-25	14.08.1987	NVS
	Pile	
Type	Dimensions	Length
Sheet-pile	Larssen (20W	5.0m
	Hammer	
Frequency	Model	Energy
50Hz	Vibrodriver (ABI 400GL)	2kJ/cycle

			Peak Particle Velocity Measurements ($mm.s^{-1}$)				
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 4.5m	C 7.0m	D 10.0m	E 18.0m
N		Radial	21.96	10.69	8.76	1.04	0.86
V		Transverse	14.21	7.81	9.44	0.92	0.89
S	2.0	Vertical	16.72	7.04	4.47	2.87	1.49
1		Resultant	25.71	11.53	11.61	2.98	1.53
N		Radial	10.26	1.46	1.19	0.50	0.80
V		Transverse	4.64	2.48	1.32	0.46	0.54
S	0.4	Vertical	8.61	3.63	0.73	0.32	0.58
2		Resultant	11.31	3.65	1.69	0.53	0.82
N		Radial	29.07	6.58	7.40	1.80	0.80
V		Transverse	7.99	3.62	3.20	1.40	0.45
S	2.0	Vertical	18.48	7.40	1.39	0.55	1.79
3		Resultant	30.30	9.00	3.87	1.51	1.81
N		Radial	29.97	9.23	4.58	1.58	0.67
V		Transverse	3.72	4.10	4.80	0.65	0.54
S	4.0	Vertical	21.32	7.94	3.55	1.96	0.72
4		Resultant	31.08	10.94	6.57	2.37	0.78
N		Radial	26.91	10.15	7.57	1.13	0.80
V		Transverse	3.99	5.72	2.43	0.65	0.54
S	4.5	Vertical	15.16	6.59	3.37	2.78	1.19
5		Resultant	27.16	10.63	8.15	2.89	1.23

Table (T5-48)

Newton Aycliffe Industrial Estate

Ground Vibration Measurements caused by **Road Traffic**		
Disc no	Date	File name
PDR2-J	20.05.1988	NAR

Peak Particle Velocity Measurements ($mm.s^{-1}$)				
File no.	Geophone-set Stand-off	A 0.5m	B 3.8m	C 10.0m
Waste lorry on the nearside				
N	Radial	2.34	0.97	0.63
A	Transverse	2.14	0.82	0.37
R	Vertical	1.86	0.97	0.45
1	Resultants	2.99	1.28	0.73
Artic empty on the farside				
N	Radial	1.35	0.51	0.45
A	Transverse	0.74	0.30	0.20
R	Vertical	1.37	0.73	0.45
2	Resultant	1.88	0.77	0.54
Waste lorry empty on the farside				
N	Radial	0.81	0.43	0.27
A	Transverse	1.02	0.26	0.37
R	Vertical	0.98	0.39	0.45
3	Resultants	1.34	0.54	0.50
six axle heavy loaded artic (farside)				
N	Radial	1.26	0.60	0.36
A	Transverse	0.74	0.33	0.46
R	Vertical	0.78	0.25	0.45
4	Resultants	1.42	0.63	0.49

Table (T5-49)

Newton Aycliffe Industrial Estate

Ground Vibration Measurements caused by **Rail Traffic**		
Disc no	Date	File name
PDR2-J	20.05.1988	NAL

Peak Particle Velocity Measurements ($mm.s^{-1}$)					
File no.	Geophone-set Stand-off	A 3.5m	B 7.5m	D 13.5m	E 18.0m
Two units local passenger train (farside)					
N	Radial	3.88	1.51	0.72	0.46
A	Transverse	2.77	0.71	0.56	0.36
L	Vertical	2.00	1.00	0.68	0.60
1	Resultants	4.41	1.52	0.89	0.71
Deltic diesel plus 15 cement wagons (nearside)					
N	Radial	4.42	1.90	0.90	0.46
A	Transverse	4.89	1.02	1.39	0.71
L	Vertical	5.28	1.69	0.88	0.80
2	Resultants	5.56	2.05	1.47	0.95
Two units local passenger train (nearside)					
N	Radial	4.96	0.99	0.63	0.46
A	Transverse	3.14	0.77	0.84	0.36
L	Vertical	5.82	1.14	0.69	0.62
3	Resultants	6.59	1.28	0.92	0.76

Table (T5-50)

Newton Aycliffe Industrial Estate

Blast Vibration Measurement

from Acliffe Church Quarry

Disc	Date	Time	File
PDR2-J	20.05.1988	13.35	nbf
Slurry base charge		ANFO Deck charge	
12.5kg/3, 10kg/3, 2.5/1		59kg/3, 61kg/3	
holes no	Delays	E.Column	Spacing
7	20 ms	27.0m	10.8m

Geophone-set	A	B	C	D	E
Stand-off	400m	402m	405m	411m	419m
Particle Velocity ($mm.s^{-1}$)					
Radial	2.88	2.19	3.10	4.06	—
Transverse	4.55	1.81	1.95	3.60	5.72
Vertical	1.76	1.62	3.25	2.00	1.31
Resultant	4.60	2.58	3.45	4.44	5.73
Particle Acceleration ($mm.s^{-2}$)					
Radial	181	247	407	350	—
Transverse	606	165	254	448	595
Vertical	135	224	435	113	76
Resultant	607	280	450	487	595
Particle Displacement (mm)					
Radial	0.023	0.025	0.034	0.026	—
Transverse	0.026	0.021	0.008	0.019	0.023
Vertical	0.009	0.015	0.025	0.011	0.007
Resultant	0.028	0.032	0.036	0.027	0.022

Table (T5-51)

Newton Aycliffe Industrial Estate

Blast Vibration Measurement

from Acliffe Church Quarry

Disc	Date	Time	File
PDR2-m	21.06.1988	13.15	acf
Base charge/hole		Deck charge/hole	
Slurry (10kg)		ANFO (56kg)	
holes no	Delays	E.Column	Spacing
5	20 ms	27.9m	10.8m

Geophone-set Stand-off	A 342m	B 347m	D 349m	E 376m
Particle Velocity ($mm.s^{-1}$)				
Radial	4.41	2.46	2.79	1.29
Transverse	2.23	1.24	1.47	0.88
Vertical	2.54	0.80	0.75	0.60
Resultant	5.00	2.55	2.82	1.43
Particle Acceleration ($mm.s^{-2}$)				
Radial	412	291	306	121
Transverse	258	132	134	116
Vertical	258	112	113	62
Resultant	490	311	308	143
Particle Displacement (mm)				
Radial	0.026	0.024	0.025	0.009
Transverse	0.023	0.017	0.103	0.008
Vertical	0.012	0.009	0.008	0.007
Resultant	0.027	0.025	0.026	0.010

Table (T5-52)

Newton Aycliffe Industrial Estate

Lyons Tetley Northern Distribution Centre

(Blast from Aycliffe Church Quarry)

Disc	Date	Time	File
PDR2-q	15.03.1989	14.15	vbf1

Geophone-set	A	B	C	C	D
Stand-off	220	261	263	265	266
Particle Velocity ($mm.s^{-1}$)					
Radial	12.45	8.64	3.11	2.56	2.43
Transverse	13.34	6.87	4.38	2.77	2.95
Vertical	8.84	—	2.69	3.03	2.00
Resultant	16.24	8.65	4.93	3.15	3.07
Particle Acceleration ($mm.s^{-2}$)					
Radial	1658	912	197	196	225
Transverse	1535	780	377	154	141
Vertical	781	—	237	276	208
Resultant	1954	936	395	282	245
Particle Displacement (mm)					
Radial	0.072	0.078	0.059	0.062	0.034
Transverse	0.058	0.051	0.038	0.079	0.056
Vertical	0.032	—	0.018	0.025	0.016
Resultant	0.077	0.081	0.066	0.086	0.058

Table (T5-53)

Reston, South Lothian, Scotland

Ground Vibration Measurements *caused by rail and road traffics*		
Disc no	Date	File name
DATA-32	23.03.1988	TR

Peak Particle Velocity Measurements ($mm.s^{-1}$)						
File no.	Geophone-set Stand-off	A 3m	B 5m	C 9m	D 12m	E 17m
A passenger train going to Newcastle						
T	Radial	0.65	0.81	0.23	0.46	0.54
R	Transverse	1.25	0.92	0.24	0.48	—
1	Vertical	1.21	0.91	1.35	0.81	0.88
A passenger train going to Edinburgh and a lorry run over the bridge						
T	Radial	0.46	0.81	0.23	0.64	0.63
R	Transverse	0.54	0.83	0.28	0.48	—
2	Vertical	0.60	0.82	0.47	0.81	0.78
A cargo train carrying aggregates going to Edinburgh						
T	Radial	0.28	0.72	0.72	0.64	0.47
R	Transverse	0.36	0.65	—	0.76	0.54
3	Vertical	0.30	0.45	1.17	1.26	1.14
A lorry running over the bridge						
L	Radial	0.28	0.63	0.06	0.37	0.54
R	Transverse	0.36	0.37	0.04	0.48	—
1	Vertical	0.30	0.36	1.07	0.72	0.78

Table (T5-54)

Reston, South Lothian, Scotland

Disc no	Date	File name
PDR2-A	09.04.1988	RSV
Pile		
Type	Dimensions	Length
Sheet-pile	Frodingham (3N)	12m
Hammer		
Frequency	Model	Enrgy
50Hz	Hydraulic-Vibrodriver (ABI)	—

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3m	B 5m	C 9m	D 12m	E 17m
R		Radial	4.94	0.99	0.57	0.59	0.28
S		Transverse	—	2.79	1.70	0.55	0.54
V	3.0m	Vertical	2.37	2.35	0.68	0.50	0.72
1		Resultant	5.29	3.58	1.77	0.65	0.77
R		Radial	15.26	4.77	1.70	1.67	0.46
S		Transverse	—	2.79	2.22	0.37	1.07
V	4.2m	Vertical	9.11	3.03	1.38	1.05	1.09
2		Resultant	17.42	5.06	2.55	1.68	1.21
R		Radial	20.11	5.49	1.50	1.22	0.28
S		Transverse	—	3.44	2.01	0.37	1.07
V	5.0m	Vertical	9.82	3.13	1.39	0.86	1.09
3		Resultant	21.86	5.64	2.27	1.33	1.32

Table (T5-55A)

Rotherhithe, E.London

Disc no	Date	File name
DATA-35	19.04.1988	RLM
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (32W)	16m
Hammer		
Frequency	Model	Energy/cycle
28Hz	Vibrodriver (MS 25H)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)						
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 4.0m	D 9.0m	E 15.0m
R		Radial	22.77	11.52	3.11	0.46
L		Transverse	9.94	5.15	1.48	0.71
M	2.0	Vertical	16.33	8.48	1.59	0.48
1		Resultant	26.45	15.13	3.18	0.79
R		Radial	18.81	21.39	6.00	2.21
L		Transverse	11.98	9.05	3.97	1.61
M	2.8	Vertical	24.06	10.09	4.32	1.49
2		Resultant	27.05	23.72	6.18	2.57
R		Radial	17.19	17.18	6.45	0.65
L		Transverse	13.47	7.91	1.48	1.07
M	4.0	Vertical	12.03	8.84	0.86	0.58
3		Resultant	22.44	20.35	6.56	1.15
R		Radial	13.05	17.55	3.92	1.29
L		Transverse	8.73	10.01	2.73	0.89
M	4.6	Vertical	9.39	6.59	0.59	0.98
4		Resultant	16.42	20.31	4.29	1.57
R		Radial	12.78	15.72	2.66	2.21
L		Transverse	7.62	5.05	3.97	0.89
M	5.1	Vertical	11.74	5.98	1.05	0.98
5		Resultant	15.08	16.82	4.36	2.35

Table (T5-55B)

Rotherhithe, E.London

Disc no	Date	File name
DATA-35	19.04.1988	RLM
	Pile	
Type	Dimensions	Length
Sheet-pile	Larssen (32W)	16m
	Hammer	
Frequency	Model	Energy/cycle
28Hz	Vibrodriver (MS 25H)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)						
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 4.0m	D 9.0m	E 15.0m
R		Radial	14.67	21.30	3.20	2.77
L		Transverse	10.40	8.77	5.08	0.89
M	6.7	Vertical	13.01	6.52	1.32	1.09
6		Resultant	16.59	22.03	5.87	2.91
R		Radial	12.51	26.51	11.77	5.35
L		Transverse	18.02	8.01	7.57	1.07
M	7.5	Vertical	14.96	10.56	3.78	1.33
7		Resultant	20.15	26.84	13.50	5.43

Table (T5-56A)

Rotherhithe, E.London

Disc no	Date	File name
PDR2-E	19.04.1988	RLV
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (32W)	16m
Hammer		
Frequency	Model	Energy/cycle
28Hz	Vibrodriver (MS 25H)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)						
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 4.0m	D 6.0m	E 8.0m
RLV1	2.0	Radial	11.25	8.04	1.89	1.11
		Transverse	3.25	3.34	1.57	2.32
		Vertical	8.22	4.76	2.09	1.81
		Resultant	14.30	9.92	3.22	3.14
RLV2	2.8	Radial	9.99	6.49	2.44	1.48
		Transverse	3.99	3.05	2.03	2.14
		Vertical	5.09	4.13	2.00	1.51
		Resultant	12.31	8.27	3.75	3.00
RLV3	3.9	Radial	15.21	12.52	6.22	5.16
		Transverse	4.83	4.76	2.31	2.23
		Vertical	6.26	6.82	2.64	1.81
		Resultant	17.14	15.03	7.14	5.90
RLV4	4.5	Radial	15.12	17.55	6.76	5.26
		Transverse	3.72	6.10	2.40	3.21
		Vertical	8.12	8.53	3.91	2.41
		Resultant	17.56	20.44	8.17	6.62
RLV5	5.2	Radial	15.03	17.82	6.40	4.70
		Transverse	5.30	6.67	3.05	3.84
		Vertical	7.43	8.80	4.09	2.31
		Resultant	17.58	20.96	8.18	6.49

Table (T5-56B)

Rotherhithe, E.London

Disc no	Date	File name
PDR2-E	19.04.1988	RLV
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (32W)	16m
Hammer		
Frequency	Model	Energy/cycle
28Hz	Vibrodriver (MS 25H)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)						
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 4.0m	D 6.0m	E 8.0m
R		Radial	13.05	19.83	8.21	4.61
L		Transverse	6.41	6.39	3.23	3.13
V	6.0	Vertical	10.17	11.23	5.87	2.41
6		Resultant	17.74	23.67	10.60	6.07
R		Radial	13.86	21.02	8.30	4.33
L		Transverse	7.80	7.43	3.23	3.66
V	6.6	Vertical	10.66	13.02	4.91	2.01
7		Resultant	19.15	25.82	10.17	6.01
R		Radial	15.03	21.84	7.49	3.96
L		Transverse	7.34	8.48	3.78	4.38
V	7.1	Vertical	10.86	12.57	5.19	2.11
8		Resultant	19.94	26.58	9.86	6.27
R		Radial	6.12	24.22	7.49	4.79
L		Transverse	14.03	8.10	2.22	3.66
V	7.5	Vertical	13.50	14.82	6.73	2.41
9		Resultant	20.41	29.53	10.31	6.49
R		Radial	14.76	22.39	6.49	5.53
L		Transverse	12.50	7.43	1.75	3.75
V	7.8	Vertical	15.45	15.72	6.46	2.31
10		Resultant	24.75	28.35	9.32	7.07

Table (T5-57A)

Rotherhithe, E.London

Disc no	Date	File name
PDR2-F	19.04.1988	RSV
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (32W)	16m
Hammer		
Frequency	Model	Energy/cycle
28Hz	Vibrodriver (MS 25H)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3.0m	B 6.0m	C 10.0m	D 14.0m	E 20.0m
R		Radial	4.95	1.65	1.20	0.36	1.01
S		Transverse	5.02	1.05	0.63	0.65	0.54
V	5.7	Vertical	6.45	2.16	0.99	0.82	2.11
1		Resultant	9.55	2.91	1.68	1.11	2.40
R		Radial	3.69	0.91	0.71	0.36	1.01
S		Transverse	3.81	1.81	0.66	1.38	0.80
V	6.4	Vertical	5.38	3.05	2.52	1.64	3.22
2		Resultant	7.55	3.66	2.70	2.17	3.47
R		Radial	2.88	1.92	1.10	0.45	0.74
S		Transverse	2.60	1.72	0.90	1.94	1.07
V	7.1	Vertical	5.09	3.77	2.81	2.09	3.82
3		Resultant	6.40	4.57	2.19	2.89	4.03
R		Radial	4.50	7.49	5.79	0.36	2.31
S		Transverse	4.27	3.34	1.78	1.02	0.71
V	7.5	Vertical	6.94	5.03	2.25	1.55	2.21
4		Resultant	9.31	9.62	6.46	1.89	3.27
R		Radial	6.48	1.55	1.44	0.45	0.92
S		Transverse	4.68	1.05	0.55	0.55	0.36
V	2.0	Vertical	8.80	1.53	1.70	0.73	0.80
5		Resultant	11.88	2.42	2.29	1.02	1.27

Table (T5-57B)

Rotherhithe, E.London

Disc no	Date	File name
PDR2-F	19.04.1988	RSV
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (32W)	16m
Hammer		
Frequency	Model	Energy/cycle
28Hz	Vibrodriver (MS 25H)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3.0m	B 6.0m	C 10.0m	D 14.0m	E 20.0m
R		Radial	2.07	1.37	1.18	0.45	0.74
S		Transverse	2.97	0.95	0.36	0.65	0.27
V	3.7	Vertical	3.91	0.90	0.74	0.91	1.00
6		Resultant	5.33	1.89	1.44	1.20	1.27
R		Radial	2.88	1.01	0.84	0.45	0.83
S		Transverse	3.72	1.24	0.40	0.46	0.63
V	5.0	Vertical	4.99	1.80	0.50	1.09	1.71
7		Resultant	6.86	2.41	1.06	1.26	1.99
R		Radial	2.70	0.64	0.82	0.45	0.92
S		Transverse	3.34	1.52	0.67	0.92	0.80
V	6.6	Vertical	5.48	2.33	1.25	1.64	2.61
8		Resultant	6.96	2.85	1.64	1.93	2.88
R		Radial	3.15	1.10	0.51	0.45	0.92
S		Transverse	3.62	1.43	0.77	1.38	0.98
V	7.4	Vertical	6.36	2.42	1.73	1.91	3.22
9		Resultant	7.97	3.02	1.96	2.40	3.49
R		Radial	3.42	1.74	1.09	0.45	0.83
S		Transverse	3.44	1.33	0.54	1.11	0.89
V	7.8	Vertical	8.70	2.60	1.15	1.91	2.81
10		Resultant	9.96	3.40	1.97	2.25	3.06

Table (T5-58)

Scarborough, Fish Dockyard

Disc no.	Date	File name
DATA32	22.02.1988	SSA
Pile		
Type	Dimensions	Length
Sheet	Larssen (16W)	10m
Hammer		
Weight	Model	Energy/blow
227kg	Air-hammer (600N)	4.1kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 4m	C 7m	D 10m	E 14m
S		Radial	2.16	0.46	0.47	0.32	0.21
S		Transverse	7.62	0.67	0.16	0.46	0.54
A		Vertical	2.93	1.29	0.46	0.23	0.38
1		Resultant	8.32	1.32	0.51	0.52	0.55
S		Radial	1.35	0.37	0.50	0.41	0.43
S		Transverse	7.71	0.67	0.16	0.46	0.36
A		Vertical	1.66	1.29	0.51	0.50	0.28
2		Resultant	7.50	1.38	0.59	0.57	0.46
S		Radial	2.07	0.37	0.48	0.32	0.30
S		Transverse	6.13	0.57	0.16	0.46	0.36
A		Vertical	2.15	1.29	0.62	0.50	0.32
3		Resultant	6.15	1.35	0.63	0.57	0.42
S		Radial	1.35	0.37	0.57	0.23	0.34
S		Transverse	4.74	0.57	0.17	0.46	0.36
A		Vertical	1.08	1.47	0.65	0.50	0.32
4		Resultant	4.79	1.52	0.66	0.57	0.39
S		Radial	1.44	0.64	0.77	0.50	0.43
S		Transverse	5.67	0.67	0.20	0.46	0.36
A		Vertical	1.37	1.92	0.57	0.50	0.72
5		Resultant	5.75	1.96	0.79	0.76	0.74

Table (T5-59A)

Monk-Fryston, Selby

Disc no	Date	File name
DATA26	03.09.1987	SCD
Pile		
Type	Dimensions	Length
Concrete	Balken (275 × 275mm)	12m
Hammer		
Weight	Model	Drop height
4000kg	Drop-hammer (Banut400)	300-400mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2m	B 5m	C 9m	D 14m	E 20m
SCD2	8.0	Radial	12.60	2.56	0.40	0.59	0.30
		Transverse	3.07	1.24	0.22	0.46	0.36
		Vertical	12.81	5.06	1.86	1.23	0.35
		Resultant	14.54	5.36	1.86	1.35	0.42
SCD3	8.5	Radial	7.11	1.65	0.44	1.04	0.62
		Transverse	2.42	0.76	0.50	1.66	0.45
		Vertical	5.67	3.09	1.08	1.05	0.73
		Resultant	7.37	3.39	1.12	1.81	0.84
SCD4	9.0	Radial	10.89	2.92	2.60	1.04	0.62
		Transverse	6.04	2.00	1.04	0.83	0.54
		Vertical	13.89	7.33	3.53	2.41	0.88
		Resultant	14.33	7.70	3.79	2.44	0.95
SCD5	9.2	Radial	3.69	1.83	0.32	1.04	0.47
		Transverse	3.62	0.86	0.77	1.20	0.36
		Vertical	5.28	2.28	0.97	0.86	0.38
		Resultant	5.62	2.69	1.06	1.24	0.63
SCD6	9.5	Radial	10.80	2.74	2.52	1.13	0.77
		Transverse	4.40	1.91	1.72	0.83	0.54
		Vertical	17.41	7.96	3.96	2.78	1.23
		Resultant	17.98	8.36	4.25	2.84	1.35

Table (T5-59B)

Monk-Fryston, Selby

Disc no	Date	File name
DATA27	03.09.1987	MCD
Pile		
Type	Dimensions	Length
Concrete	Balken (275 × 275mm)	12m
Hammer		
Weight	Model	Drop height
4000kg	Drop-hammer (Banut400)	300-400mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.8m	B 5m	C 8m	D 14m	E 20m
M		Radial	20.07	3.75	0.73	3.48	0.49
C		Transverse	7.34	1.24	0.23	0.65	0.63
D	7.2	Vertical	16.23	5.78	1.05	1.05	0.72
1		Resultant	23.21	6.44	1.10	2.51	0.774
M		Radial	5.40	1.10	1.01	0.77	0.99
C		Transverse	1.95	0.95	0.21	1.02	1.03
D	7.8	Vertical	4.11	2.37	0.94	0.86	0.78
3		Resultant	5.89	2.59	1.03	1.17	1.22
M		Radial	18.00	2.86	1.71	1.04	0.58
C		Transverse	9.66	2.67	1.00	1.20	0.63
D	8.2	Vertical	18.19	6.88	3.27	3.05	1.43
4		Resultant	22.85	7.31	3.45	3.18	1.50
M		Radial	17.82	2.74	1.84	1.22	0.67
C		Transverse	10.40	3.24	0.94	1.20	0.63
D	8.4	Vertical	18.68	6.79	3.52	3.14	1.43
5		Resultant	21.51	7.26	3.64	3.23	1.49
M		Radial	18.09	3.11	1.89	1.79	0.80
C		Transverse	10.59	2.95	1.04	1.48	0.63
D	8.8	Vertical	19.78	7.42	4.09	3.23	1.05
6		Resultant	21.17	7.99	4.18	3.40	1.53

Table (T5-60A)

Sheffield, River Don

Disc no	Date	File name
PDR2-X	25.10.1988	FDH
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 79kg/m	12m
Hammer		
Blow rate	Model	Energy/blow
80-100 bl/min	Diesel-hammer (B15/7)	37.2kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	set/blow (mm)	Geophone-set Stand-off	A 2m	B 5m	C 7m	D 15m	E 13m*
FDH1	5.00	20	Radial	16.69	6.85	4.61	1.53	0.81
			Transverse	11.97	3.24	2.66	0.84	0.65
			Vertical	17.69	3.41	2.13	1.86	1.18
			Resultant	22.76	6.94	5.21	2.15	1.41
FDH2	5.80	15	Radial	11.71	9.41	9.67	2.52	0.99
			Transverse	11.16	9.24	3.71	1.11	0.55
			Vertical	14.57	8.26	3.49	2.45	1.64
			Resultant	18.50	11.66	9.69	3.35	1.84
FDH3	6.50	15	Radial	17.52	12.34	8.51	2.25	1.17
			Transverse	19.29	12.48	2.73	1.48	0.55
			Vertical	23.12	10.33	5.35	2.93	1.91
			Resultant	28.77	12.75	8.83	3.76	2.23
FDH4	7.00	20	Radial	11.71	6.31	4.71	1.71	0.90
			Transverse	6.34	4.48	1.79	0.65	0.74
			Vertical	12.26	4.94	2.28	1.76	1.46
			Resultant	14.09	7.05	5.13	2.02	1.67
FDH5	7.60	10	Radial	8.57	10.14	5.86	2.16	1.17
			Transverse	6.52	5.81	2.76	1.11	0.74
			Vertical	14.77	5.12	2.90	1.85	2.37
			Resultant	17.00	11.27	6.14	2.32	2.45

Table (T5-60B)

Sheffield, River Don

Disc no	Date	File name
PDR2-X,Y	25.10.1988	FDH
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 79kg/m	12m
Hammer		
Blow rate	Model	Energy/blow
80-100 bl/min	Diesel-hammer (B15/7)	37.2kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	set/blow (mm)	Geophone-set Stand-off	A 2m	B 5m	C 7m	D 15m	E 13m*
F			Radial	6.55	14.72	7.11	3.33	1.08
D			Transverse	5.09	8.77	2.77	1.67	0.74
H	8.00	4	Vertical	8.84	5.21	3.00	2.25	2.37
6			Resultant	9.95	16.01	7.15	3.68	2.52
F			Radial	7.01	17.27	8.80	4.32	1.26
D			Transverse	5.18	9.05	3.11	1.86	0.83
H	8.10	3	Vertical	13.37	6.02	3.16	2.35	2.46
7			Resultant	14.42	18.82	8.93	4.91	2.63
F			Radial	5.07	15.36	10.34	5.13	1.35
D			Transverse	5.98	8.48	2.74	2.69	0.74
H	8.20	3	Vertical	10.95	5.84	3.11	2.05	2.46
8			Resultant	11.68	17.19	10.40	5.35	2.69
F			Radial	6.27	20.66	13.34	—	1.53
D			Transverse	11.70	11.05	4.43	—	1.12
H	8.25	1	Vertical	13.27	7.54	4.09	—	2.64
9			Resultant	15.43	22.80	13.43	—	3.01

* This set of geophones was placed on pipe culvert 1.2m below the ground level.

Table (T5-61A)

Sheffield, River Don, Pile no.2

Disc no	Date	File name
PDR2-Y,Z	27.10.1988	SDH
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 79kg/m	15m
Hammer		
Blow rate	Model	Energy/blow
80-100 bl/min	Diesel-hammer (B15/7)	37.2kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	set/blow (mm)	Geophone-set Stand-off	A 2m	B 5m	C 8m	D 12m	E 4m*
SDH 2	6.00	20	Radial	16.29	7.77	11.08	4.24	8.94
			Transverse	5.57	4.57	3.99	3.88	14.73
			Vertical	10.86	4.67	3.68	2.82	10.75
			Resultant	17.87	9.09	11.10	4.74	17.99
SDH 3	6.50	30	Radial	15.21	7.86	7.36	3.52	7.10
			Transverse	4.18	4.76	2.92	4.06	10.89
			Vertical	12.91	4.49	5.79	2.82	10.25
			Resultant	17.53	8.00	7.36	4.78	15.60
SDH 4	7.00	30	Radial	15.57	8.68	11.35	7.49	10.70
			Transverse	6.04	7.15	5.56	4.61	17.68
			Vertical	12.71	4.58	5.25	2.91	12.26
			Resultant	16.48	9.32	12.85	8.45	21.49
SDH 5	7.50	25	Radial	11.16	13.25	8.70	6.22	5.81
			Transverse	6.87	5.43	5.99	5.81	7.32
			Vertical	11.15	5.03	3.84	2.82	7.44
			Resultant	14.66	13.55	10.90	7.08	9.09
SDH 7	8.20	10	Radial	28.35	36.47	10.61	8.75	5.44
			Transverse	15.14	8.48	4.14	7.57	5.54
			Vertical	53.01	5.84	2.84	1.73	10.15
			Resultant	55.15	36.96	10.74	9.75	11.04

Table (T5-61B)

Sheffield, River Don, Pile no.2

Disc no	Date	File name
PDR2-Y,Z	27.10.1988	SDH
	Pile	
Type	Dimensions	Length
H-pile	305 × 305 × 79kg/m	15m
	Hammer	
Blow rate	Model	Energy/blow
80-100 bl/min	Diesel-hammer (B15/7)	37.2kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	set/blow (mm)	Geophone-set Stand-off	A 2m	B 5m	C 8m	D 12m	E 4m*
S			Radial	23.22	44.33	11.73	20.57	5.44
D			Transverse	18.67	13.63	5.24	15.78	6.97
H	8.25	3	Vertical	49.29	11.67	15.56	6.82	17.39
8			Resultant	50.19	45.83	17.72	25.16	17.39
S			Radial	19.98	40.86	14.14	19.93	6.45
D			Transverse	21.18	10.29	5.45	15.32	5.80
H	8.30	3	Vertical	45.18	9.97	15.59	6.64	14.37
9			Resultant	46.42	42.04	19.02	24.38	15.51
S			Radial	23.40	43.51	10.64	22.01	7.10
D			Transverse	22.95	11.63	5.92	18.00	5.80
H	8.35	3	Vertical	48.31	10.60	18.16	7.55	15.48
10			Resultant	49.24	44.77	20.82	28.23	17.61

(*) This set of geophone was placed on the sewage pipe some 3m below the ground level.

Table (T5-62A)

Sheffield, River Don, Raking pile (1/4)

Disc no	Date	File name
PDR2-j,k	23.02.1989	SHF
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 79kg/m	15m
Hammer		
Blow rate	Model	Energy/blow
80-100 bl/min	Diesel-hammer (B15/7)	37.2kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	E 2.0m	D 4.0m	A 6.0m	B 8.0m	C 10.0m
SHF 2	4.0	Radial	24.43	46.45	5.94	13.23	3.80
		Transverse	45.36	11.26	4.57	8.55	0.98
		Vertical	15.98	14.10	3.23	13.30	1.59
		Resultant	59.72	46.66	8.06	17.92	3.83
SHF 4	5.2	Radial	18.81	47.53	7.95	10.98	3.19
		Transverse	36.43	13.84	6.67	9.75	3.62
		Vertical	13.27	13.46	3.86	16.04	1.67
		Resultant	41.19	47.68	10.28	17.05	4.23
SHF 5	5.8	Radial	20.37	46.27	9.87	7.74	3.40
		Transverse	32.32	11.91	7.91	12.36	4.05
		Vertical	11.56	13.10	3.95	13.49	1.56
		Resultant	38.08	46.52	11.32	14.87	4.78
SHF 6	6.1	Radial	18.71	41.58	10.14	9.81	2.60
		Transverse	28.75	10.98	10.38	10.13	3.52
		Vertical	9.65	10.46	4.94	17.31	1.83
		Resultant	33.96	49.10	10.77	19.13	3.70
SHF 7	6.4	Radial	10.14	38.15	11.24	10.08	2.80
		Transverse	28.66	11.17	10.48	10.40	3.37
		Vertical	7.84	9.28	4.67	17.70	1.69
		Resultant	29.78	38.59	12.28	18.99	3.49

Table (T5-62B)

Sheffield, River Don, Raking pile (1/4)

Disc no	Date	File name
PDR2-j,k	23.02.1989	SHF
Pile		
Type	Dimensions	Length
H-pile	305 × 305 × 79kg/m	15m
Hammer		
Blow rate	Model	Energy/blow
80-100 bl/min	Diesel-hammer (B15/7)	37.2kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	E 2.0m	D 4.0m	A 6.0m	B 8.0m	C 10.0m
S		Radial	7.65	34.99	11.24	9.90	2.69
H		Transverse	27.86	11.54	11.44	10.47	3.41
F	6.6	Vertical	7.34	8.74	5.03	17.21	1.49
8		Resultant	28.30	35.30	12.47	18.67	3.50

Table (T5-63A)

St. Annes, Sandgate Sewage System

Disc no	Date	File name
DATA-10	25.11.1986	POL
	Pile	
Type	Dimensions	Length
Sheet-pile	Larssen (32W)	14m
	Hammer	
Frequency	Model	Energy/cycle
28Hz	Vibrodriver (PTC 50H3)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 12.0m	E 18.0m
P		Radial	7.74	4.46	3.20	2.35	2.17
O		Transverse	9.48	8.79	3.43	2.31	1.13
L	0.5	Vertical	8.02	4.26	1.98	2.06	1.92
4		Resultant	12.01	9.38	8.23	3.36	2.34
P		Radial	18.90	17.82	6.39	3.52	2.35
O		Transverse	14.68	18.72	6.47	2.22	1.46
L	1.0	Vertical	28.26	10.91	11.01	2.88	2.22
5		Resultant	29.41	25.40	5.85	5.29	3.33
P		Radial	18.99	14.09	4.57	2.71	1.89
O		Transverse	11.33	9.13	1.98	3.05	1.94
L	3.0	Vertical	10.07	4.09	7.07	1.87	1.02
6		Resultant	20.14	14.61	11.70	3.23	2.45
P		Radial	18.09	17.82	8.86	3.52	2.63
O		Transverse	10.87	12.09	3.77	2.22	2.62
L	6.0	Vertical	8.61	5.33	4.77	2.51	2.22
7		Resultant	19.05	17.86	8.68	4.40	3.57
P		Radial	12.87	9.83	12.43	4.33	3.27
O		Transverse	12.73	13.92	10.67	4.06	3.24
L	7.0	Vertical	9.78	5.01	2.51	2.42	2.52
8		Resultant	14.87	15.40	16.29	5.65	3.54

Table (T5-63B)

St.Annes, Sandgate Sewage System

Disc no	Date	File name
DATA-10	25.11.1986	POL
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (32W)	14m
Hammer		
Frequency	Model	Energy/cycle
28Hz	Vibrodriver (PTC 50H3)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)

File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 12.0m	E 18.0m
P		Radial	7.47	17.82	10.69	6.86	4.75
O		Transverse	11.52	17.32	5.72	2.95	2.35
L	8.0	Vertical	13.79	9.61	4.58	1.60	2.52
9		Resultant	18.42	23.69	12.11	7.49	4.96
P		Radial	14.31	10.36	4.02	4.06	1.06
O		Transverse	5.95	13.34	1.52	2.22	1.37
L	10.0	Vertical	10.17	11.22	4.85	5.51	1.92
10		Resultant	14.59	17.13	5.81	6.27	2.19

Table (T5-64A)

St.Annes, Sandgate Sewage System

Disc no	Date	File name
DATA-10	01.12.1986	ANS
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (32W)	14m
Hammer		
Weight	Model	Drop height
7000kg	Hydraulic-hammer (BSP 357)	800-1200mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 12.0m	E 18.0m
A		Radial	23.13	17.82	27.60	13.71	8.16
N		Transverse	11.71	10.24	4.48	3.23	—
S	9.25	Vertical	41.57	18.77	12.84	7.77	4.01
4		Resultant	43.13	27.19	28.83	14.09	8.43
A		Radial	21.33	17.82	18.10	15.42	8.25
N		Transverse	11.61	14.15	4.00	4.06	—
S	9.50	Vertical	19.46	14.81	10.96	6.04	4.31
5		Resultant	23.92	23.17	18.64	15.76	8.88
A		Radial	29.16	17.82	36.01	17.32	7.24
N		Transverse	21.27	13.11	5.62	3.78	—
S	9.65	Vertical	30.90	18.77	17.33	5.50	5.04
6		Resultant	39.12	27.50	36.50	17.92	7.62
A		Radial	29.79	17.82	35.65	17.23	7.33
N		Transverse	21.18	12.36	5.62	3.78	—
S	9.75	Vertical	30.81	18.77	17.42	5.50	5.34
7		Resultant	37.24	26.76	36.16	17.97	7.88
A		Radial	15.75	17.81	18.28	9.56	6.50
N		Transverse	8.55	12.21	3.34	2.95	—
S	10.0	Vertical	12.32	9.87	7.09	5.31	5.14
8		Resultant	17.73	21.22	18.67	10.37	7.29

Table (T5-64B)

St.Annes, Sandgate Sewage System

Disc no	Date	File name
DATA-10	01.12.1986	ANS
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (32W)	14m
Hammer		
Weight	Model	Drop height
7000kg	Hydraulic-hammer (BSP 357)	800-1000mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 8.0m	D 12.0m	E 18.0m
A		Radial	36.72	17.82	37.38	16.33	8.71
N		Transverse	19.97	12.62	5.67	4.52	—
S	10.20	Vertical	35.01	18.77	18.41	5.06	5.24
9		Resultant	40.20	26.09	38.21	17.65	8.97
A		Radial	20.70	17.81	20.66	10.73	6.41
N		Transverse	7.52	9.09	3.14	2.58	—
S	10.25	Vertical	14.38	12.02	7.99	3.33	3.63
10		Resultant	21.98	21.39	21.01	11.47	6.75
A		Radial	41.40	17.82	43.05	17.68	9.36
N		Transverse	24.06	13.37	5.62	4.61	—
S	10.50	Vertical	37.56	18.77	20.20	6.06	6.04
11		Resultant	46.16	26.54	43.87	19.22	11.24
A		Radial	21.78	16.44	22.21	10.01	5.12
N		Transverse	8.36	9.06	3.91	3.05	—
S	10.65	Vertical	9.58	14.29	22.52	10.32	3.03
12		Resultant	23.58	21.49	22.52	10.32	6.54
A		Radial	22.14	17.82	47.44	19.66	7.61
N		Transverse	22.48	10.73	6.19	4.25	—
S	10.75	Vertical	21.32	18.77	19.22	6.42	6.34
13		Resultant	28.96	26.99	48.00	20.96	8.82

Table (T5-65)

St.Helens, Cofferdam Construction

Disc no	Date	File name
DATA-28	04.09.1987	SSA
	Pile	
Type	Dimensions	Length
Sheet-pile	Larssen (16W)	12m
	Hammer	
Weight	Model	Max.Energy
385kg	Air-hammer (BSP 700N)	6.4kJ

			Peak Particle Velocity Measurements ($mm.s^{-1}$)				
File no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 4.0m	C 6.0m	D 9.0m	E 12.0m
S		Radial	10.08	4.11	0.80	0.59	0.53
S		Transverse	14.21	5.53	0.75	0.46	0.89
A	1.2	Vertical	10.37	3.99	0.97	0.68	0.58
1		Resultant	14.70	6.04	1.11	0.88	1.00
S		Radial	5.94	4.11	0.56	0.86	0.43
S		Transverse	5.95	3.81	0.38	0.46	0.63
A	2.0	Vertical	4.30	2.46	0.83	0.50	0.58
2		Resultant	8.54	2.84	1.84	0.93	0.73
S		Radial	9.09	3.20	0.84	0.59	0.49
S		Transverse	9.10	4.48	0.33	0.92	0.71
A	2.5	Vertical	6.45	3.90	1.07	2.50	0.48
3		Resultant	9.94	4.92	1.08	2.52	0.75
S		Radial	8.19	4.11	1.00	0.68	0.49
S		Transverse	9.57	5.81	0.32	0.65	0.89
A	3.0	Vertical	6.75	3.27	1.29	0.86	0.72
4		Resultant	10.24	6.46	1.31	1.01	0.99
S		Radial	6.84	3.84	0.84	0.68	0.49
S		Transverse	9.29	3.62	0.28	0.65	0.80
A	5.6	Vertical	5.48	2.64	0.99	0.68	0.72
6		Resultant	10.16	5.15	1.00	0.75	0.80

Table (T5-66)

Swillington, (Miller Mine)

Disc no	Date	File name
DATA-30	10.12.1987	SSV
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (25W)	16m
Hammer		
Frequency	Model	Energy/cycle
28Hz	Vibrodriver (MS 25H)	10.7kJ

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Pile no.	Depth (m)	Geophone-set Stand-off	A 2.0m	B 5.0m	C 9.0m	D 14.0m	E 20.0m
S			Radial	10.98	3.56	3.02	1.04	0.18
S			Transverse	3.72	2.29	0.44	1.48	0.89
V	A	4.8	Vertical	12.42	6.86	3.45	1.05	1.70
1			Resultant	15.09	6.99	4.41	2.02	1.99
S			Radial	4.95	3.47	8.91	0.86	0.28
S			Transverse	2.60	2.29	1.47	1.11	0.89
V	B	5.0	Vertical	12.62	2.64	3.08	0.50	0.88
2			Resultant	13.53	4.08	9.03	1.45	1.18
S			Radial	7.47	2.10	8.26	0.77	0.28
S			Transverse	2.23	1.91	0.81	0.83	0.88
V	B	6.5	Vertical	8.80	2.73	2.06	0.59	0.78
3			Resultant	11.47	3.56	8.29	1.09	0.94
S			Radial	3.69	1.92	6.50	0.77	0.27
S			Transverse	2.32	2.00	0.76	1.11	1.16
V	A	6.2	Vertical	7.14	3.99	1.55	0.50	0.72
4			Resultant	7.22	4.05	6.58	1.24	1.30

Table (T5-67)

Waltham Cross, North London

Disc no	Date	File name
DTAT-33	17.03.1988	WSH
Pile		
Type	Dimensions	Length
Sheet-pile	Larssen (25W)	12m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP 357)	400-800mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)							
File no.	Depth (m)	Geophone-set Stand-off	A 3.0m	B 5.0m	C 8.0m	D 12.0m	E 17.0m
W		Radial	51.12	13.71	9.61	2.66	0.46
S		Transverse	10.40	4.19	4.67	0.46	1.25
H	6	Vertical	33.25	9.38	13.03	4.05	3.10
1		Resultant	57.42	15.98	14.03	4.11	3.13
W		Radial	68.94	16.73	11.52	2.84	0.28
S		Transverse	12.91	5.43	5.91	0.28	1.43
H	6.4	Vertical	40.10	11.35	16.09	4.87	3.50
2		Resultant	69.18	19.41	17.19	4.99	3.61
W		Radial	70.56	17.37	18.56	2.93	0.28
S		Transverse	12.82	5.34	6.20	0.37	1.52
H	6.7	Vertical	41.86	11.62	16.50	4.78	3.50
3		Resultant	70.87	20.25	23.01	4.85	3.51
W		Radial	77.58	18.92	13.25	3.29	0.28
S		Transverse	14.96	6.00	6.87	0.46	1.79
H	7.3	Vertical	44.79	11.89	17.65	4.87	3.90
4		Resultant	77.72	22.13	19.40	4.91	3.91
W		Radial	75.51	21.20	15.31	4.37	0.28
S		Transverse	14.86	5.34	9.88	0.46	1.52
H	8.0	Vertical	43.81	13.07	18.77	5.41	4.10
11		Resultant	75.76	25.39	23.61	5.80	4.11

Table (T5-68)

Whalley, Accrington road

Disc no	Date	File name
DATA-1	22.09.1986	WAL
Pile		
Type	Dimensions	Length
Concrete	Balken (250 × 250mm)	13m
Hammer		
Weight	Model	Drop height
4000kg	Drop-hammer(Herkules)	300-1000mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Drop (mm)	Geophone-set Stand-off	A 2m	B 4m	C 6m	D 10m	E 15m
WAL5	6.0	600	Radial	4.14	1.47	6.86	—	0.50
			Transverse	2.97	1.76	1.90	0.57	0.52
			Vertical	3.81	1.78	1.35	0.64	0.40
			Resultant	4.54	2.17	7.11	2.67	0.62
WAL6	11.0	600	Radial	2.78	1.06	2.56	—	0.33
			Transverse	3.07	1.29	1.61	2.57	0.34
			Vertical	2.43	0.98	0.90	0.46	0.20
			Resultant	3.66	1.38	2.61	1.71	0.39
WAL7	12.0	900	Radial	3.78	1.59	6.22	—	0.42
			Transverse	2.60	1.26	2.01	0.82	0.61
			Vertical	5.38	2.39	1.26	0.64	0.50
			Resultant	5.42	2.75	6.46	2.60	0.70
WAL8	12.5	900	Radial	3.24	1.38	3.02	—	0.42
			Transverse	2.32	0.93	1.06	0.47	0.34
			Vertical	2.35	1.18	0.64	0.37	0.30
			Resultant	3.57	1.56	3.03	0.56	0.47

Table (T5-69)

Whalley, Accrington Rd.

Disc no	Date	File name
DATA-1	22.09.1986	WAL
Pile		
Type	Dimensions	Length
Concrete	Balken (250 × 250mm)	13m
Hammer		
Weight	Model	Drop height
4000kg	Drop-hammer(Herkules)	300-1000mm

Peak Particle Velocity Measurements ($mm.s^{-1}$)								
File no.	Depth (m)	Drop (mm)	Geophone-set Stand-off	A 2m	B 4m	C 6m	D 8m	E 10m
WAL 9	7.0	600	Radial	19.71	13.33	23.12	—	7.65⊕
			Transverse	8.92	3.60	5.41	2.41	2.91
			Vertical	12.03	9.25	6.91	6.56	4.92
			Resultant	23.50	13.88	23.42	7.37	8.28
WAL 10	7.5	600	Radial	27.36	18.16	16.36	—	7.65⊙
			Transverse	11.06	3.19	20.37	1.93	17.91
			Vertical	17.11	8.90	7.09	5.91	8.24
			Resultant	29.28	19.18	21.02	6.35	19.28
WAL 11	8.0	600	Radial	22.77	14.26	15.45	—	7.10
			Transverse	8.08	5.67	4.94	2.69	15.84
			Vertical	15.84	7.61	6.47	5.20	19.79
			Resultant	25.24	14.61	16.40	6.30	25.78
WAL 12	11.0	900	Radial	8.10	9.85	16.73	—	6.55
			Transverse	12.73	2.10	4.79	6.01	15.40
			Vertical	7.14	6.11	4.85	6.38	6.44
			Resultant	15.40	10.27	17.17	7.92	15.64
WAL 13	12.0	900	Radial	8.28	9.83	14.72	—	6.09
			Transverse	12.82	2.66	4.17	4.63	14.59
			Vertical	7.04	5.48	4.76	5.93	5.93
			Resultant	16.25	10.46	15.44	7.30	14.72

⊕ This set of geophones was placed on the wall 6m from the pile.

⊙ This set of geophones was placed on the wall 1m from the pile.

Site General Information									Peak Resultant Vectors(mm/s)				
Site			Hammer		Pile				Geophones Stand-off(m)				
location	ground	file	model	weight	type	size	length	depth	2-3	4-6	7-9	11-14	16-22
1.Drop-hammer													
Whalley	silty clay	WAL13	Hercules	4000kg	Concrete	250×250mm	13m	12.0m	16.25	10.46	15.44	7.30	14.72
Selby	sandy silt	SCD6	Banut	4000kg	concrete	275×275mm	12m	9.5m	17.98	8.36	4.25	2.84	1.35
Newark	soft marl	NDH6	Banut	5000kg	H-steel	305 × 305 × 126kg/m	12m	9.0m	18.74	13.79	3.07	2.14	1.92
Newark	silty clay	NHD7	Banut	5000kg	H-steel	305 × 305 × 186kg/m	12m	10.0m	25.99	16.47	7.65	4.09	2.26
2.Diesel-hammer													
Blaydon	glacial clay	FAR7	DS-50c	4000kg	H-pile	356 × 368 × 152kg/m	32m	25.0m	13.59	7.30	4.10	5.14	4.06
Blaydon	sandstone	DIS13	DS-50c	4000kg	H-pile	356 × 368 × 152kg/m	27m	23.25m	12.82	9.48	12.26	10.80	6.80
Grimsby	boulder clay	GRD7	DS-B15	1500kg	Sh-pile	Larssen (25W)	16m	12.5m	19.88	17.72	5.67	4.40	3.52
Keighley	sandy clay	KDH2	DS-50c	4000kg	H-pile	305 × 305 × 134kg/m	32m	14.5m	13.03	12.77	16.86	19.61	12.08
Sheffield	silty clay	SDH7	DS-B15	4000kg	H-pile	305 × 305 × 79kg/m	12m	8.2m	55.15	36.96	10.74	9.75	

Table (T5-70a) Summary of Ground Vibration Measurements

Site General Information									Peak Resultant Vectors(mm/s)				
Site			Hammer		Pile				Geophones Stand-off(m)				
location	ground	file	model	weight	type	size	length	depth	2-3	4-6	7-9	11-14	16-22
3.Air-hammer													
Blaydon	glacial clay	BAH5	BSP 900N	2000kg	H-pile	356 × 368 × 152kg/m	21m	15.3m	14.81	8.18	7.88	6.70	8.20
Blaydon	alluvial deposit	BSA14	BSP 600N	1200kg	Sh-pile	Larssen (16W)	9m	7.2m	11.73	10.46	5.55	3.04	2.57
Scarborough	coastal deposit	SSA5	BSP 600N	1200kg	Sh-pile	Larssen (16W)	10m	6.2m	5.75	1.96	0.79	0.76	0.74
St.Helens	silty clay	SSA6	BSP 700N	3000kg	Sh-pile	Larssen (16W)	12m	5.6m	10.16	5.15	1.00	0.75	0.80
4.Hydraulic-hammer													
Blaydon	glacial stiff clay	BLH11	BSP 357	5000kg	H-pile	356 × 368 × 152kg/m	23m	20.0m	16.73	21.56	18.68	12.66	7.42
Blaydon	glacial stiff clay	BHH8	BSP 357	5000kg	H-pile	356 × 368 × 152kg/m	23m	21.5m	14.36	13.46	7.73	6.24	8.73
Blaydon	glacial sandy clay	BHC2	BSP 357	5000kg	H-pile	356 × 368 × 152kg/m	35m	19.0m	15.21	13.96	9.35	4.15	3.20
Blaydon	sandy silt	BDH10	BSP 357	5000kg	H-pile	356 × 368 × 152kg/m	23m	17.0m	42.40	11.65	7.61	5.26	5.31
Edinburgh	silty clay	ESH5	BSP 357	5000kg	Sh-pile	Frodinghamm (3N)	9m	8.2m	28.44	11.09	1.64	1.36	0.73
Keighley	dense gravel	KGL14	BSP 357	3000kg	H-pile	305 × 305 × 126kg/m	32m	30.5m	6.17	4.79	5.81	7.00	4.65
Keighley	silty clay	KHH5	BSP 357	3000kg	H-pile	305 × 305 × 126kg/m	32m	21.5m	10.74	7.19	7.82	11.26	10.22
St.Annes	dense sand	ANS13	BSP 357	5000kg	Sh-pile	Larssen (16W)	14m	10.75m	28.96	26.99	48.00	20.96	8.82
Waltham X	brown clay	WSH11	BSP 357	5000kg	Sh-pile	Larssen (25W)	12m	8.0m	75.76	25.39	23.61	5.80	4.11

Table (T5-70b) Summary of Ground Vibration Measurements

Site General Information									Peak Resultant Vectors(mm/s)				
Site			Hammer		Pile				Geophones Stand-off(m)				
location	ground	file	model	frequency	type	size	length	depth	2-3	4-6	7-9	11-14	16-22
5.Vibrodriver													
Newbiggin	dense sand	NVS5	ABI	50Hz	Sh-pile	Larseen (20W)	5.0m	4.5m	27.16	10.63	8.15	2.89	1.23
Blaydon	alluvial clay	HOW4	PTC 50c	25Hz	Tube-pile	740mm diameter	20m	2.7m	61.29	31.66	15.04	15.28	3.90
Blaydon	glacial clay	RIV11	PTC 25c	30Hz	H-pile	$356 \times 368 \times 152$kg/m	13m	11.0m	38.79	18.89	12.95	9.53	4.03
G.Yarmouth	dense gravel	YTV12	PTC 23HF	45Hz	Tube-pile	1200mm diameter	21m	14.7m	1.64	4.07	2.61	2.74	1.34
Keighly	silty clay	KVS8	MS25H	28Hz	Sh-pile	Frodinghamm (3N)	9m	6.5m	25.18	11.09	8.22	5.99	2.77
Keighley	clayey silt	KVH5	MS25H	28Hz	H-pile	$356 \times 368 \times 134 kg/m$	16m	11.0m	14.73	8.18	4.20	4.58	3.00
Newark	dense silt	NSV5	PTC13H/1	44Hz	Sh-pile	Larssen (6)	9.5m	4.7m	25.62	12.95	7.82	5.51	6.49
Rotherhithe	dense sand	RLM7	MS 25H	28Hz	Sh-pile	Larssen (32W)	16m	7.5m	20.15	26.84	13.50	5.43	
St.Annes	sand & gravel	POL7	PTC 30	30Hz	Sh-pile	Larssen (16W)	14m	6.0m	19.05	17.86	8.68	4.40	3.57
Swillington	sandy clay	SSV1	MS 25H	28Hz	Sh-pile	Larssen (25W)	16m	4.8m	15.09	6.99	4.41	2.02	1.99

Table (T5-70c) Summary of Ground Vibration Measurements

Figure (5.1) Locations of the visited sites around Britain

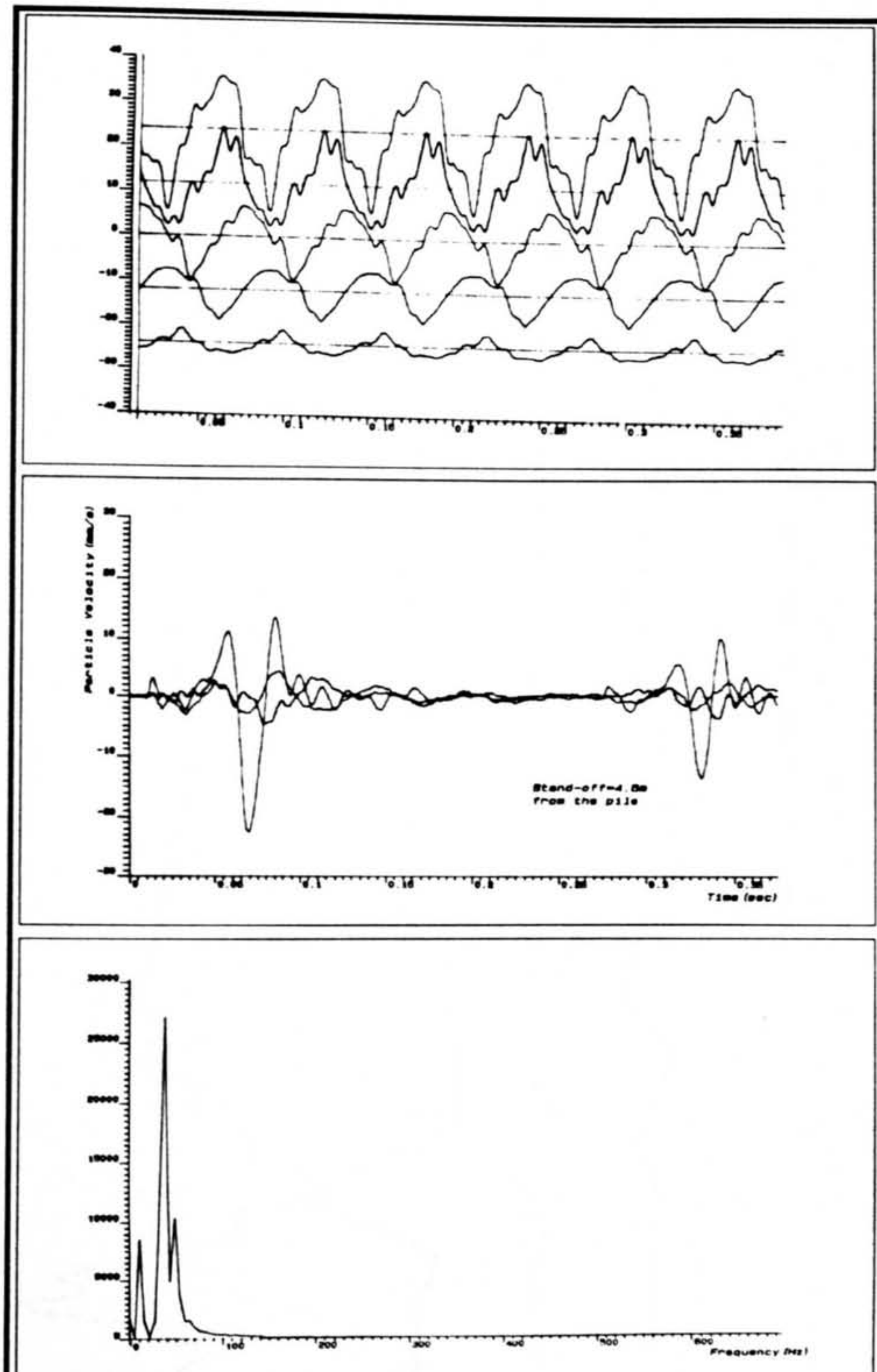


Figure (5.5) Calculation of frequency spectrum from
a. periodic vibration b. transient vibration c. FFT analysis

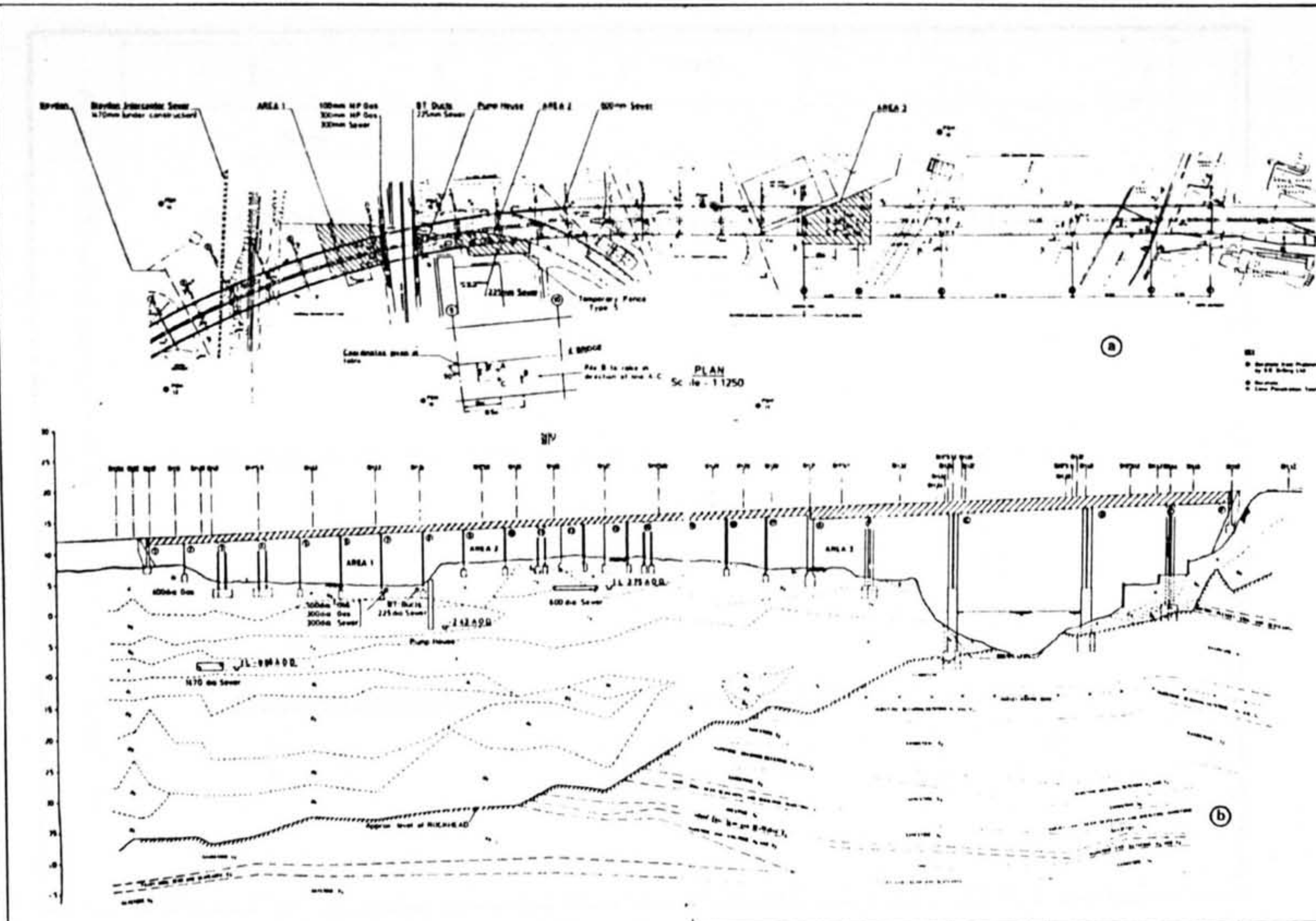


Figure (5.8) A general view of the construction site at Blaydon, *a.Plan view* *b.Cross—section view*

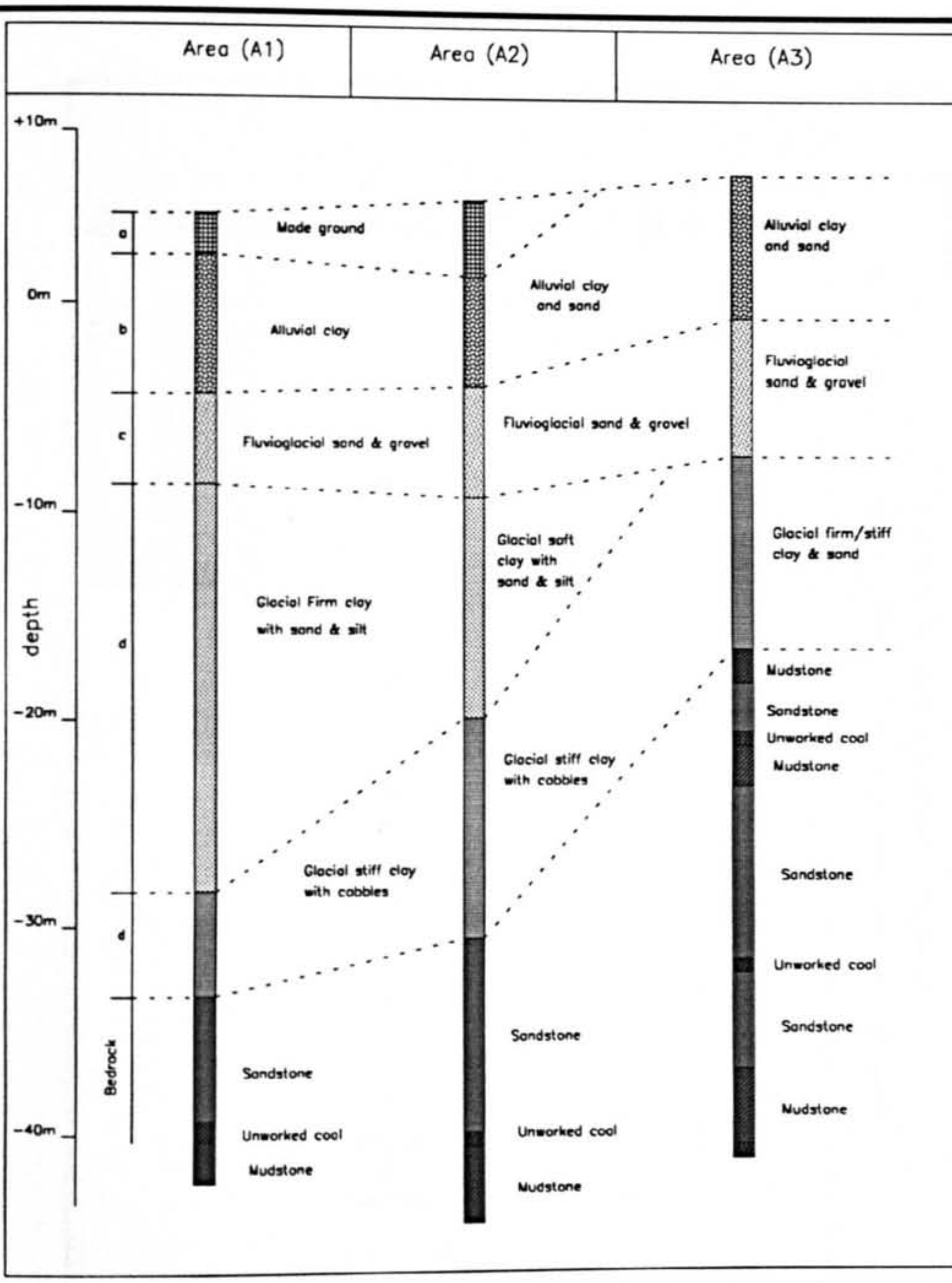


Figure (5.9) Simplified ground conditions of different area of Blaydon site

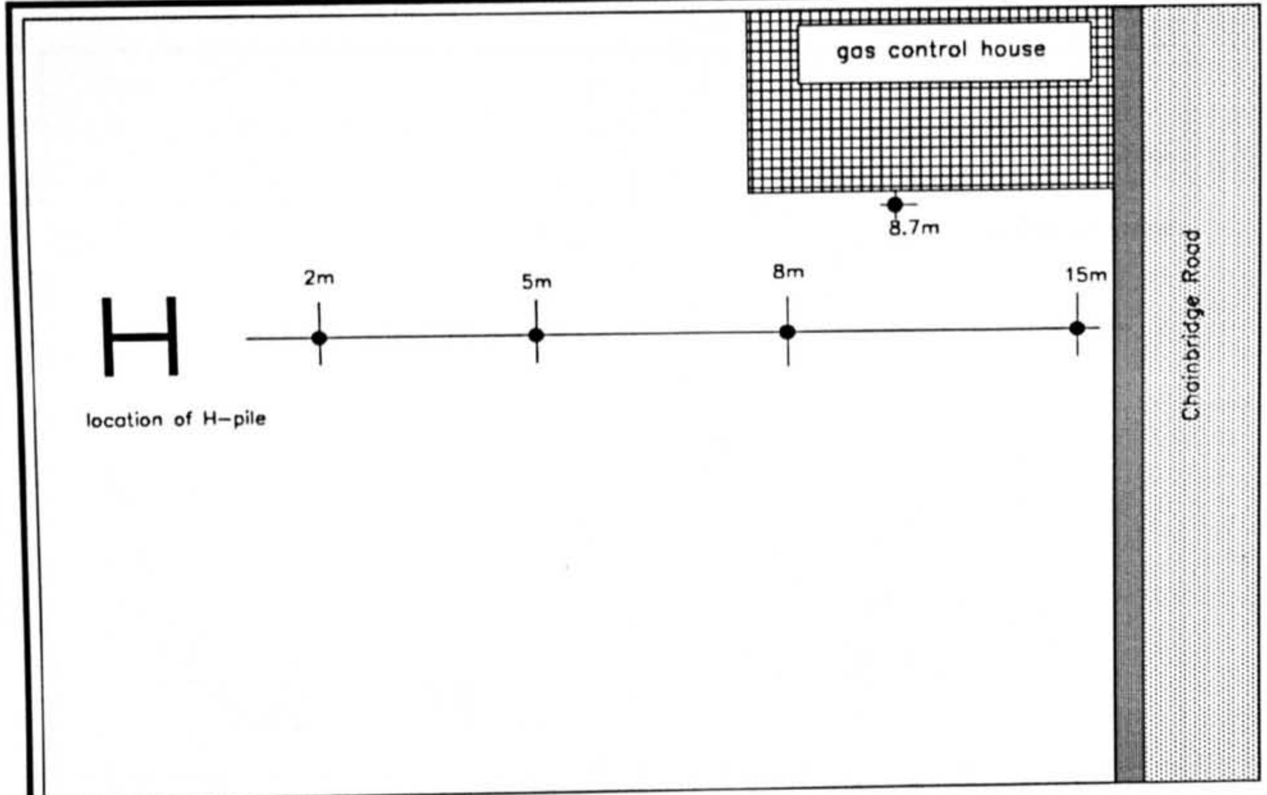


Figure (5.10) A plan view of a site in Blaydon, area(A1), contract(one)
the site was visited on 25.09.1986, file-names(TYN)

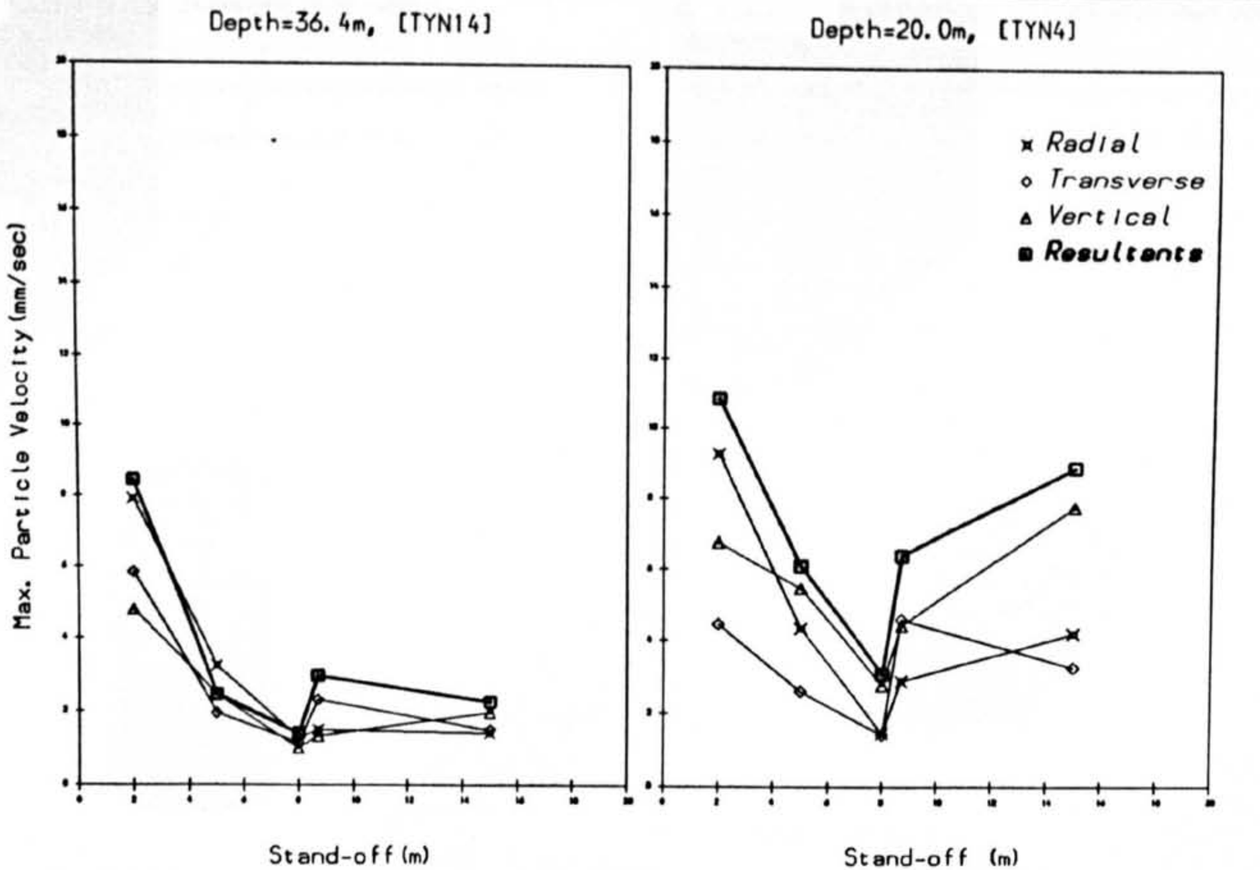


Figure (5.11) Attenuation of Vibration with distance

Blaydon (contract one), H-pile, Diesel-hammer, Different toe-depths

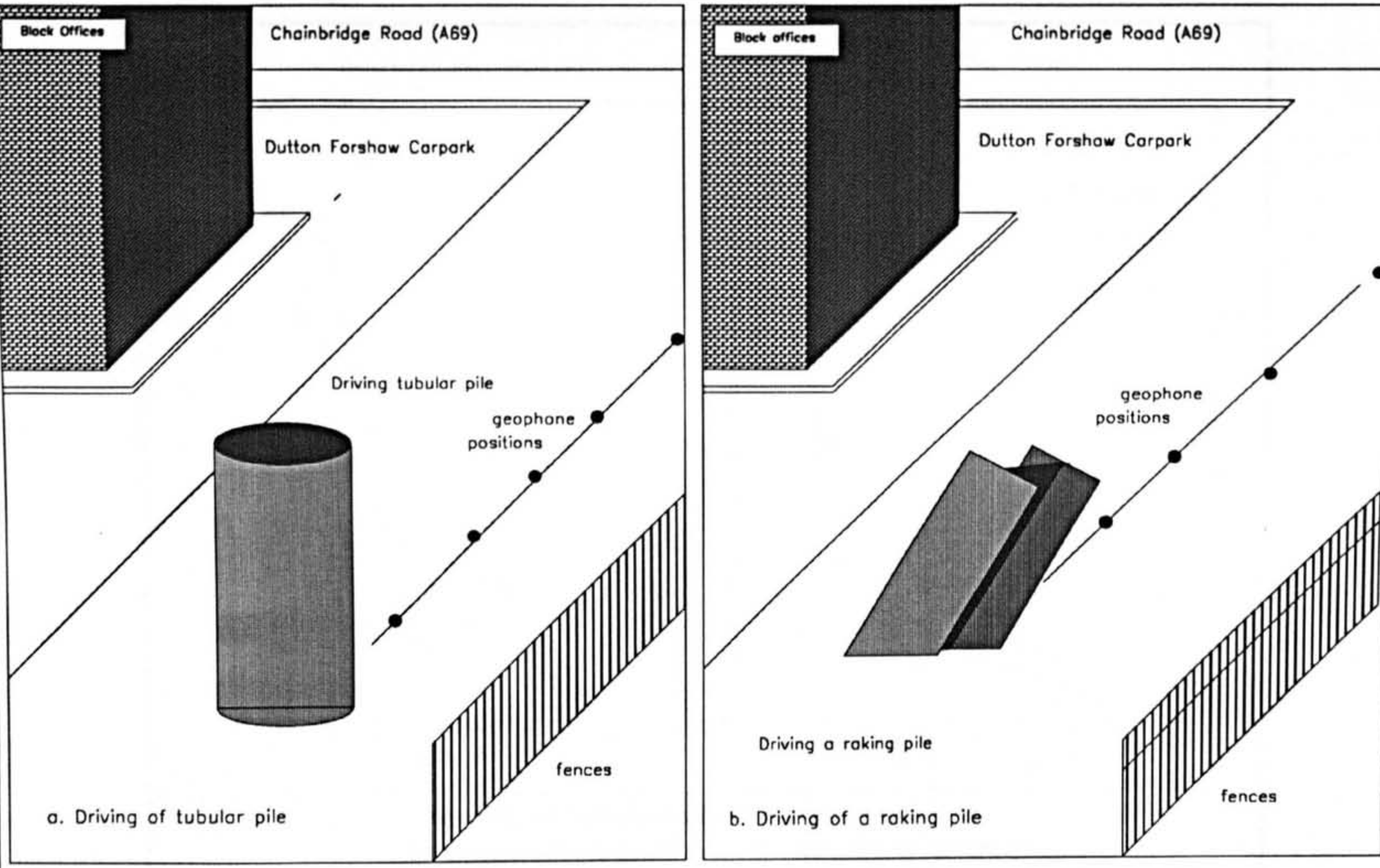


Figure (5.12) Location of pile driving from the block offices in Blaydon

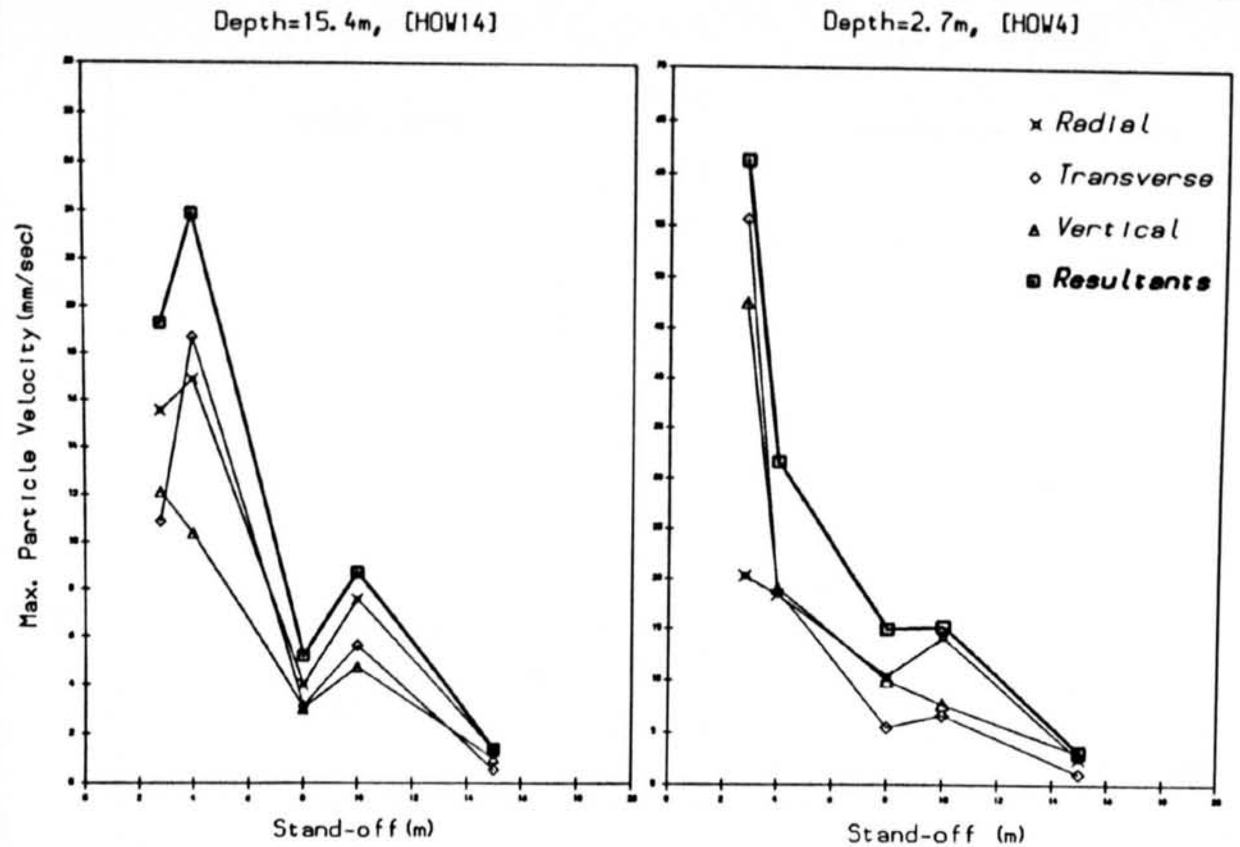


Figure (5.13) Attenuation of Vibration with distance

Blaydon (contract one), Vibrodriver, Tubular-pile, Different toe-depths

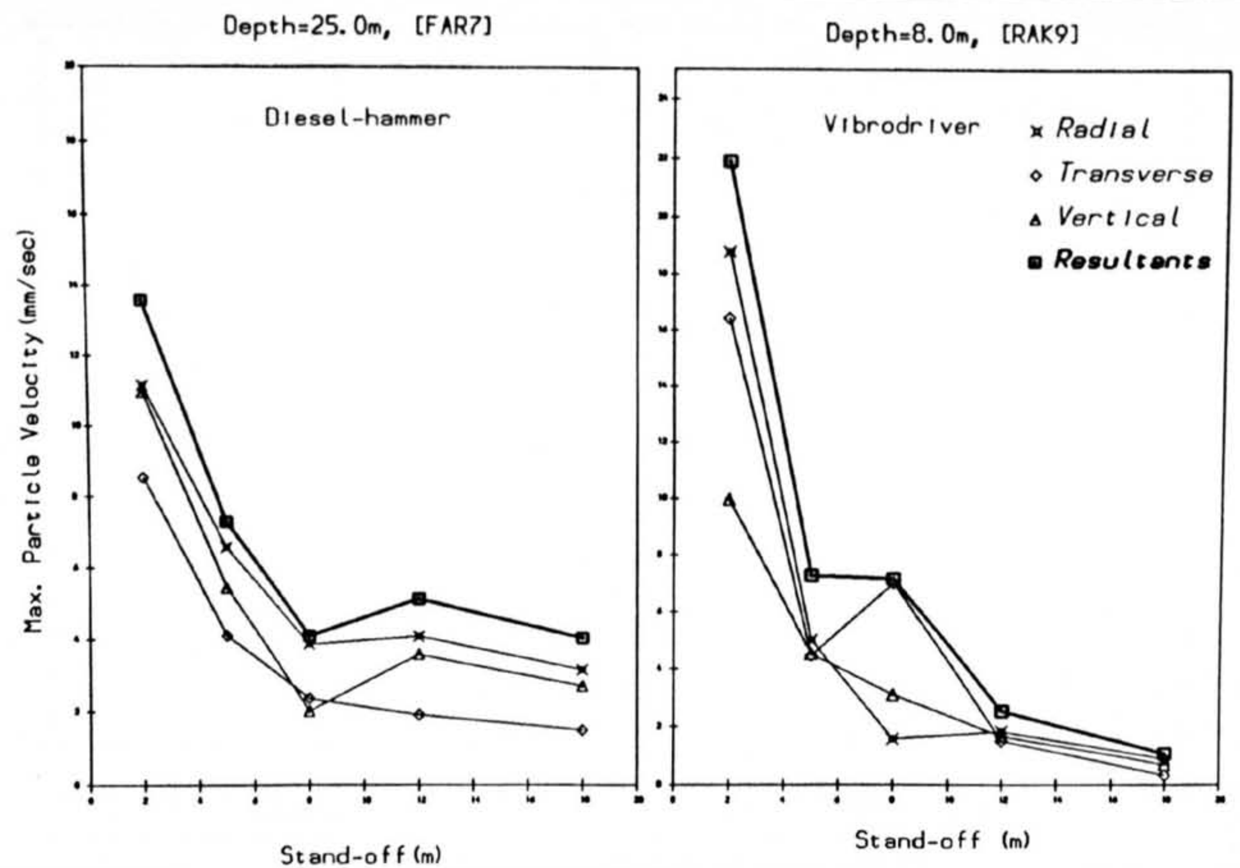


Figure (5.14) Attenuation of Vibration with distance

Blaydon (contract one), Raked H-pile, Different driving hammers

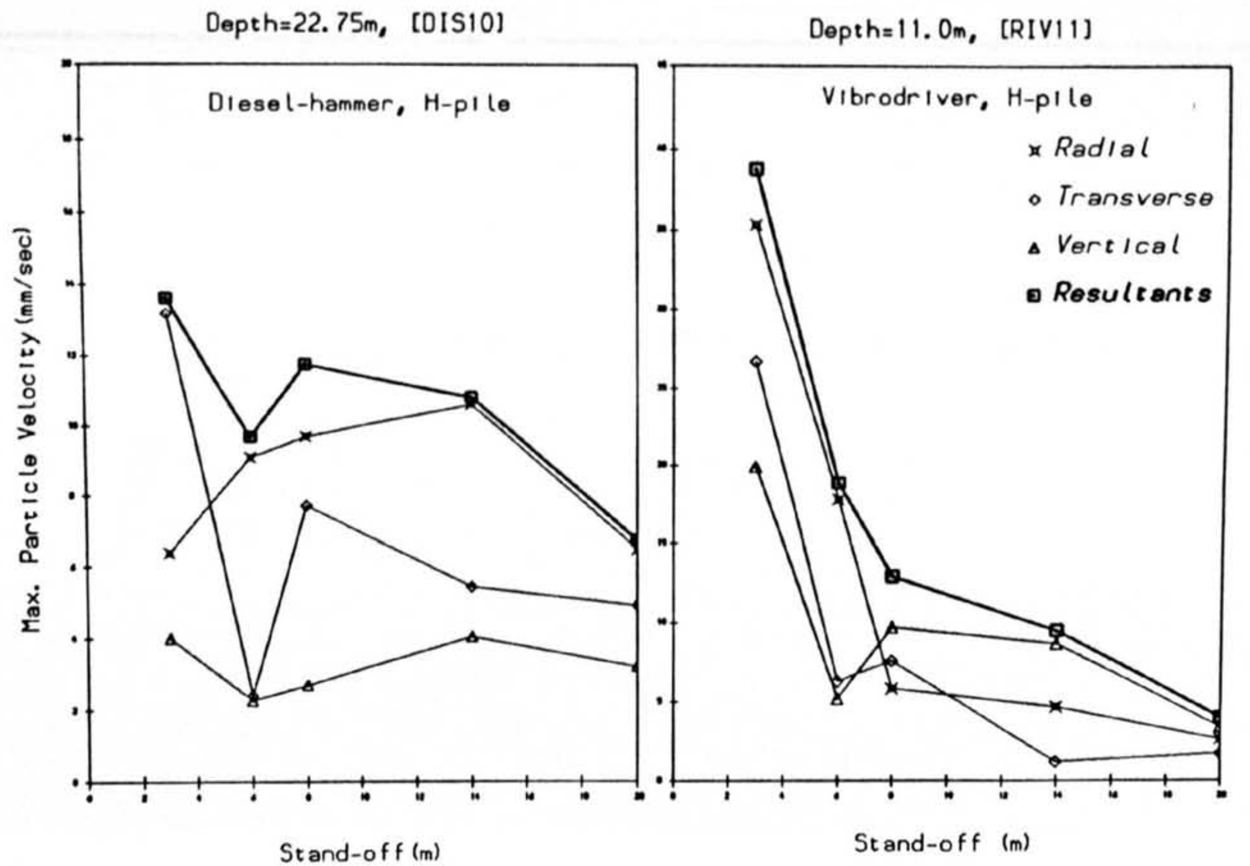


Figure (5.15) Attenuation of Vibration with distance

Blaydon (contract one), H-pile, Different hammers, Different toe-depths

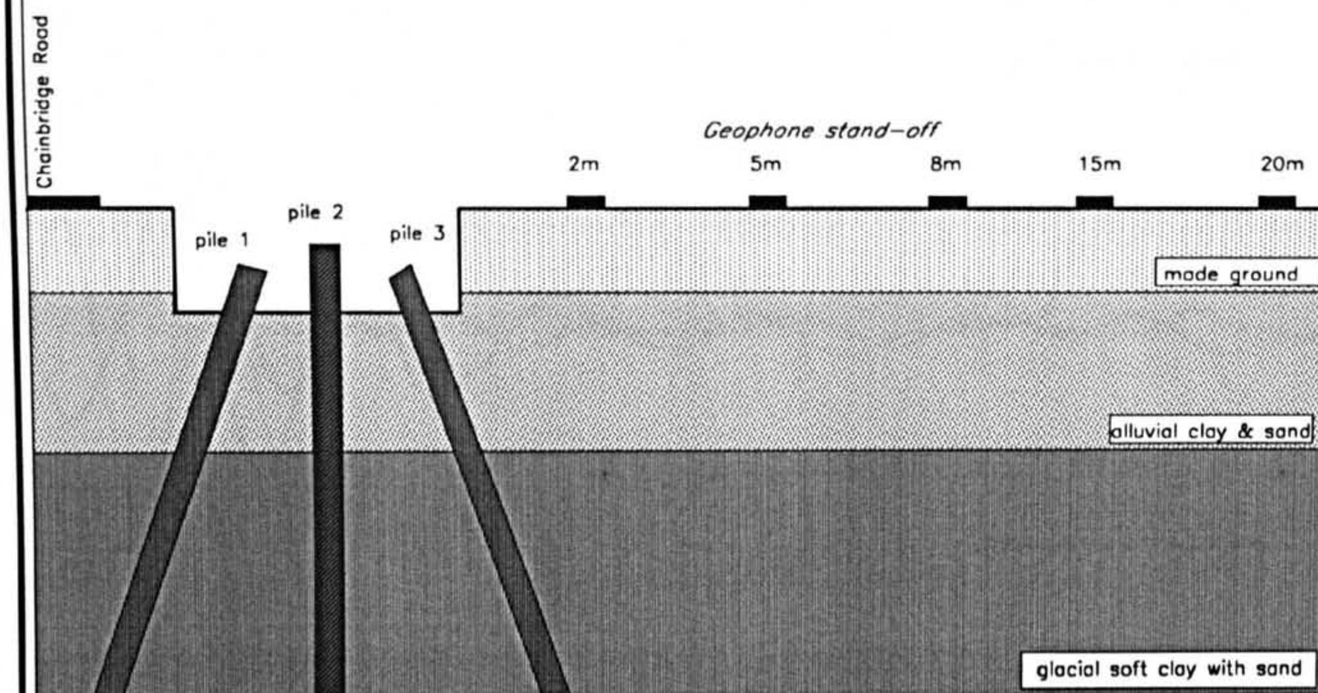


Figure (5.16) Layout of a site visit to Blaydon on 24.05.1988
during driving H-pile by a vibrodriver

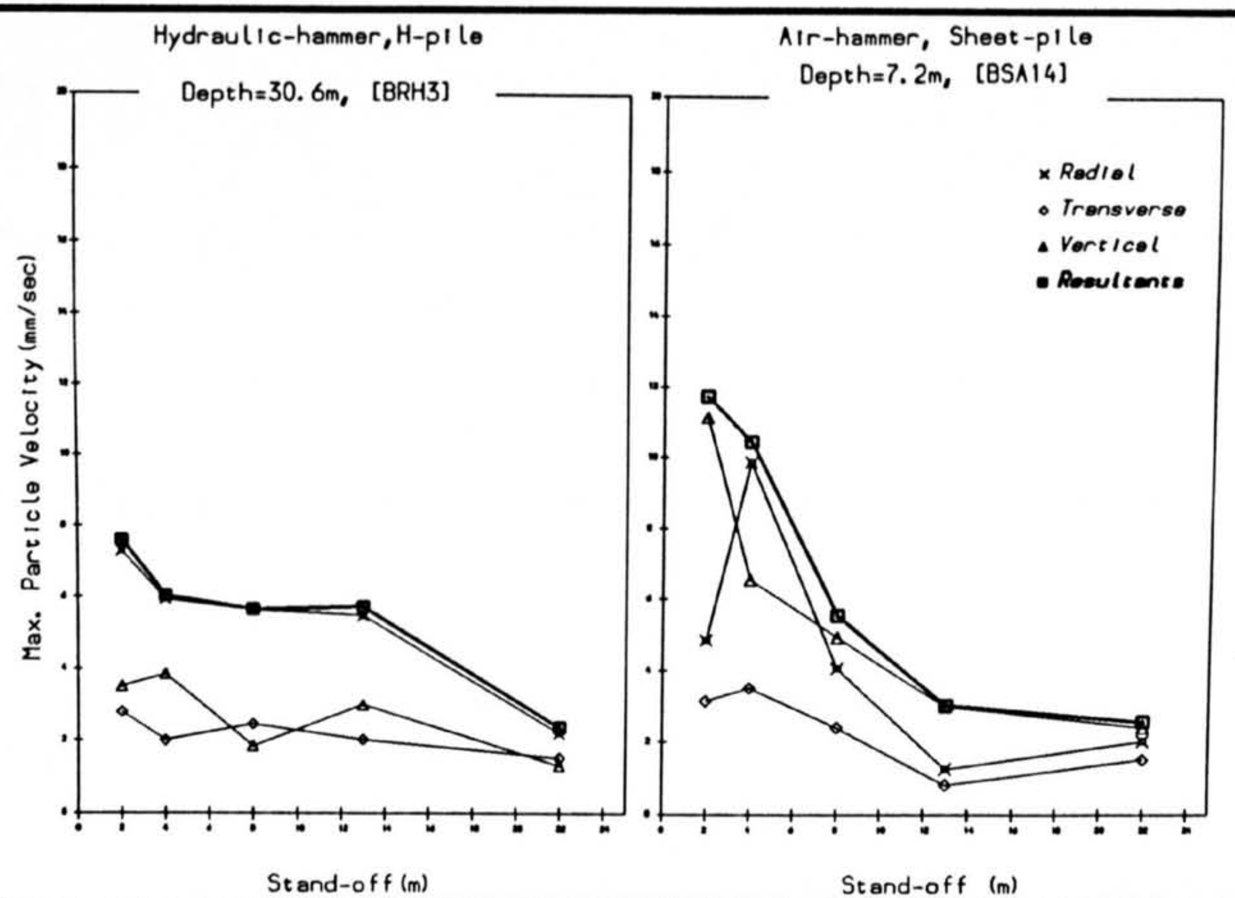


Figure (5.20) Attenuation of Vibration with distance

Blaydon (contract two), H-pile, Different hammers, Different toe-depths

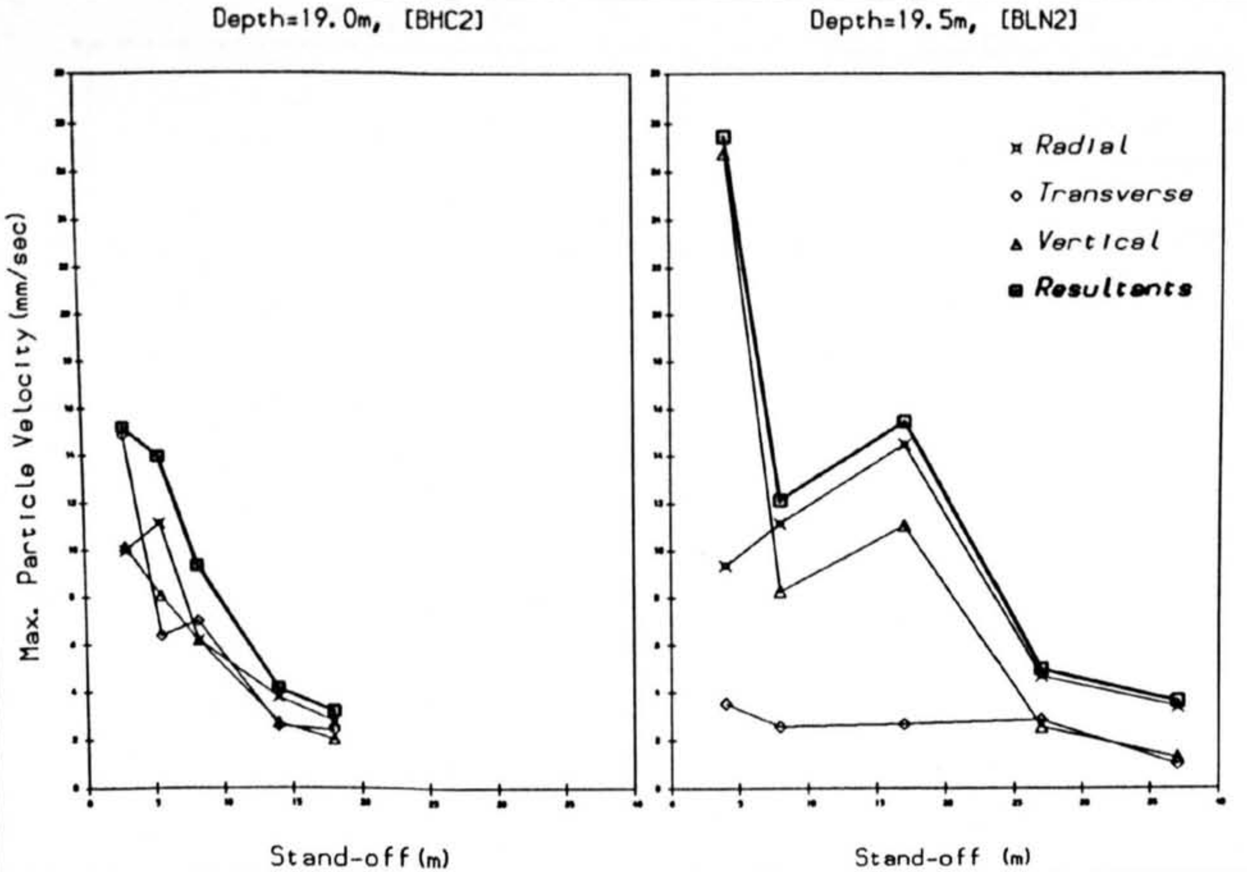


Figure (5.28) Attenuation of Vibration with distance

Blaydon (contract two), H-pile, Hydraulic-hammer, Different sites

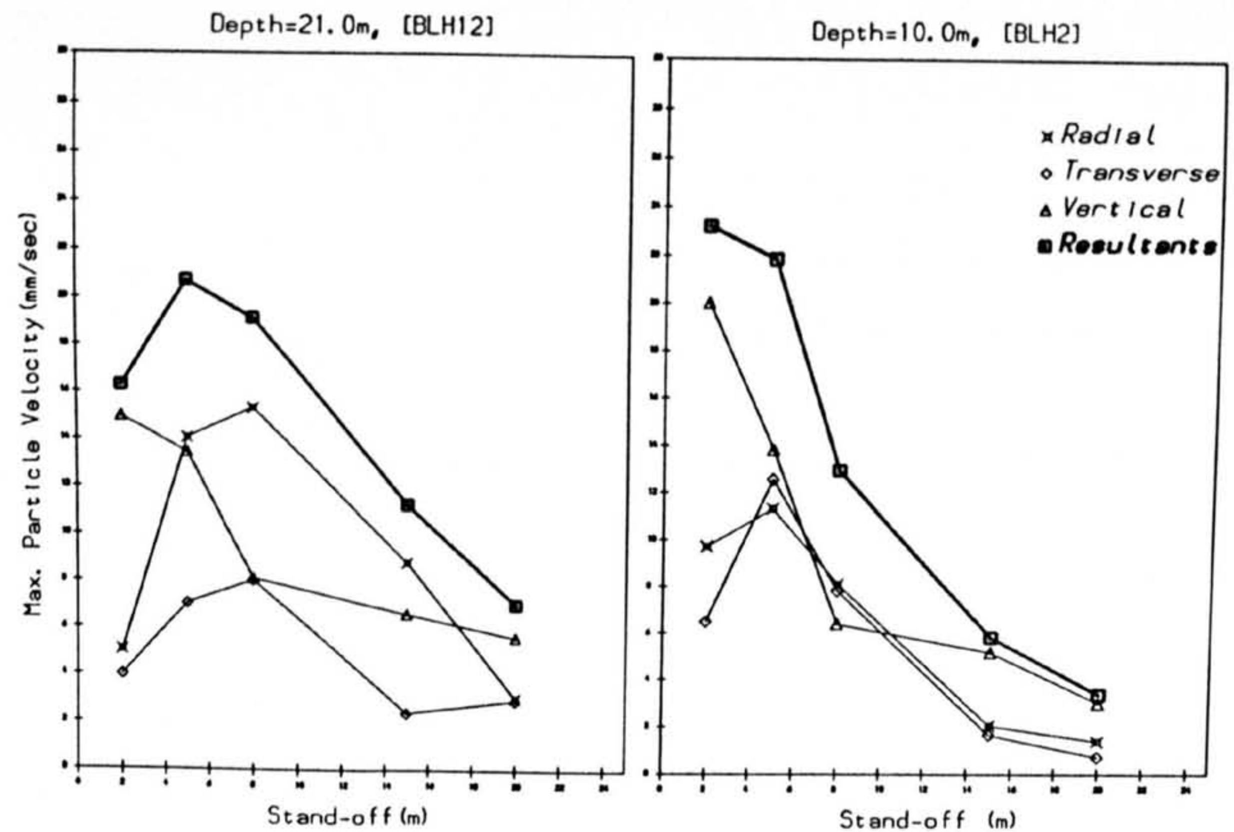


Figure (5.29) Attenuation of Vibration with distance

Blaydon (contract two), H-pile, Hydraulic-hammer, Different toe-depths

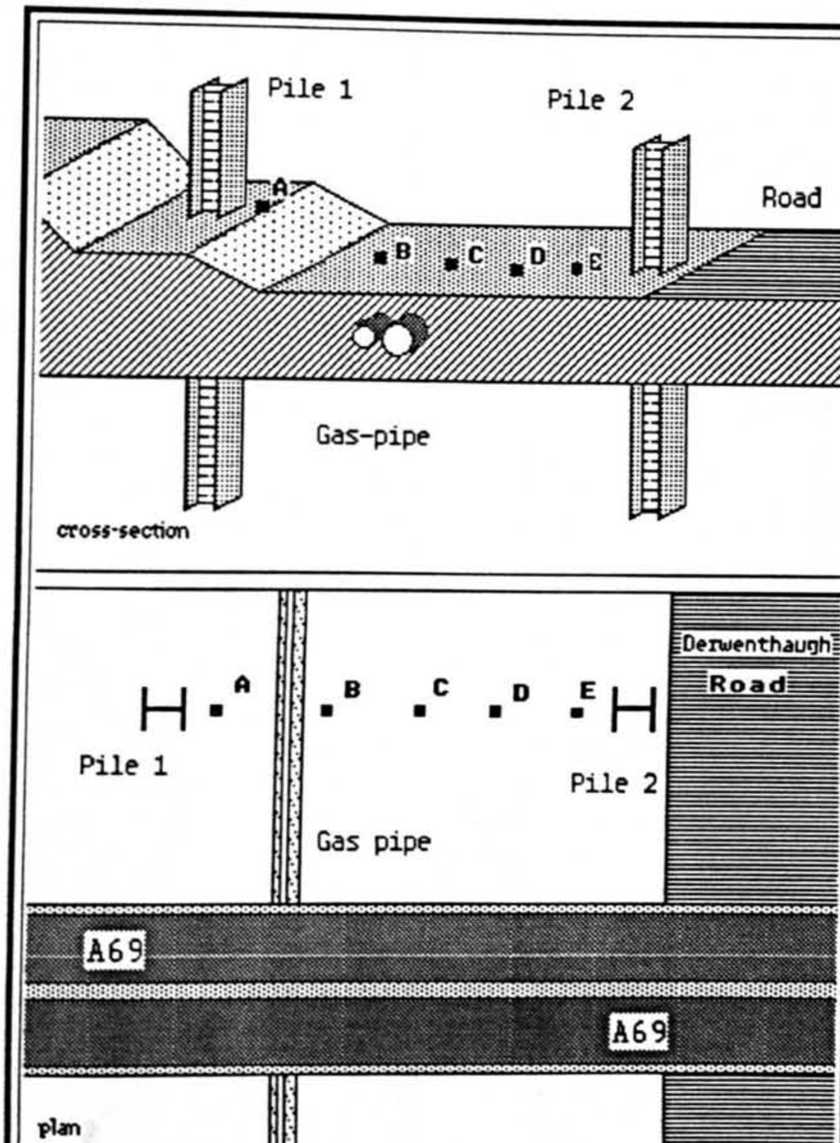


Figure (5.32) Schematic layout of pile driving site in Blaydon during trial driving of H-pile, contract three

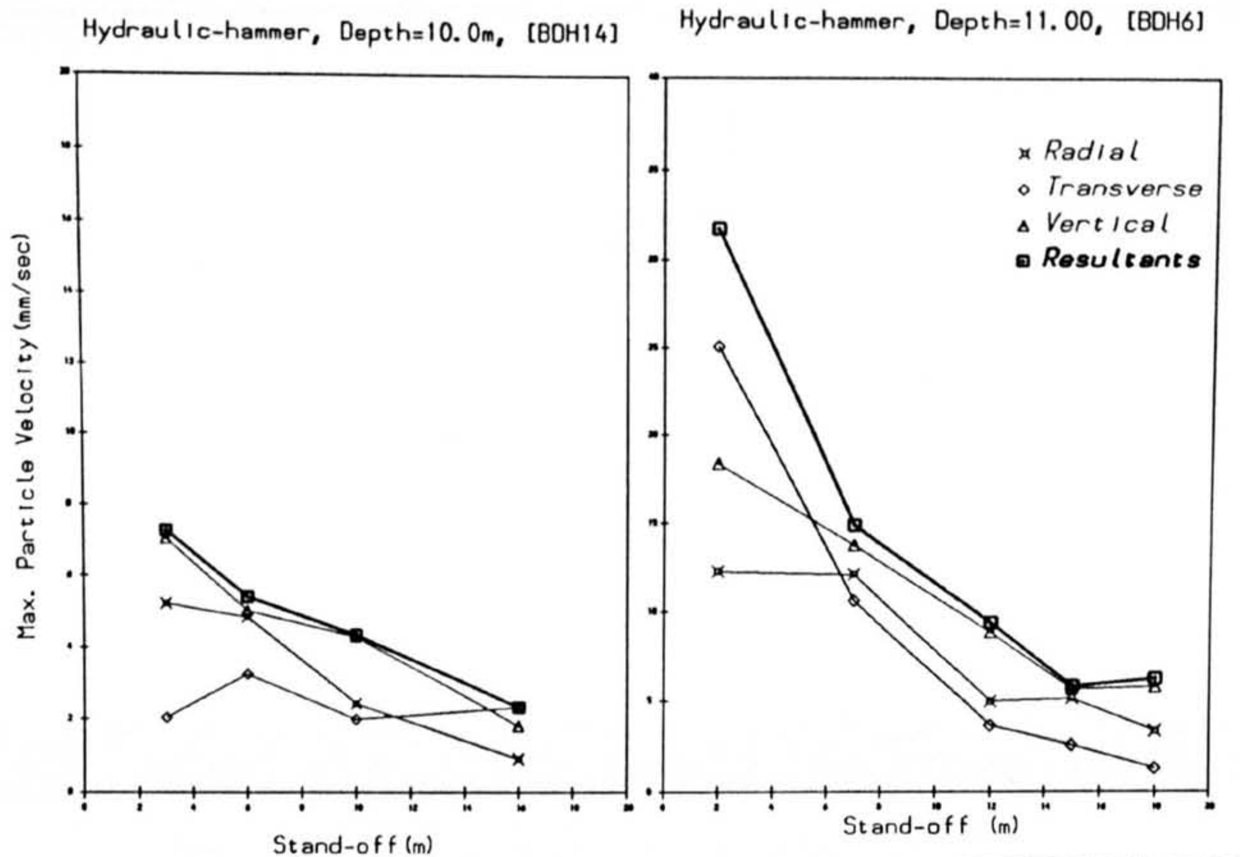


Figure (5.35) Attenuation of Vibration with distance

Blaydon (contract three), H-pile, Hydraulic-hammer, Different piles

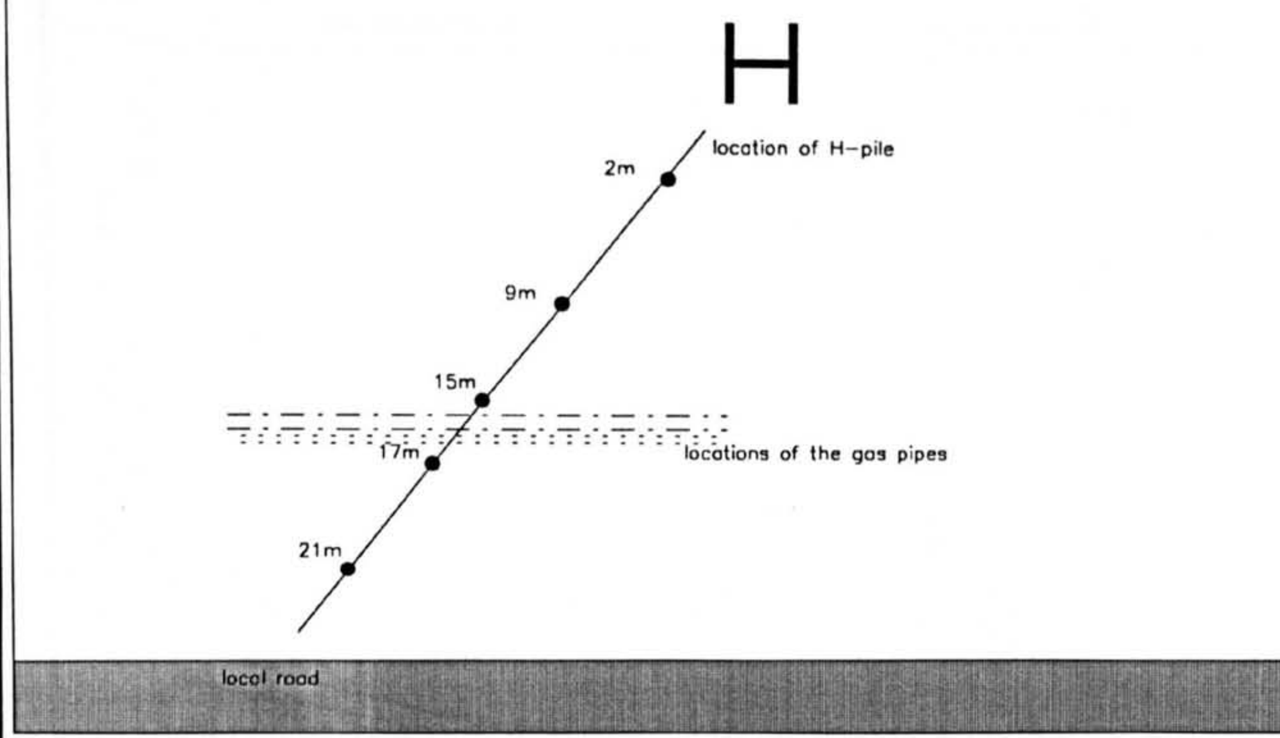


Figure (5.36) Layout of a site visit to Blaydon related to files (GHH) during driving H-pile by a hydraulic-hammer on 21.03.1989

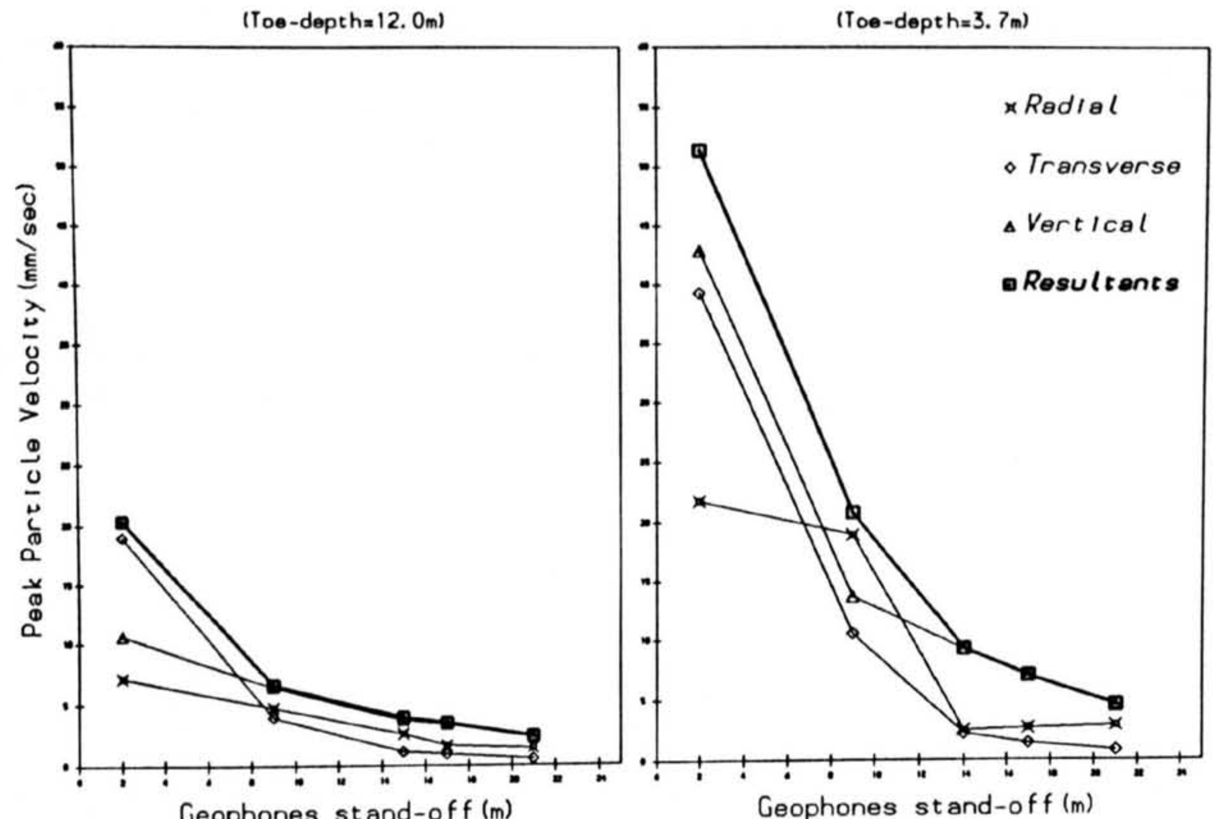


Figure (5.37) Attenuation of Vibration with distance

Blaydon (contract three), H-pile, Hydraulic-hammer, Different toe-depths

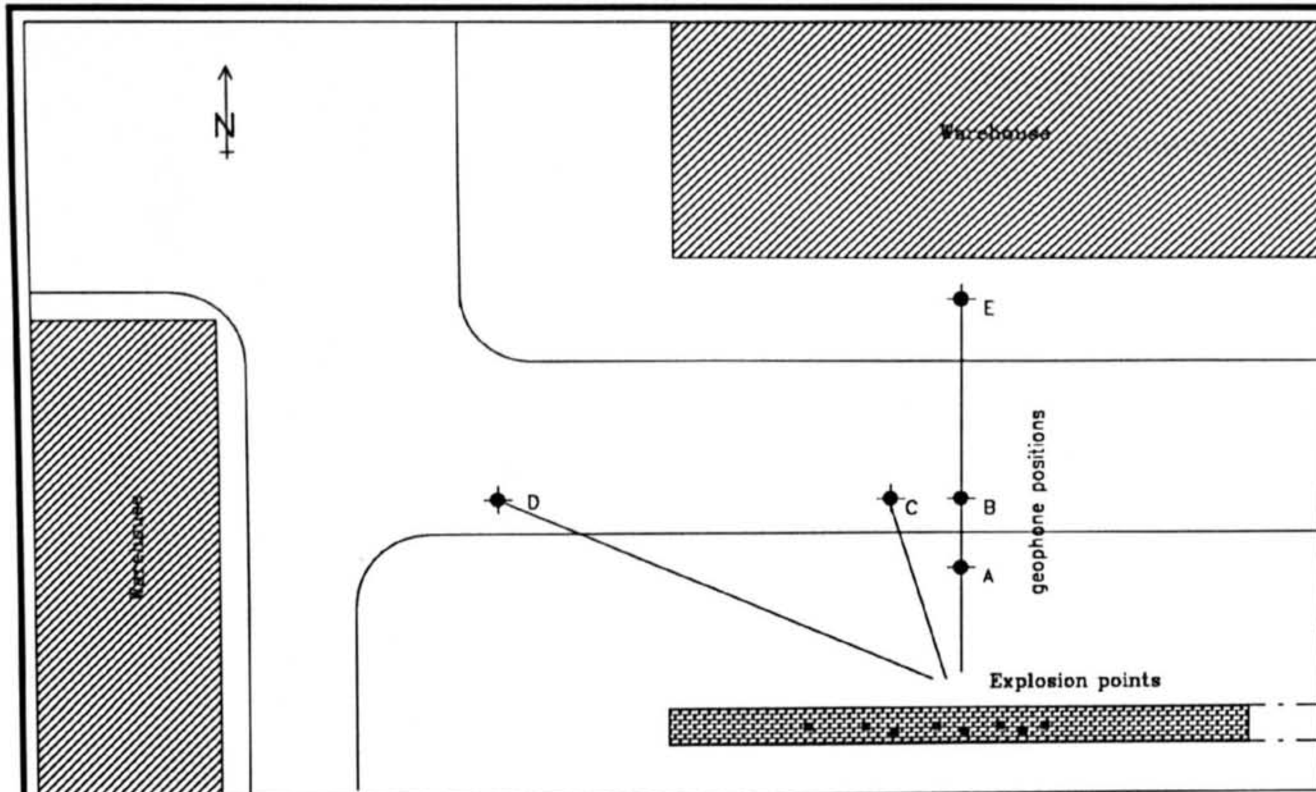


Figure (5.40) Layout of a site visit to Darlington
during blasting operation on 22.03.1989

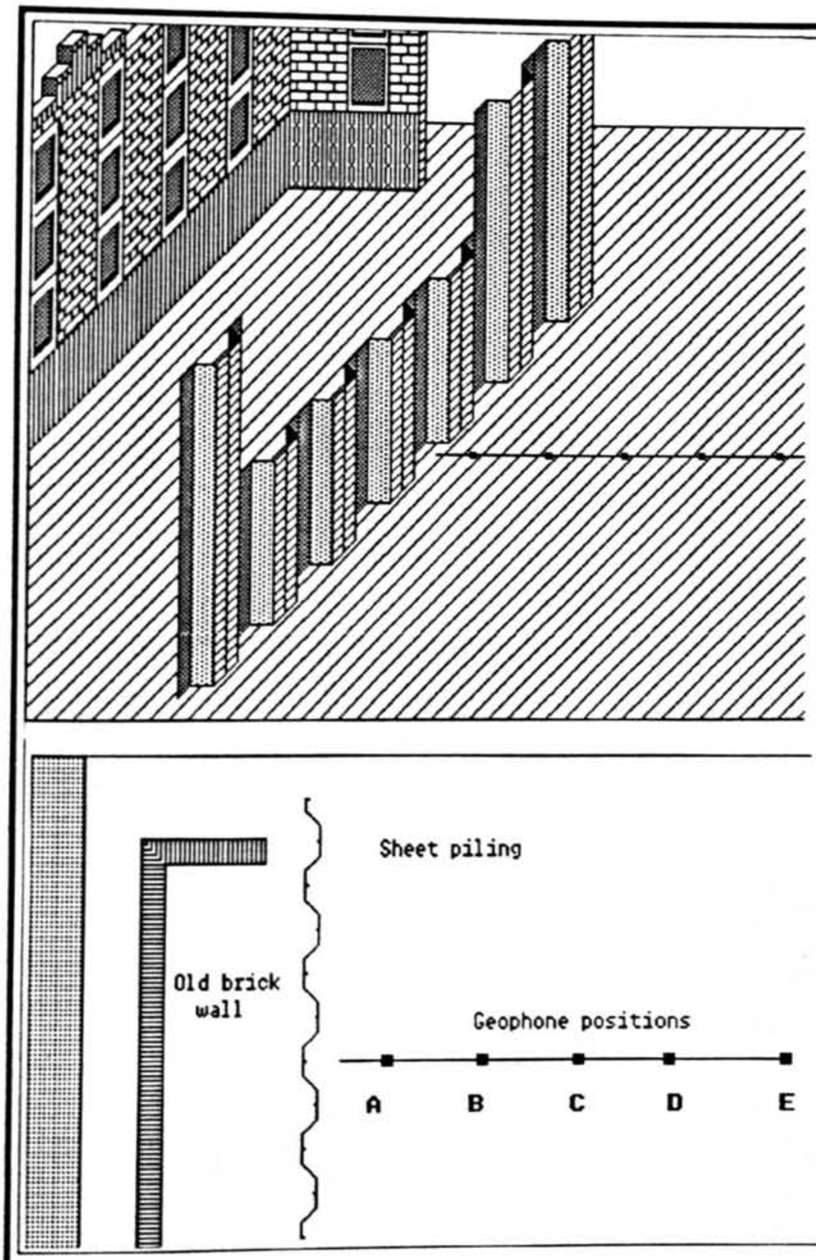


Figure (5.42) Schematic layout of pile driving site in Edinburgh during driving sheet piles using hydraulic-hammer

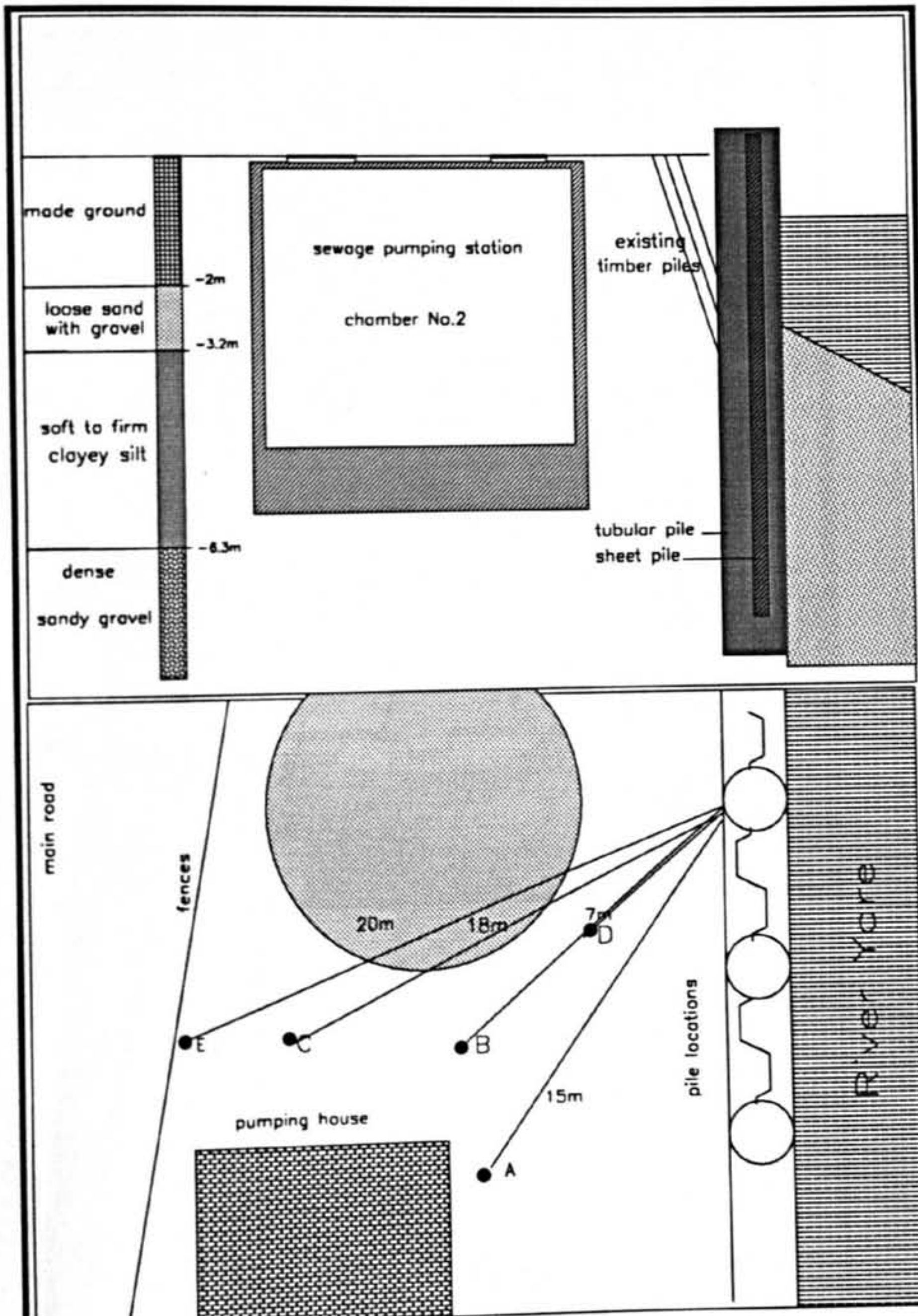
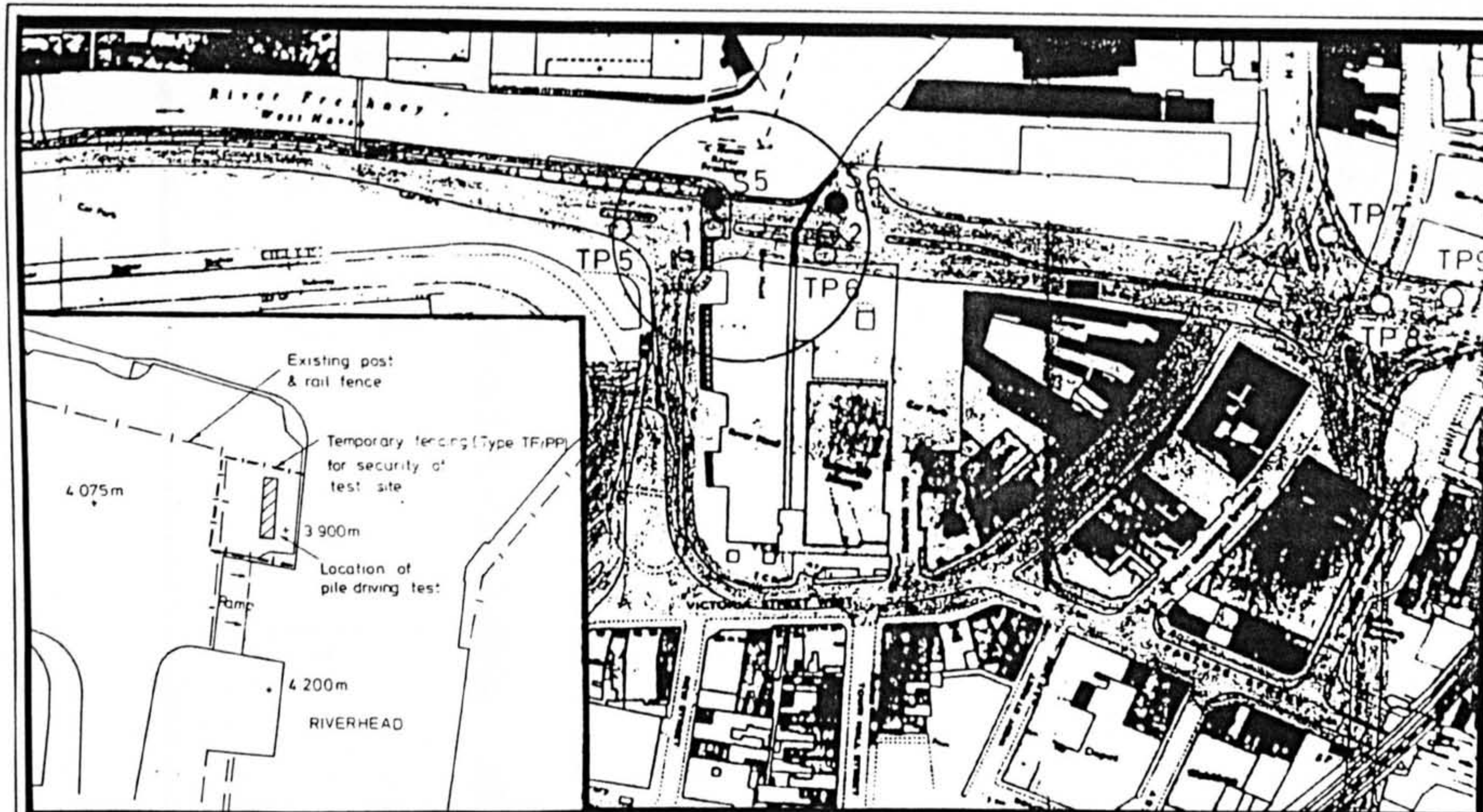
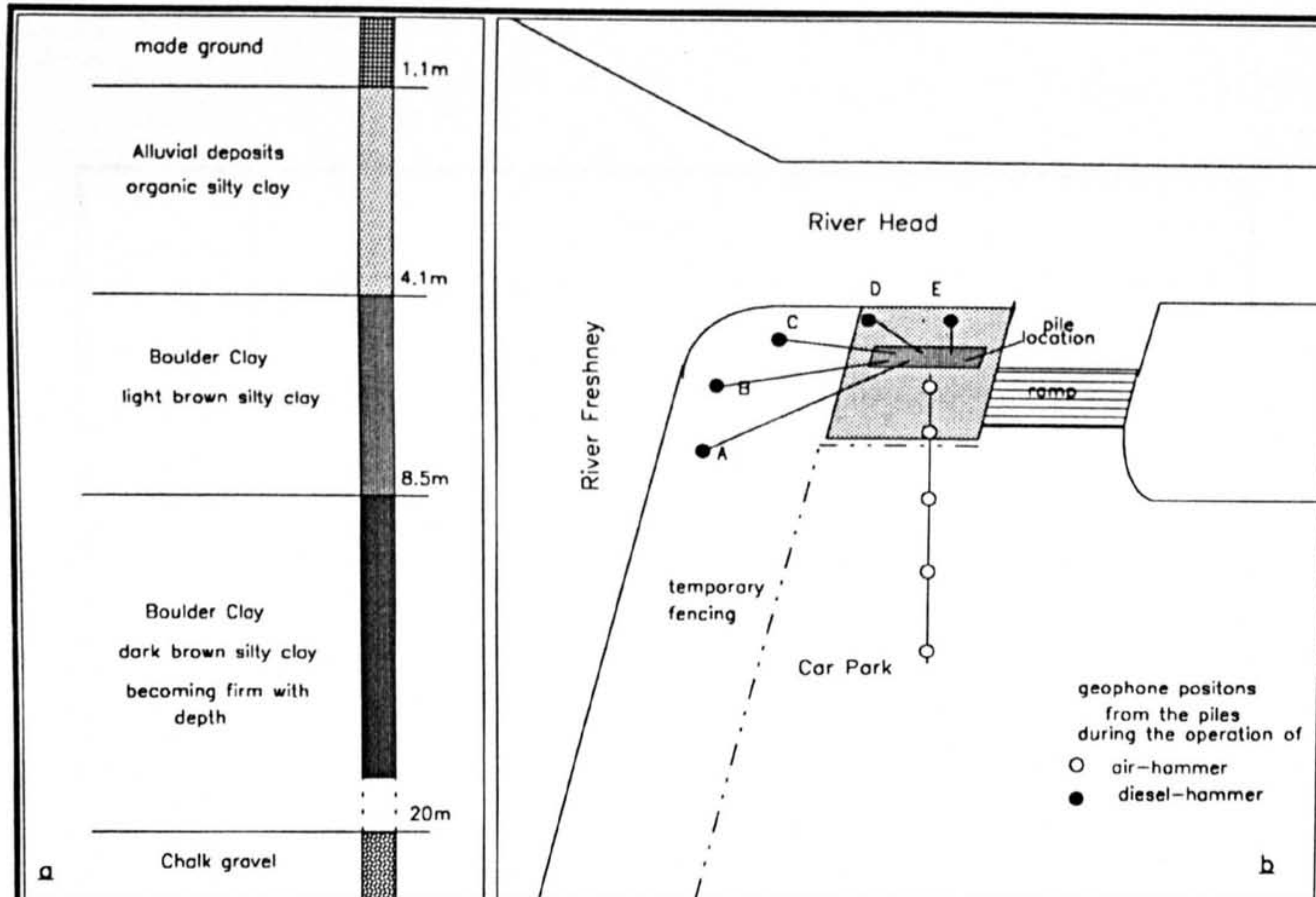


Figure (5.43) A schematic layout of Great Yarmouth site
visited on 03.02.1989



Figure(5.44) The location of the construction site in Grimsby



a. simplified ground conditions coloumn

b. layout of the site during trial piling

Figure (5.45) Grimsby site

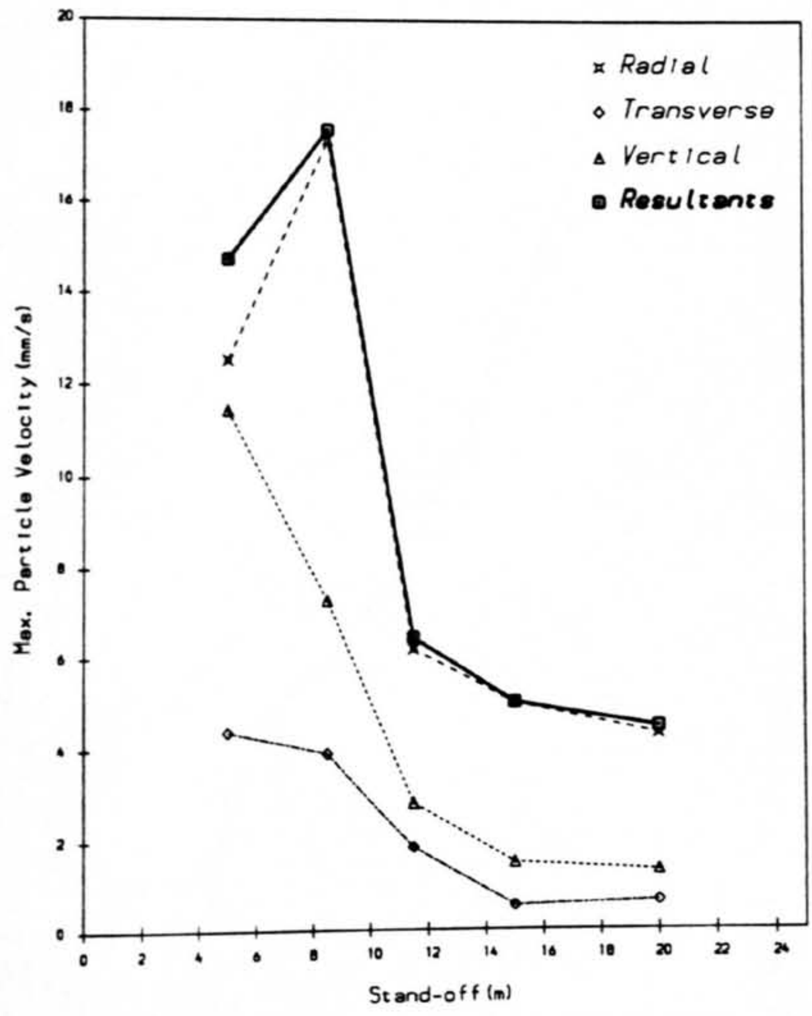
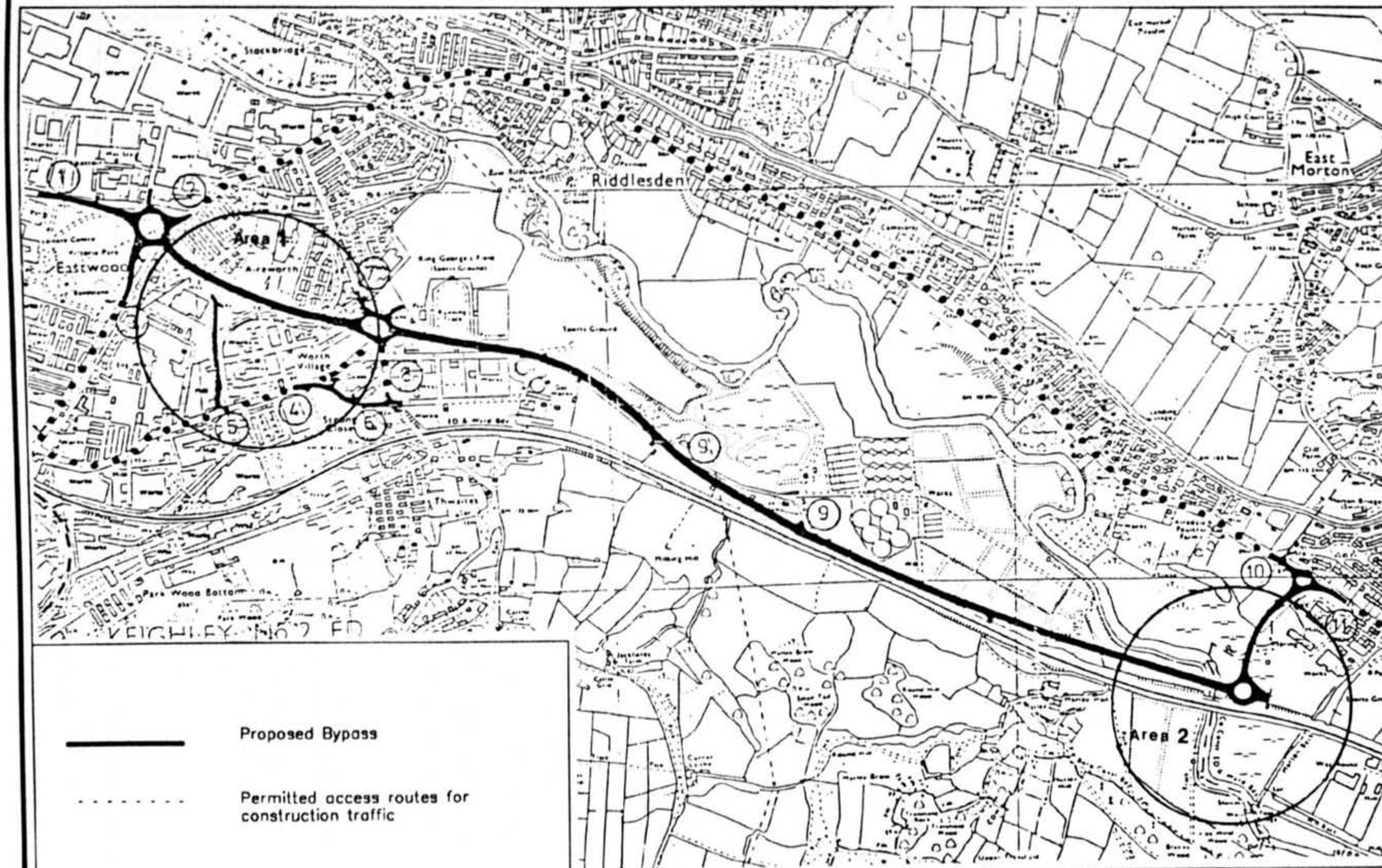


Figure (5.46) Attenuation of vibration with distance

Grimsby, Diesel-hammer(BSP-B15), Sheet-pile

toe-depth=13.0m. file-name (GRS-2)



Figure(5.47) A general view of the construction site at Keighley

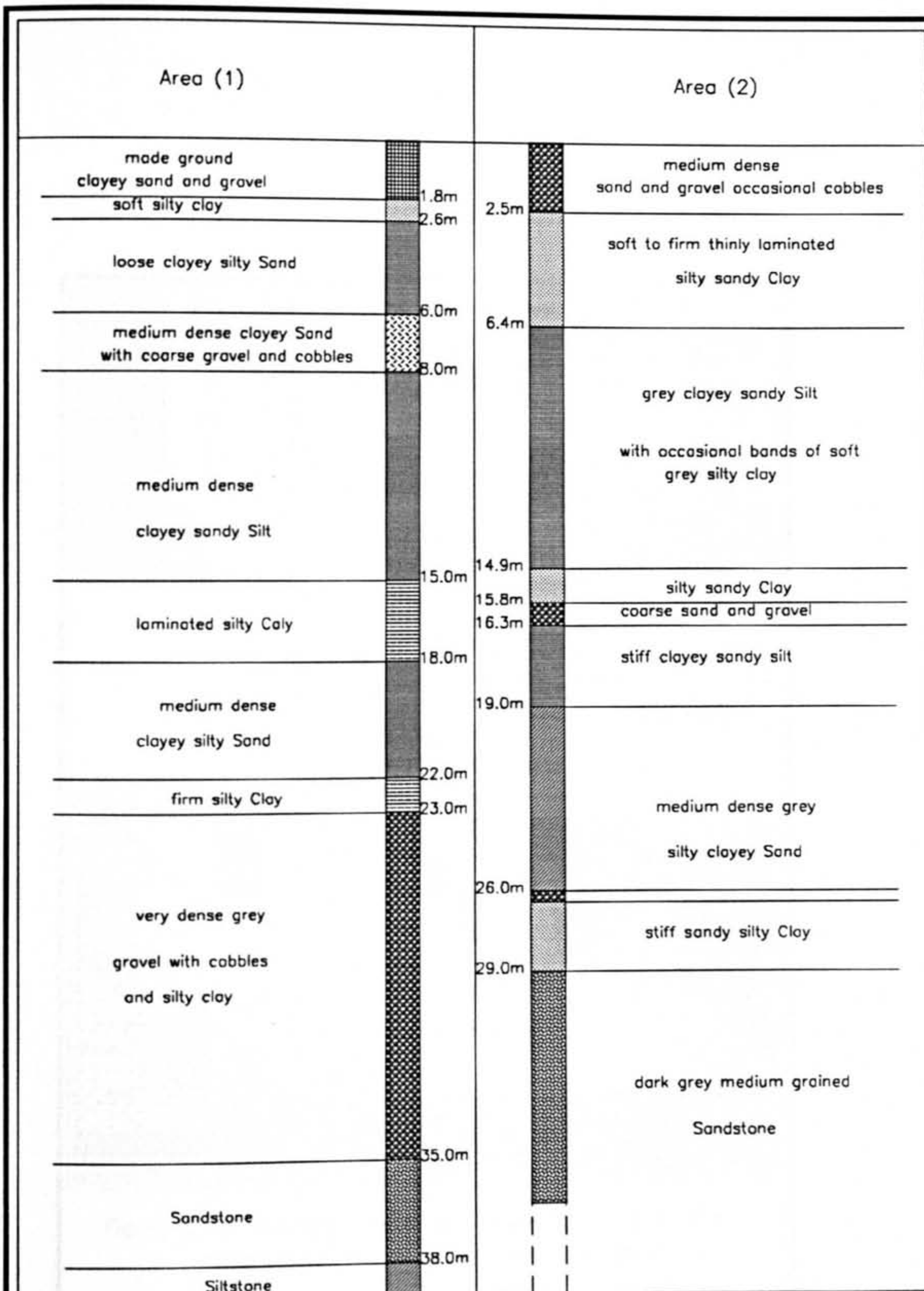


Figure (5.48) Simplified ground conditions of Keighley sites

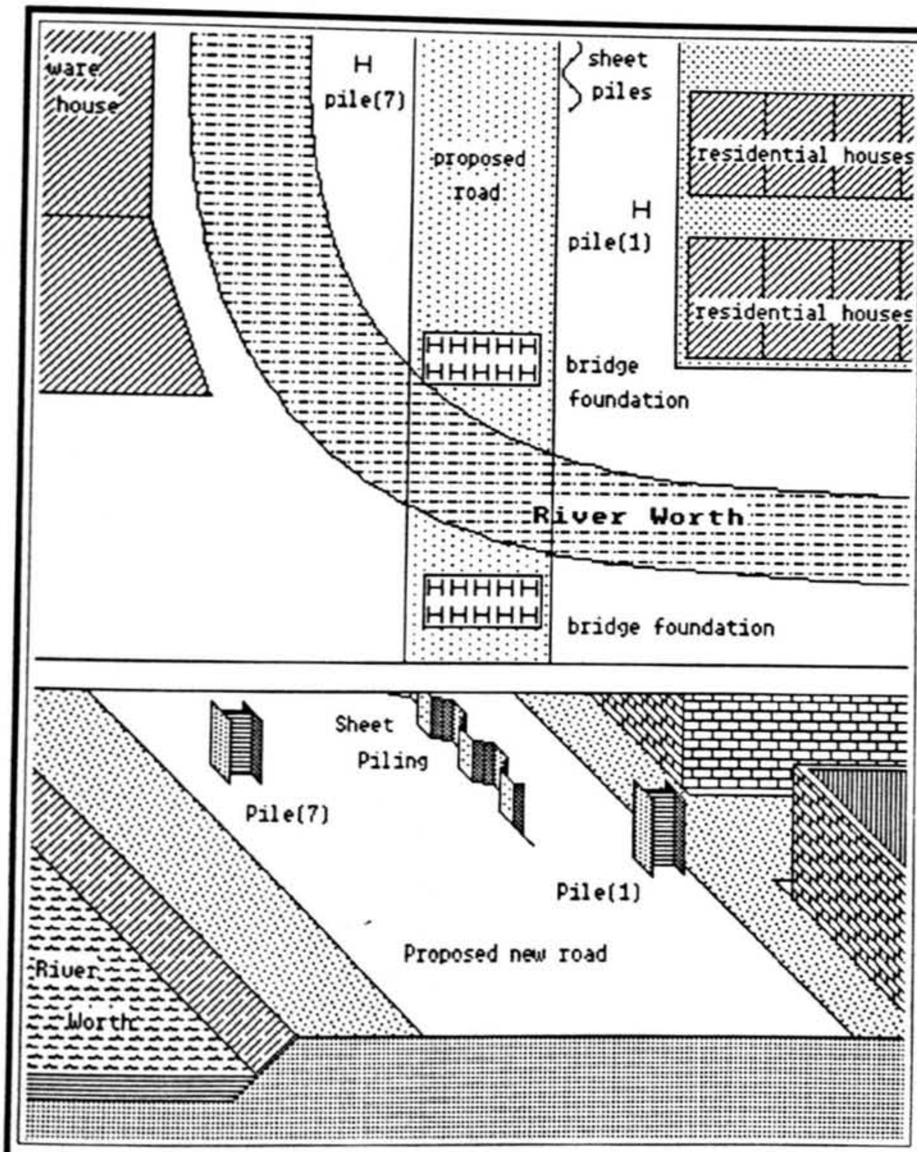


Figure (5.49) Schematic layout of pile driving site in Keighley during driving different piles in area-1, river Worth

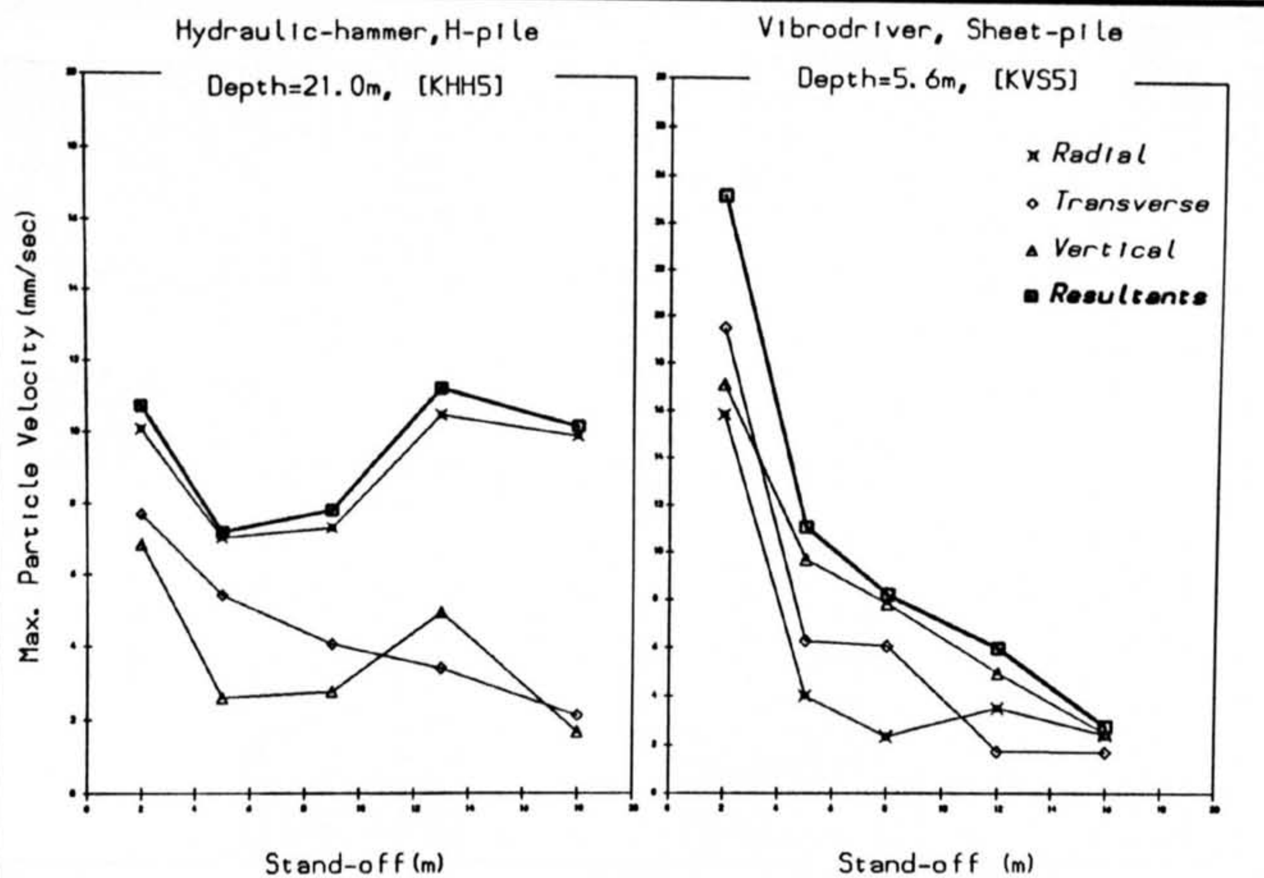


Figure (5.52) Attenuation of Vibration with distance

Keighley (River Worth), Different piles, Different hammers, Different toe-depths

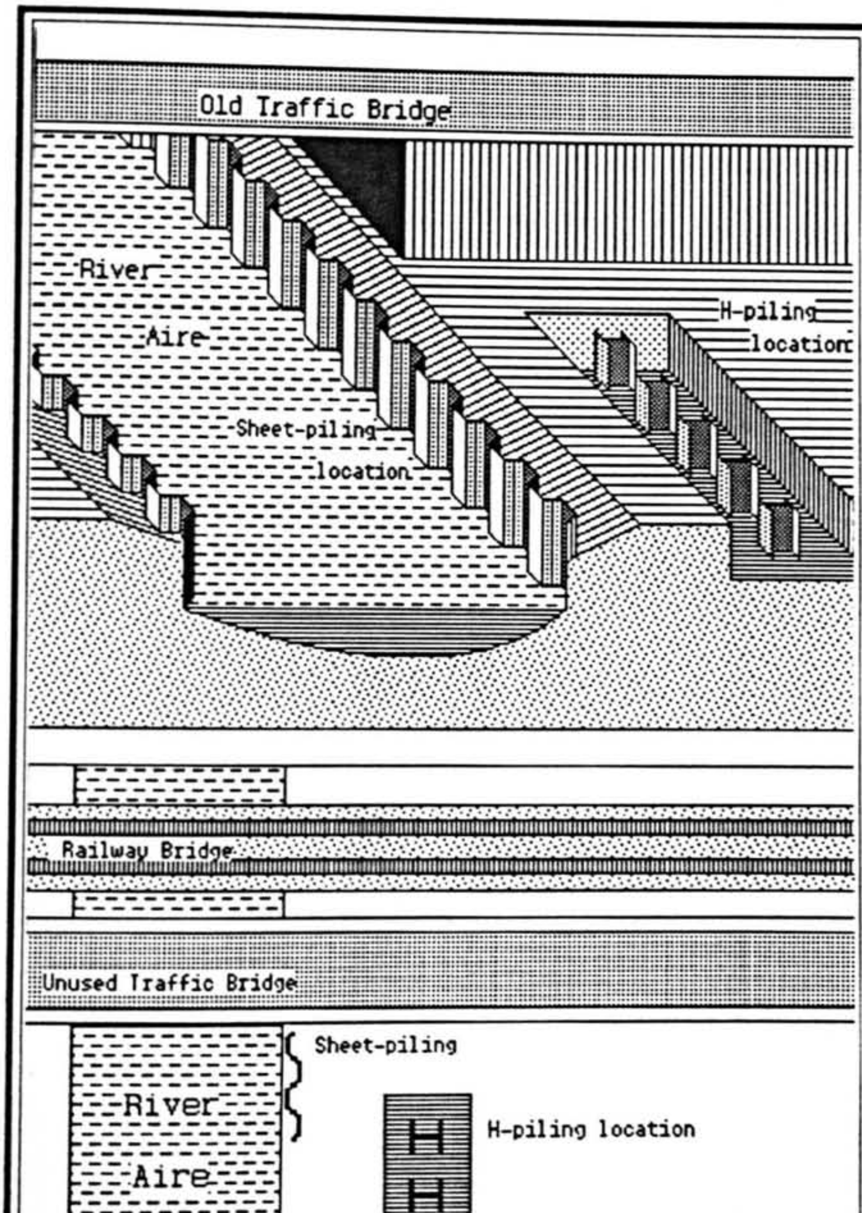


Figure (5.53) Schematic layout of pile driving site in Keighley during driving different piles in area-2, river Aire

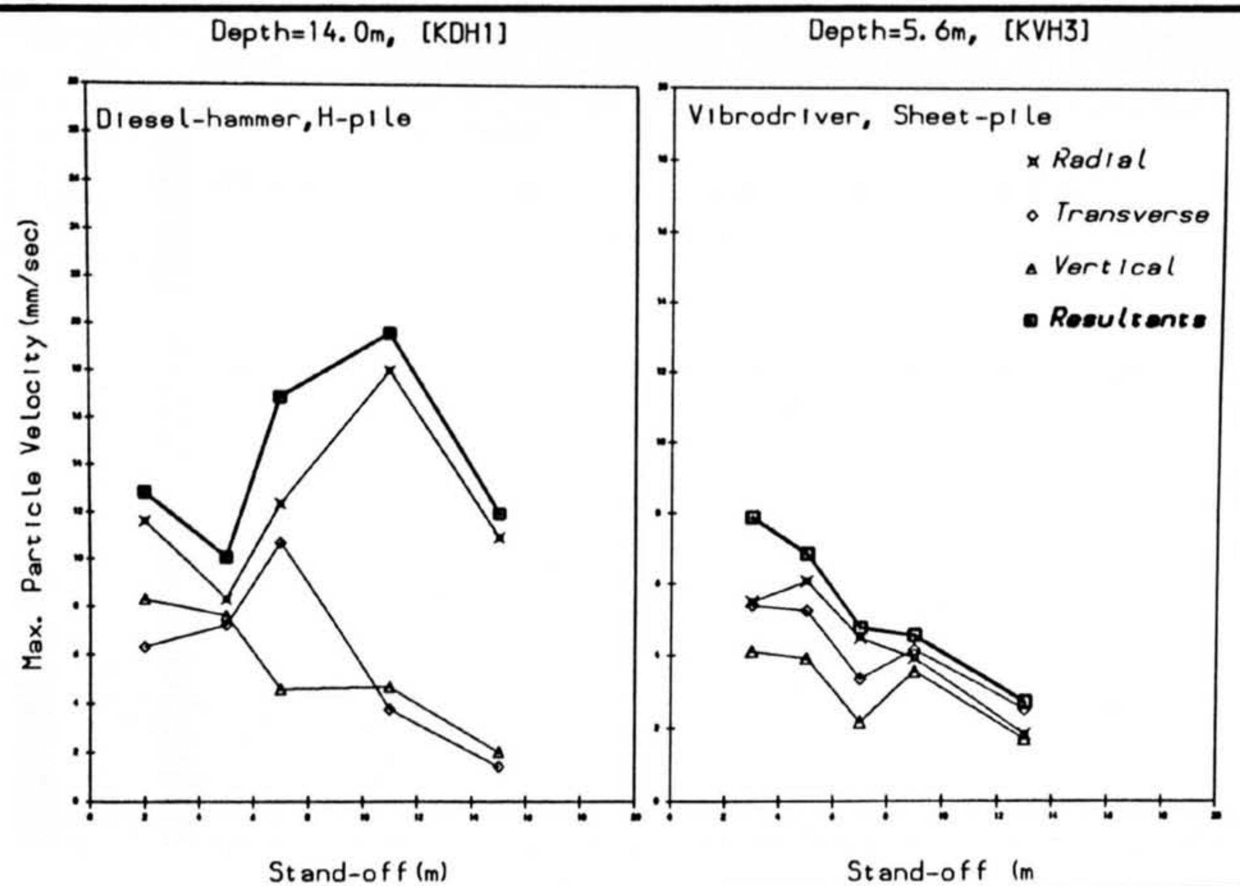


Figure (5.56) Attenuation of Vibration with distance

Keighley (River Aire), Different piles, Different hammers, Different toe-depths

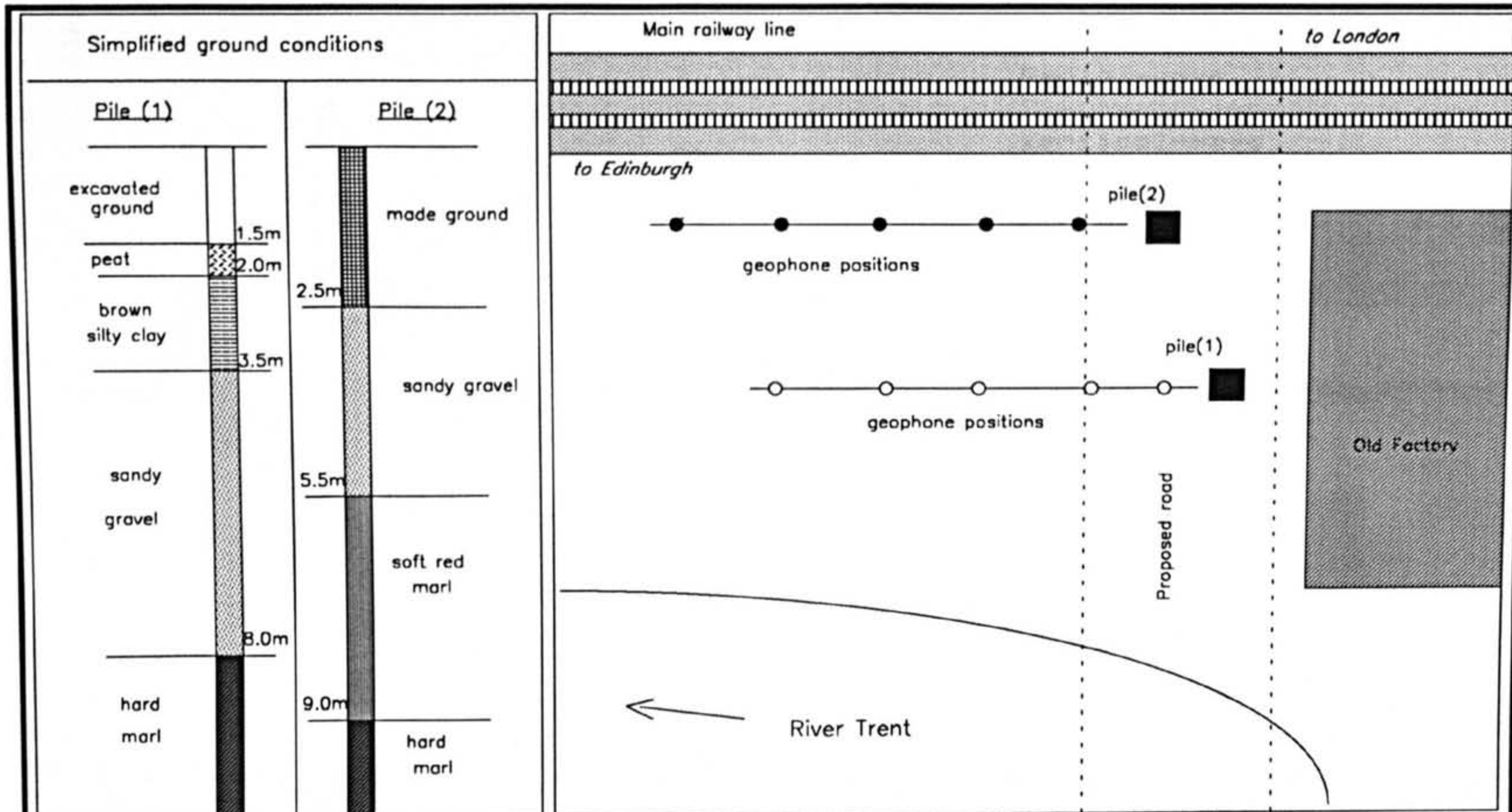


Figure (5.57) A schematic layout of the site (Newark on Trent)

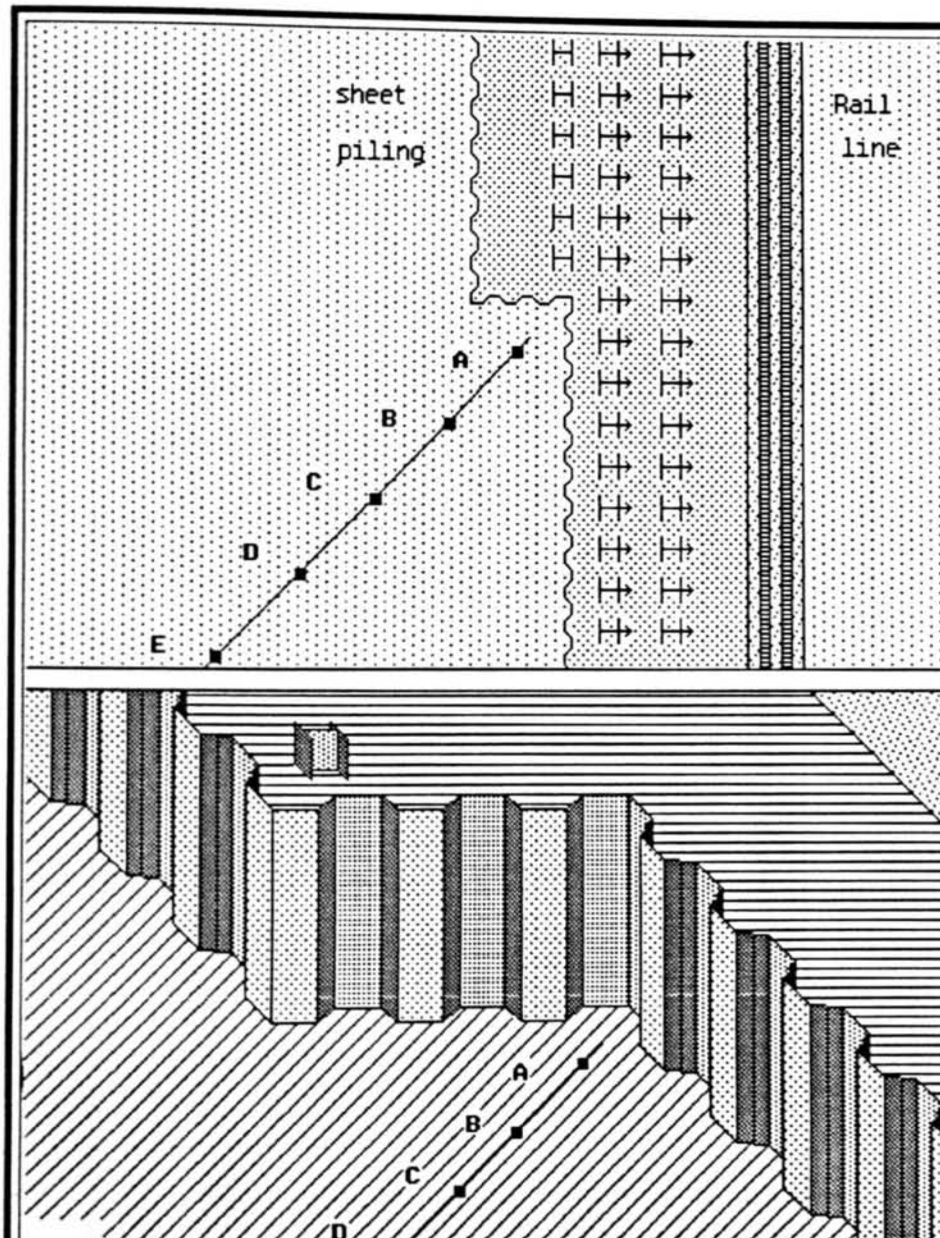


Figure (5.62) Schematic layout of pile driving site in Newark during driving sheet-piles by vibrodriver (PTC13HF)

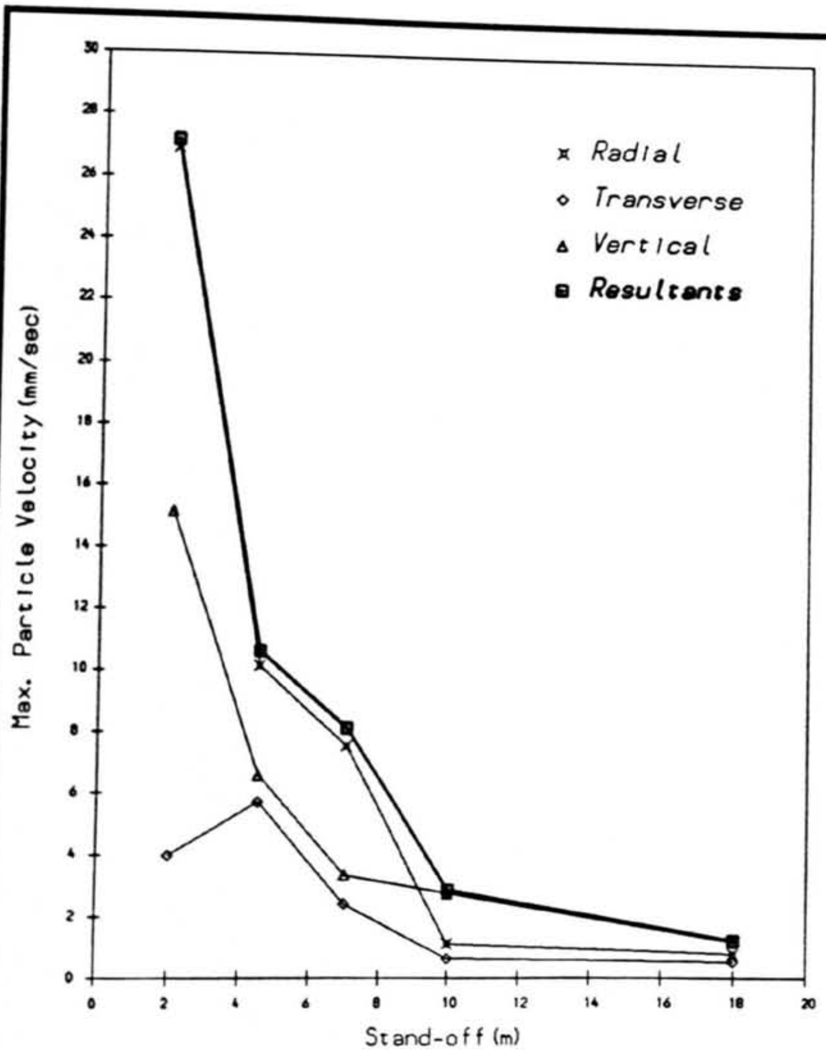


Figure (5.63) Attenuation of vibration with distance

Newbiggin, Vibrodriver(ABI), Sheet-pile

toe-depth=4.5m, file-name (NVS-5)

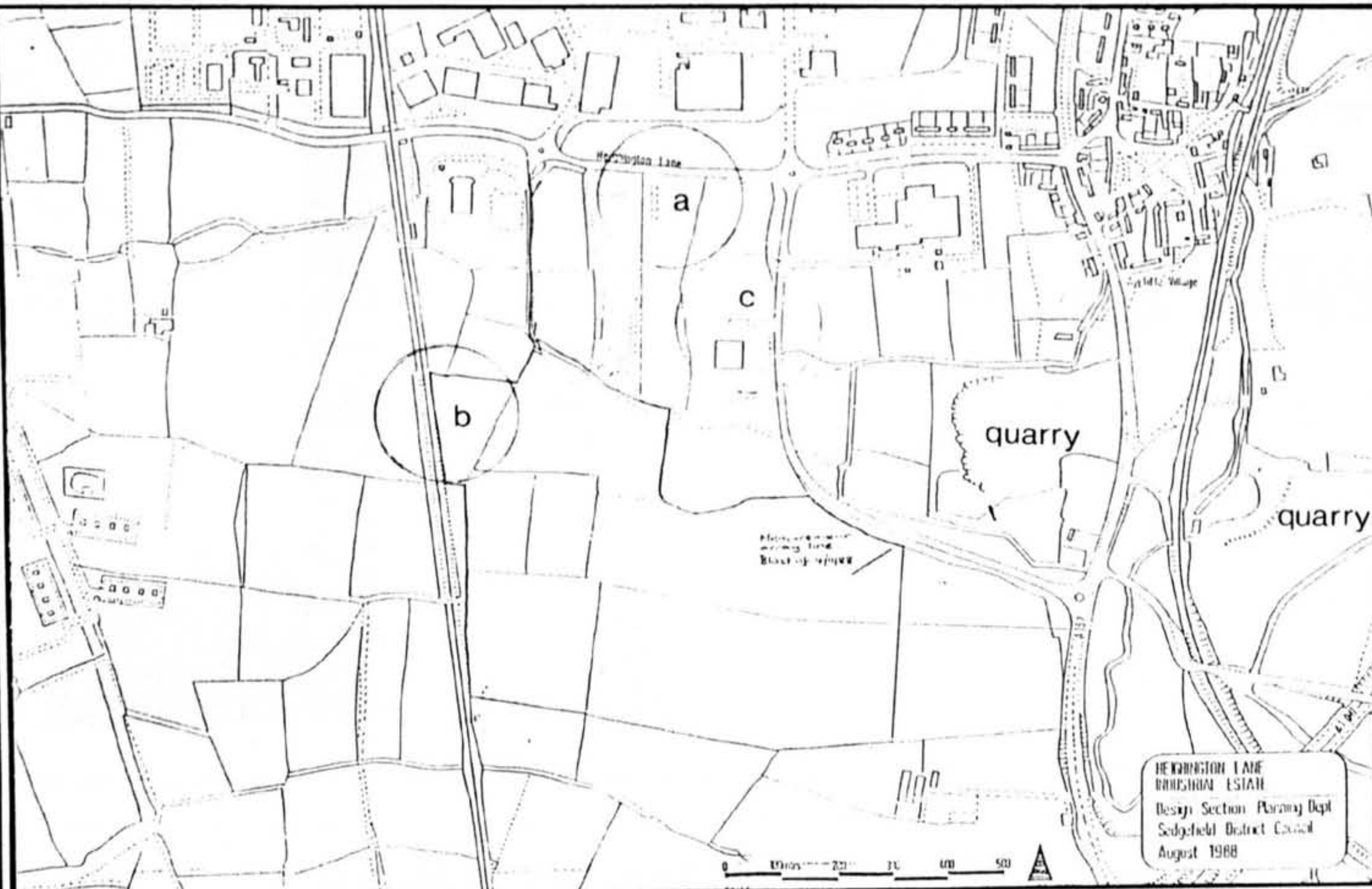


Figure (5.65) A general view of Newton Aycliff site

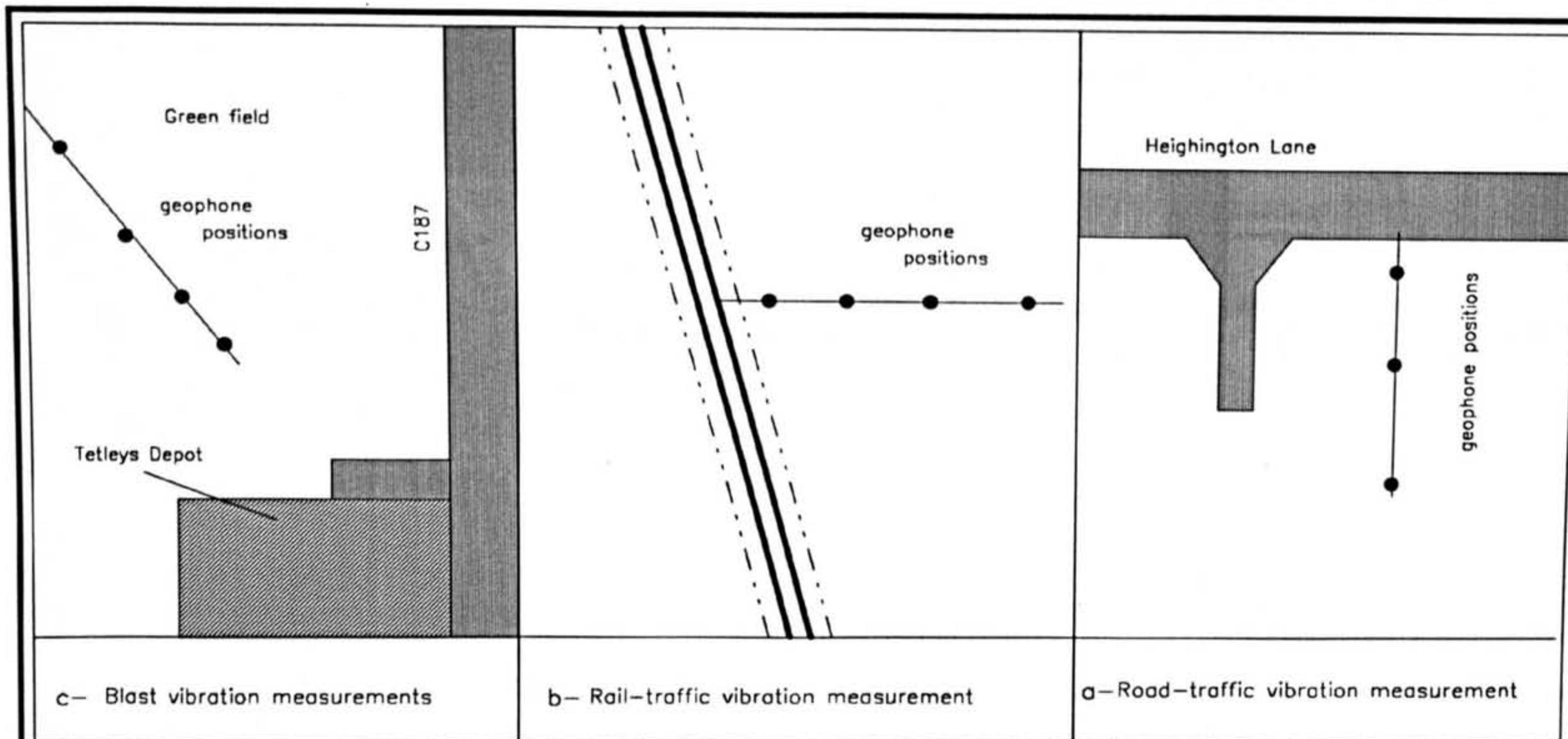


Figure (5.66) A schematic layout of the Newton Aycliffe Site

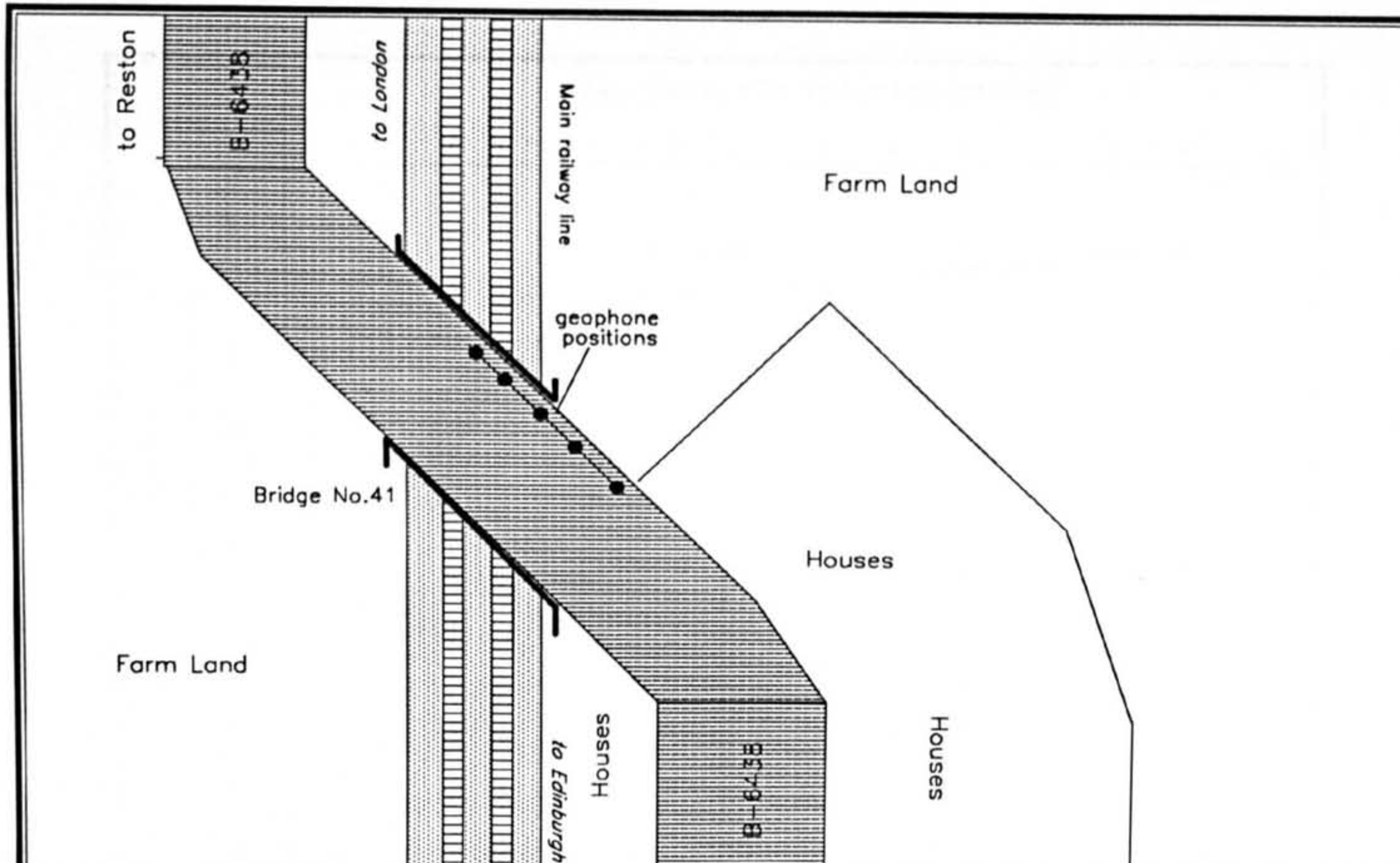


Figure (5.70) A schematic layout of a site visit to Reston

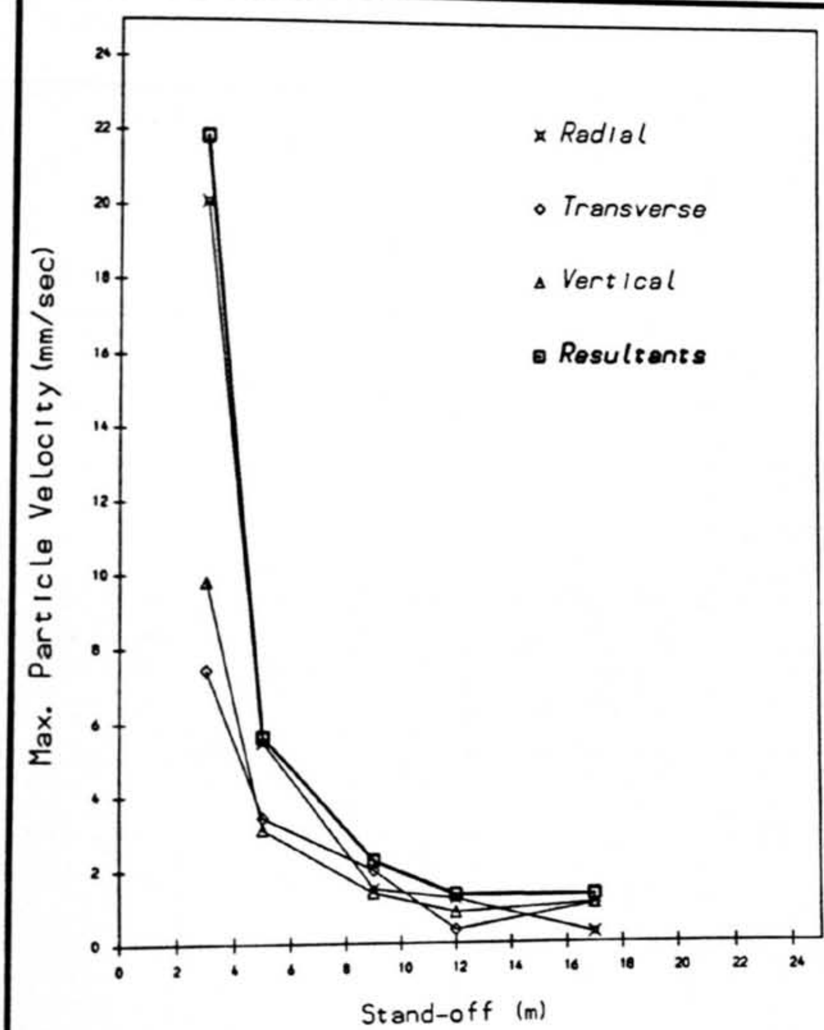


Figure (5.71) Attenuation of vibration with distance
Reston, Vibrodriver (ABI), Sheet-pile(3N)
toe-depth=5.0m, file-name (RSV-4)

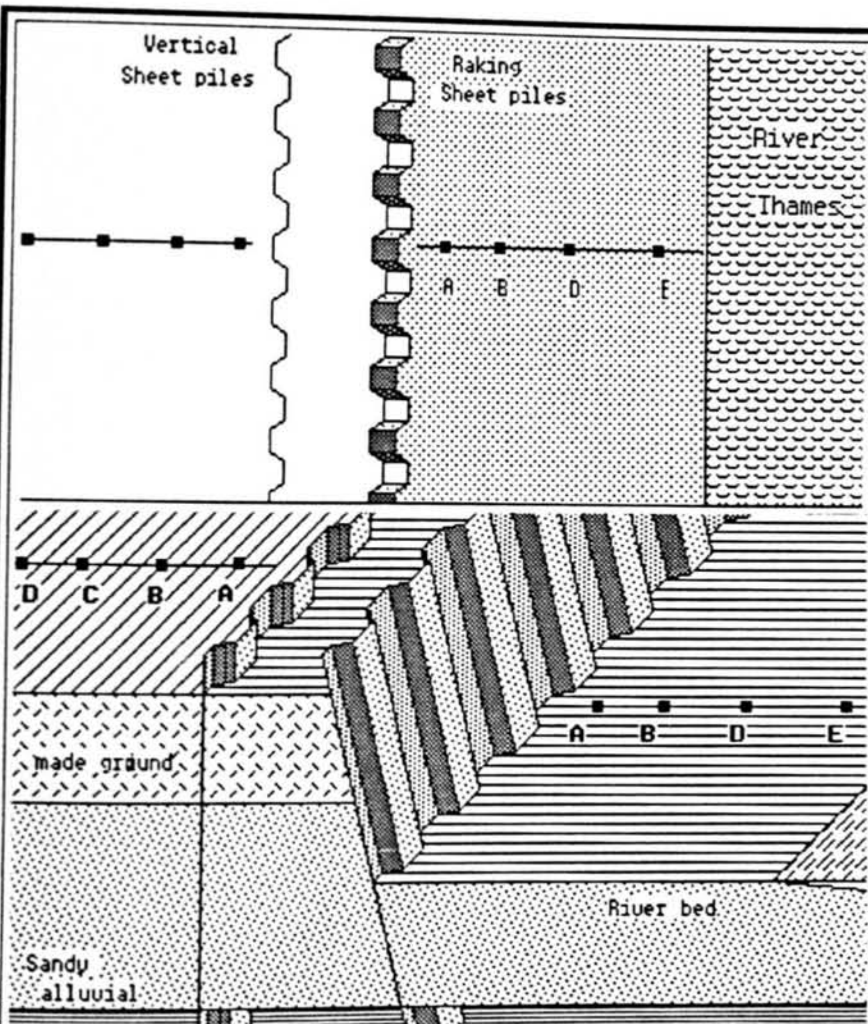


Figure (5.72) Schematic layout of pile driving site in Rotherhithe during driving sheet-pile along the south bank of river Thame

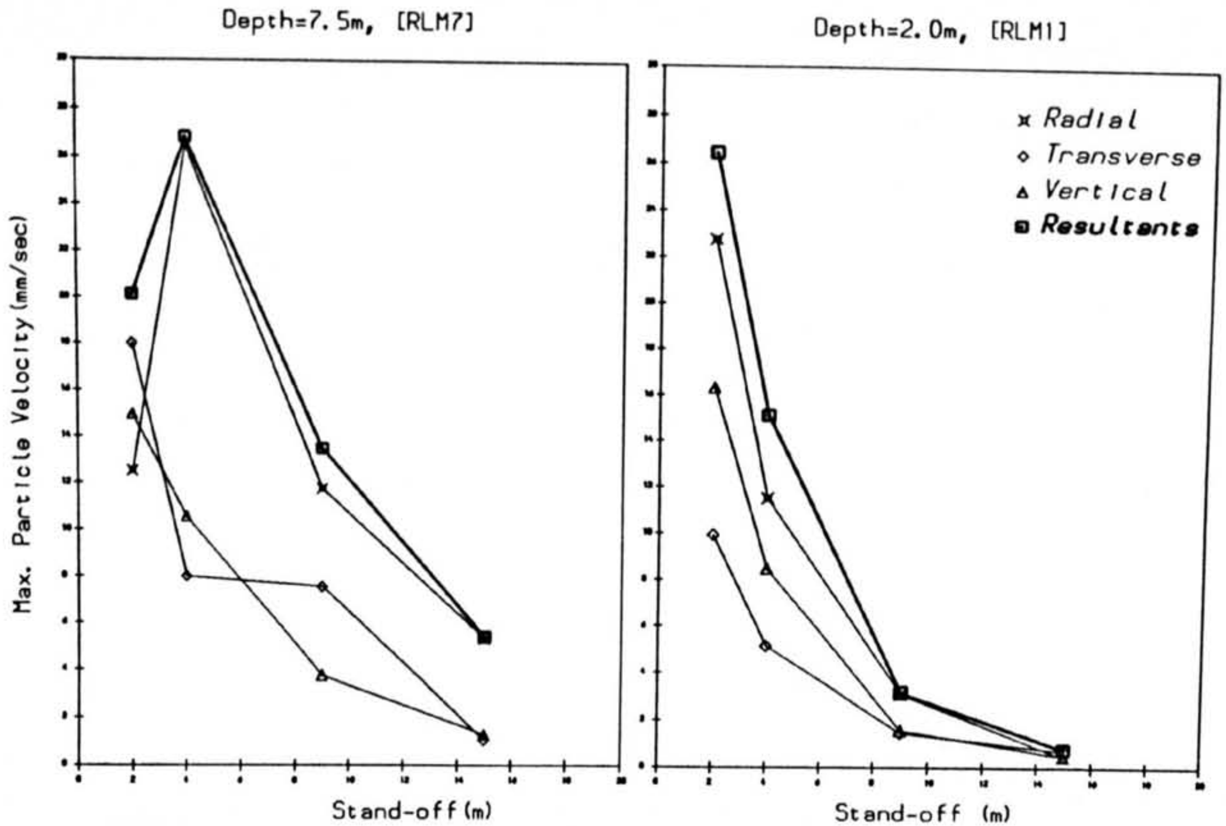


Figure (5.73) Attenuation of Vibration with distance

Rotherhithe, Sheet-pile(Larssen 25W), Vibrodriver(Muller MS-25H), Different toe-depths

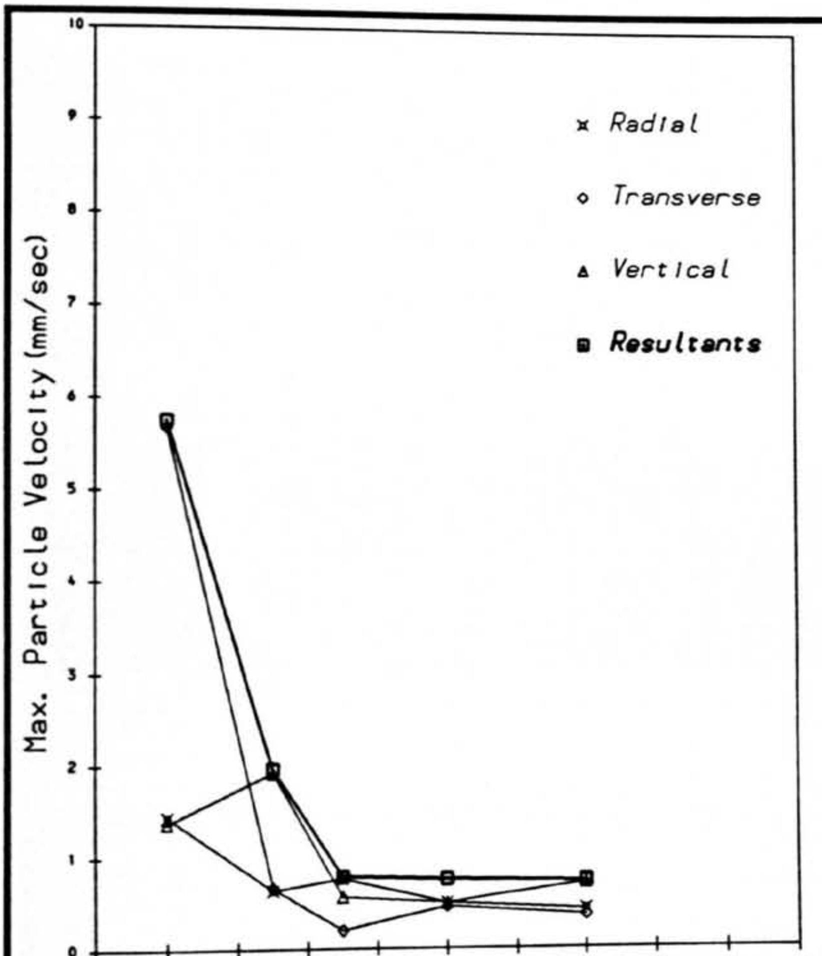


Figure (5.75) Attenuation of vibration with distance
Scarborough, Air-hammer(BSP-600N), Sheet-pile
toe-depth=11.0m, file-name (SSA-5)

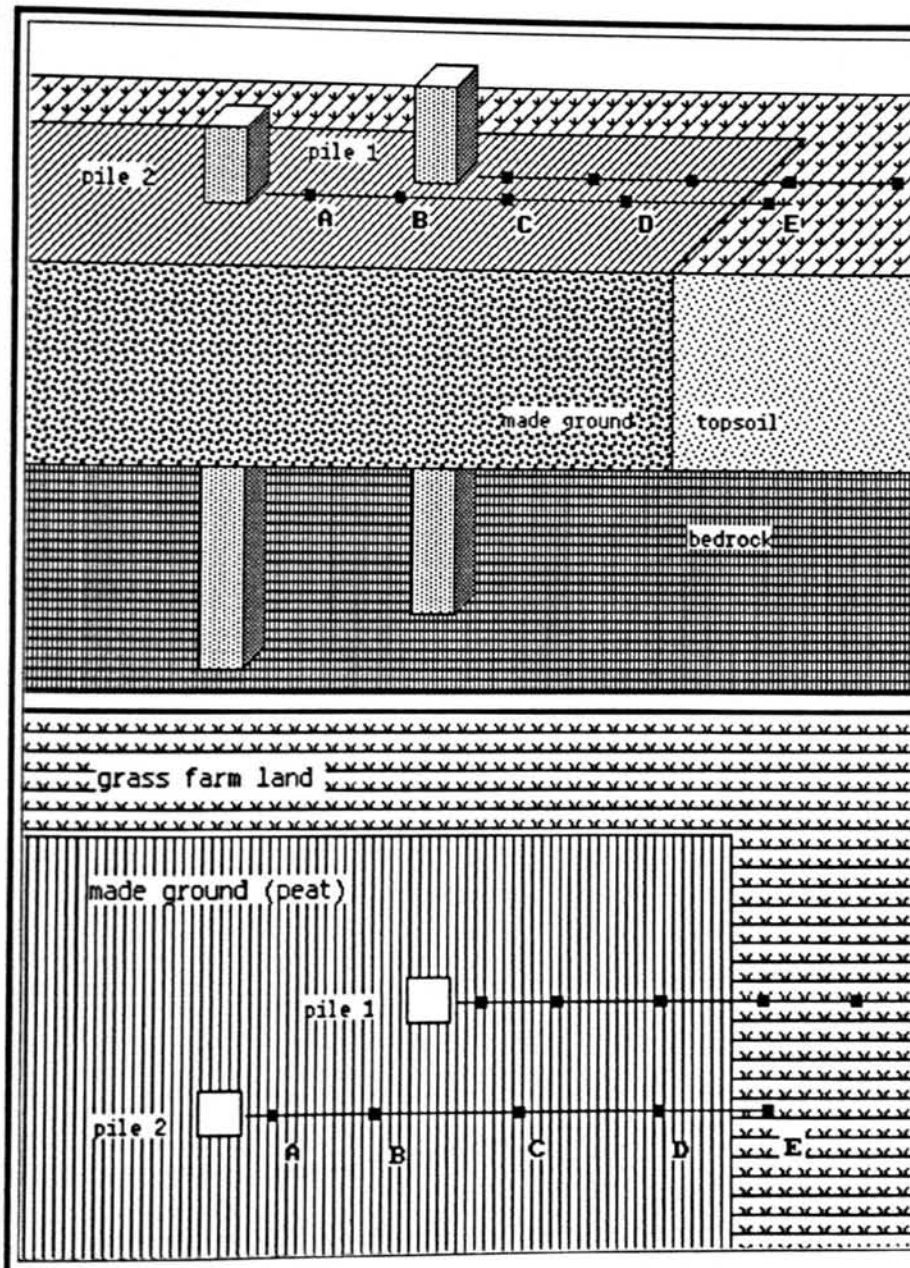


Figure (5.76) Schematic layout of pile driving site in Monk Fr yston during driving concrete-piles using drop-hammer(Banut-400)

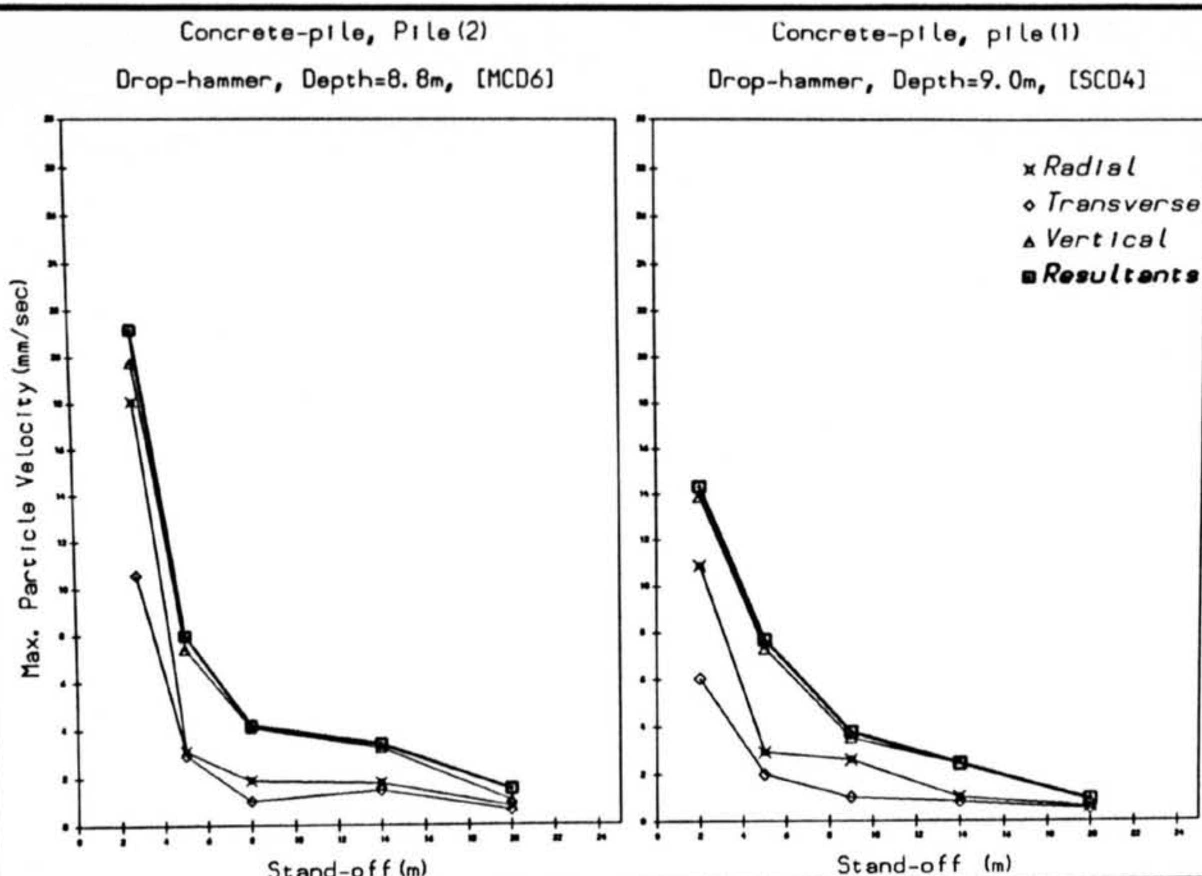


Figure (5.77) Attenuation of vibration with distance

Monk Fryston, Drop-hammer, Concrete pile, Different piles

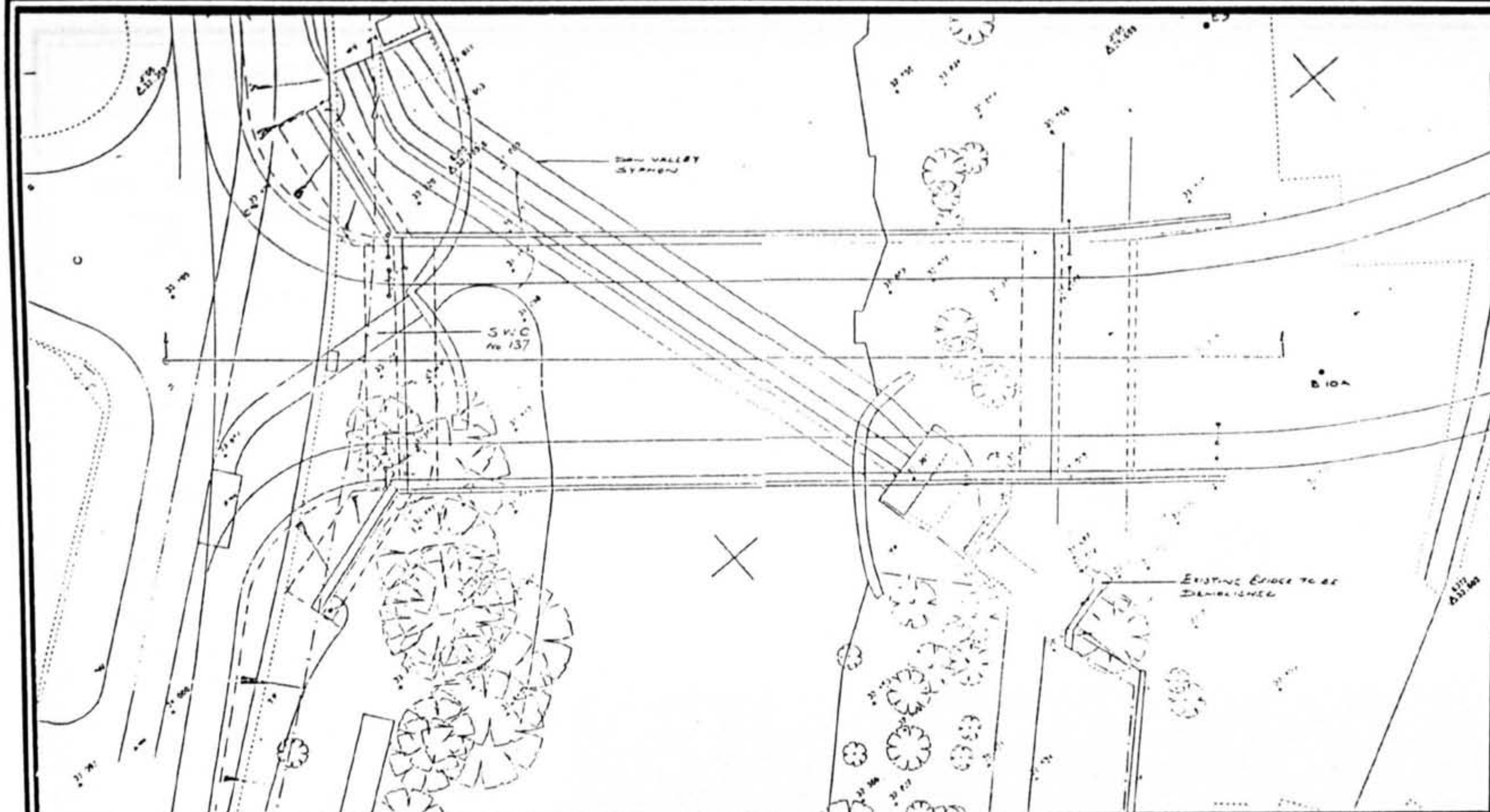


Figure (5.79) A general view of the Sheffield construction site

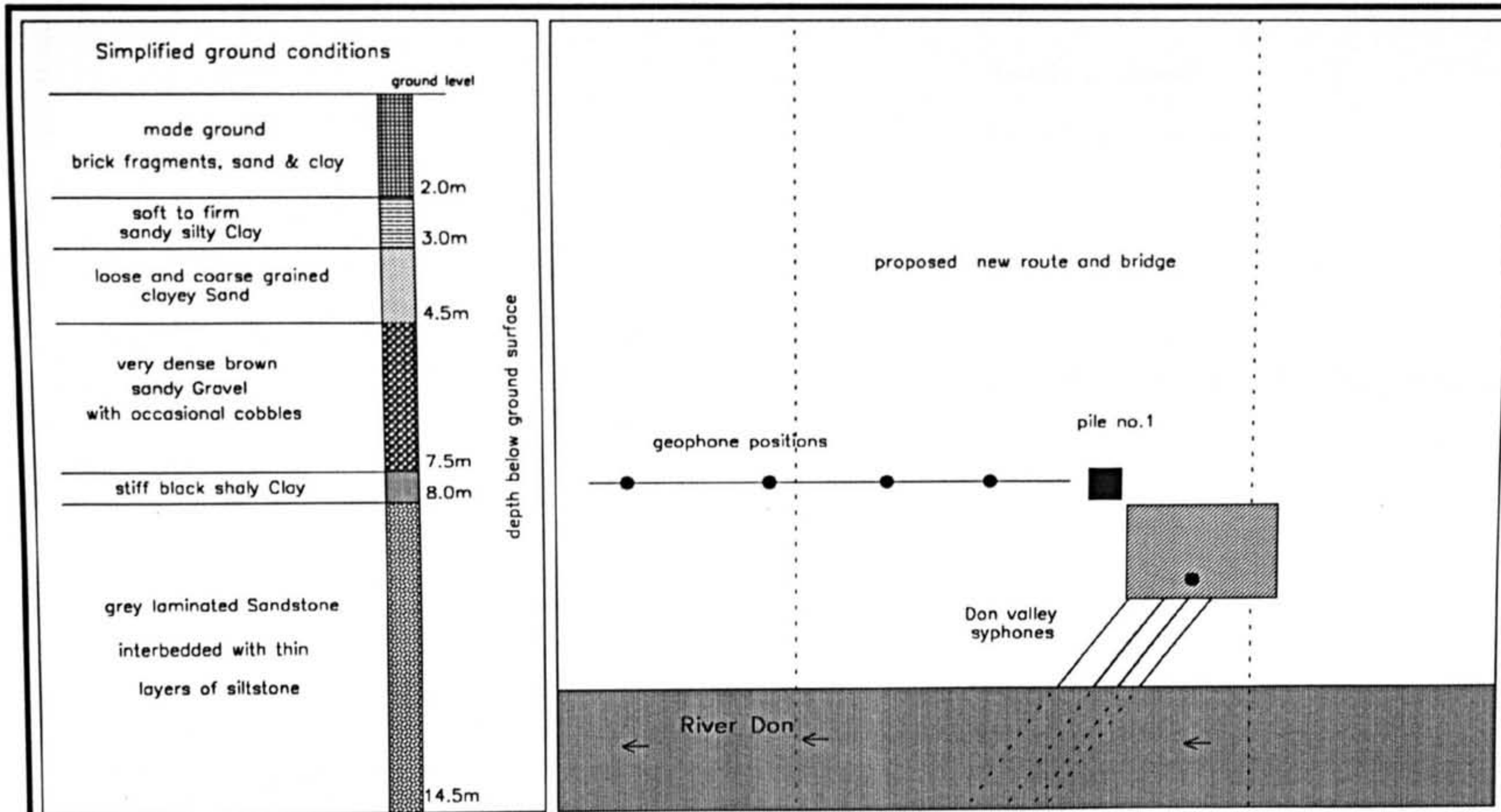


Figure (5.80) A schematic layout of the site during trial pile driving at Sheffield

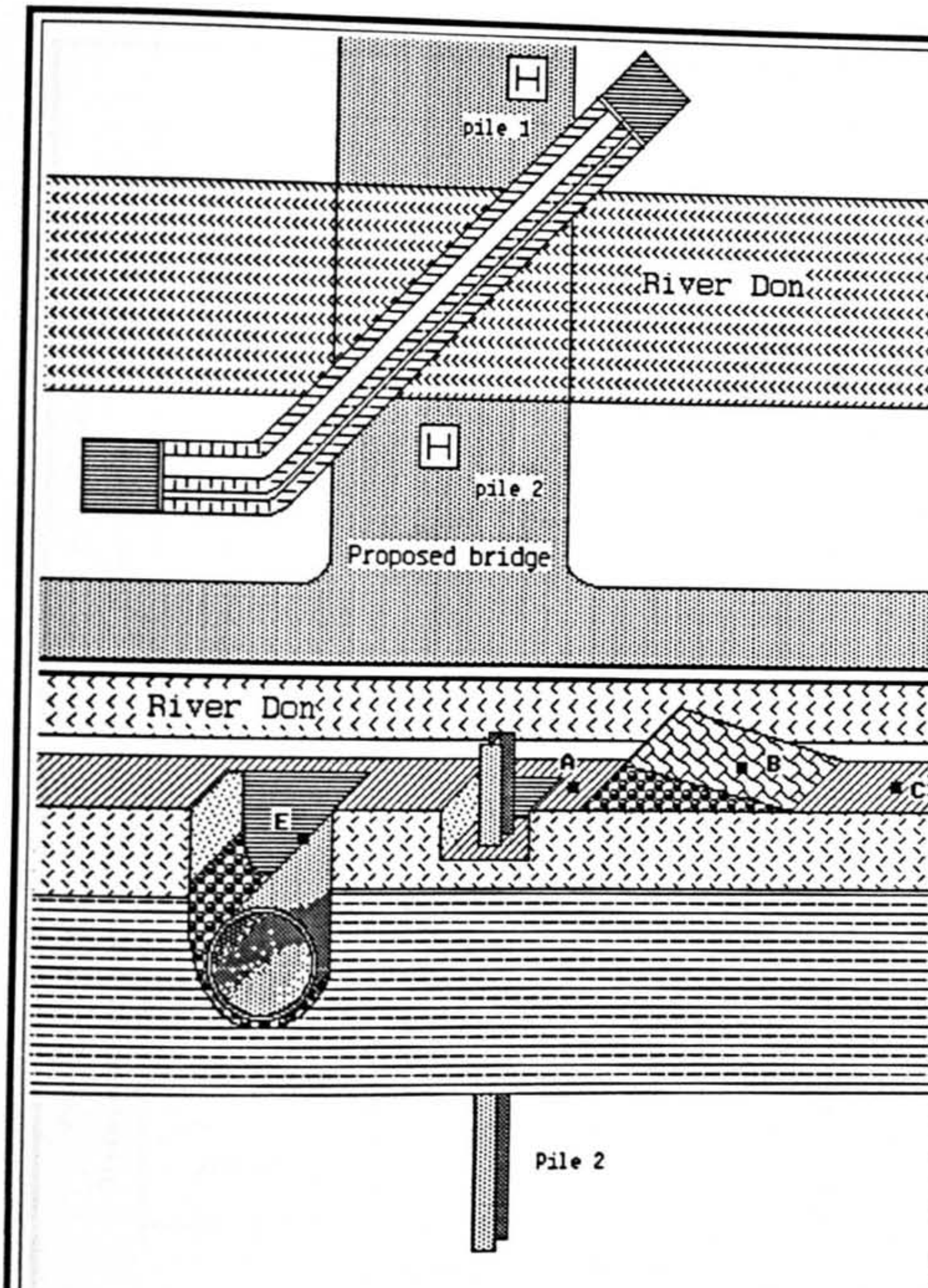


Figure (5.82) Schematic layout of pile driving site in Sheffield

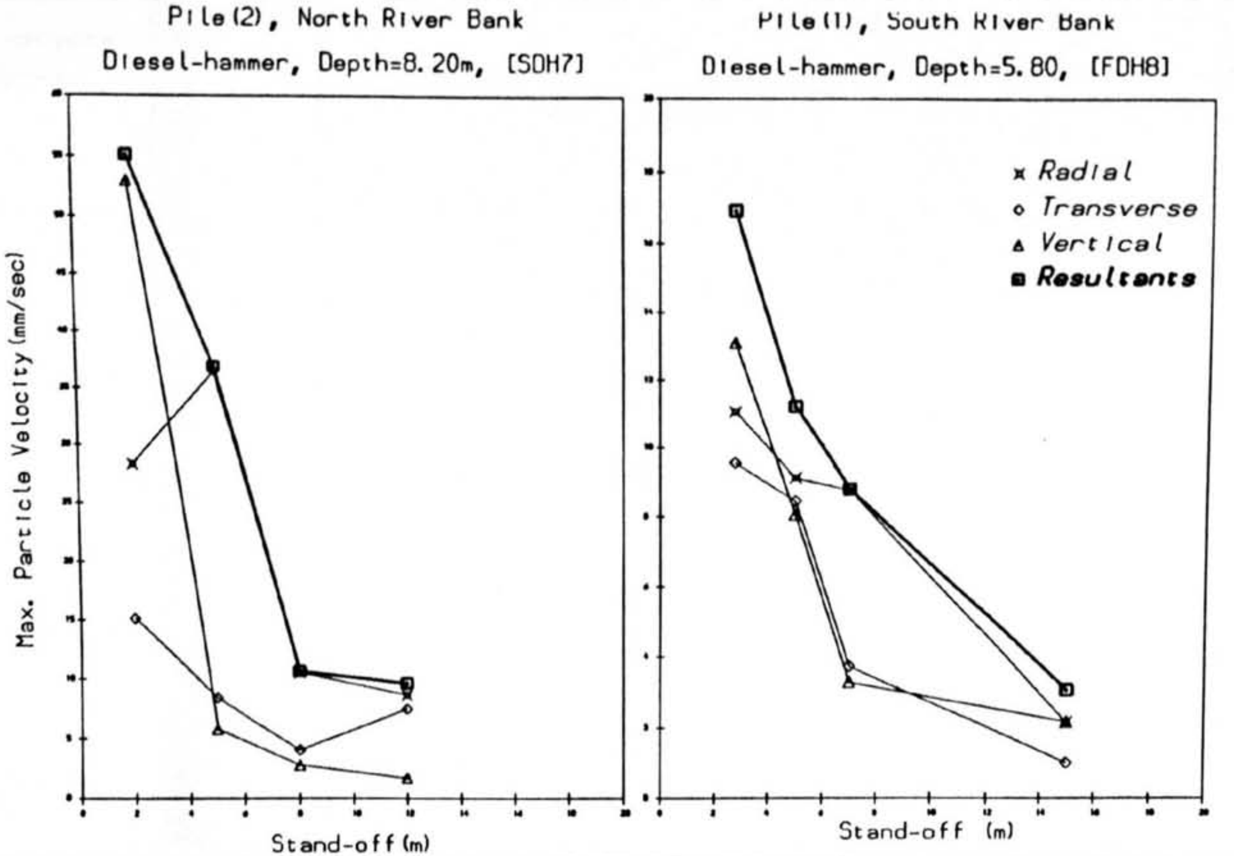


Figure (5.83) Attenuation of vibration with distance

Sheffield, Diesel-hammer, H-pile, Different piles

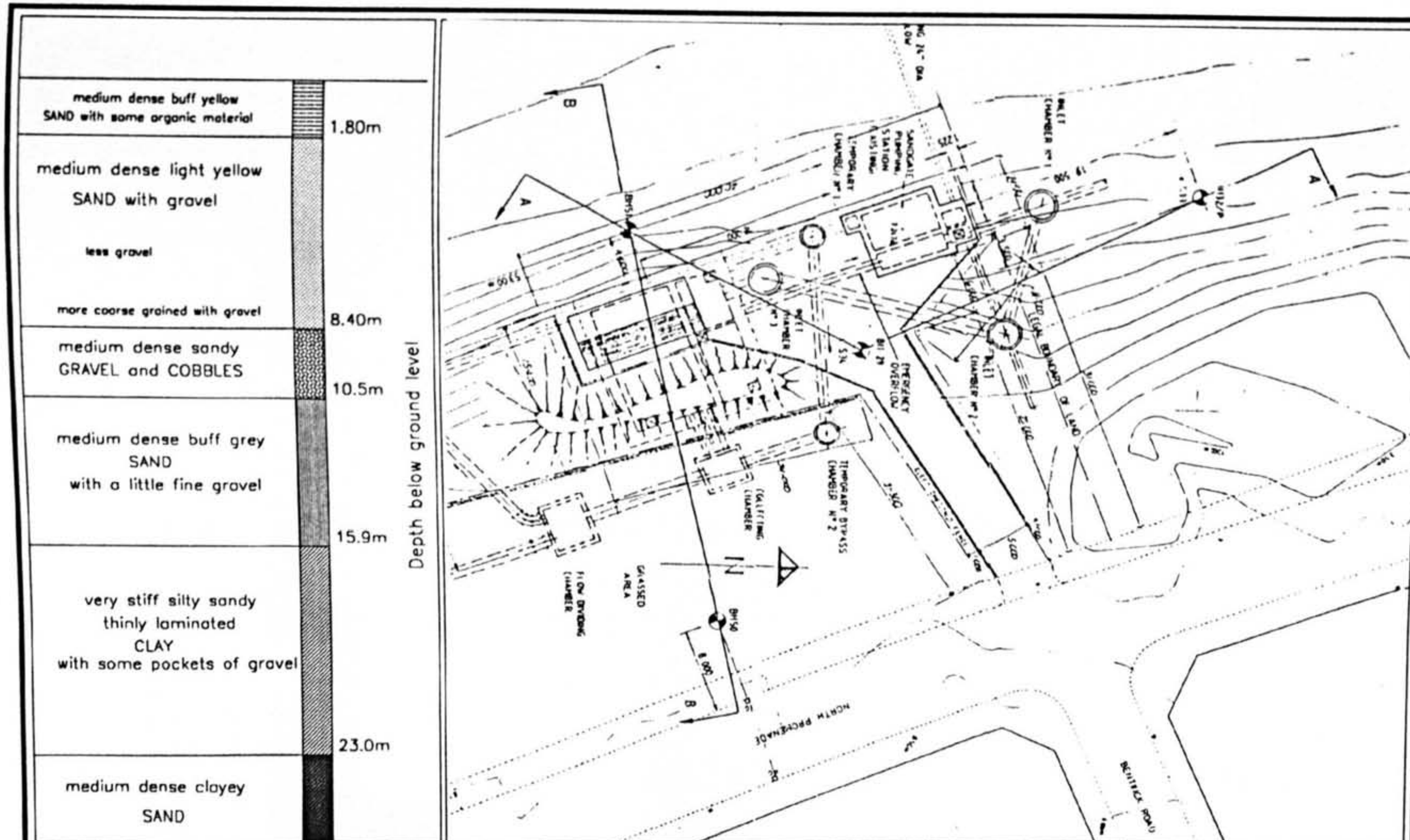


Figure (5.84) Display of ground conditions and plan view of St.Annes Site

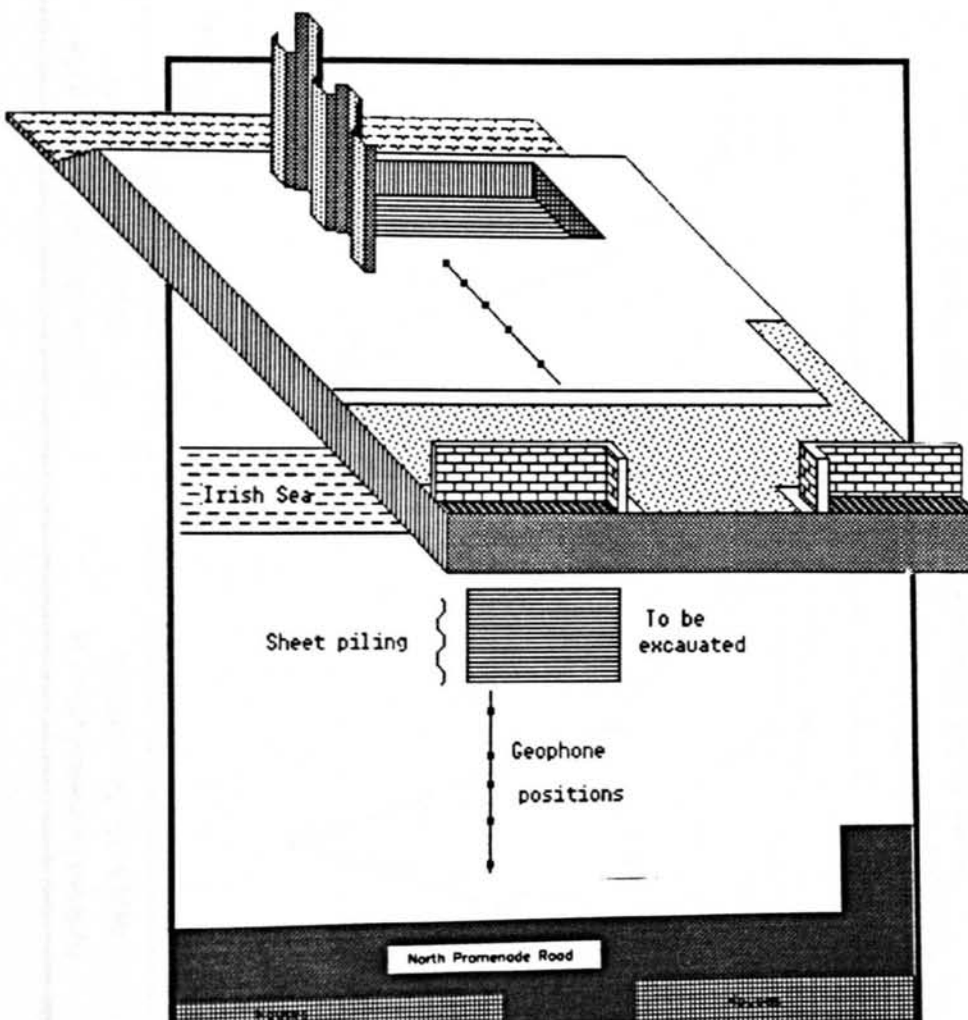


Figure (5.85) Schematic layout of pile driving site
St.Annes, Sandgate Project
during driving sheet-piles using hydraulic-hammer

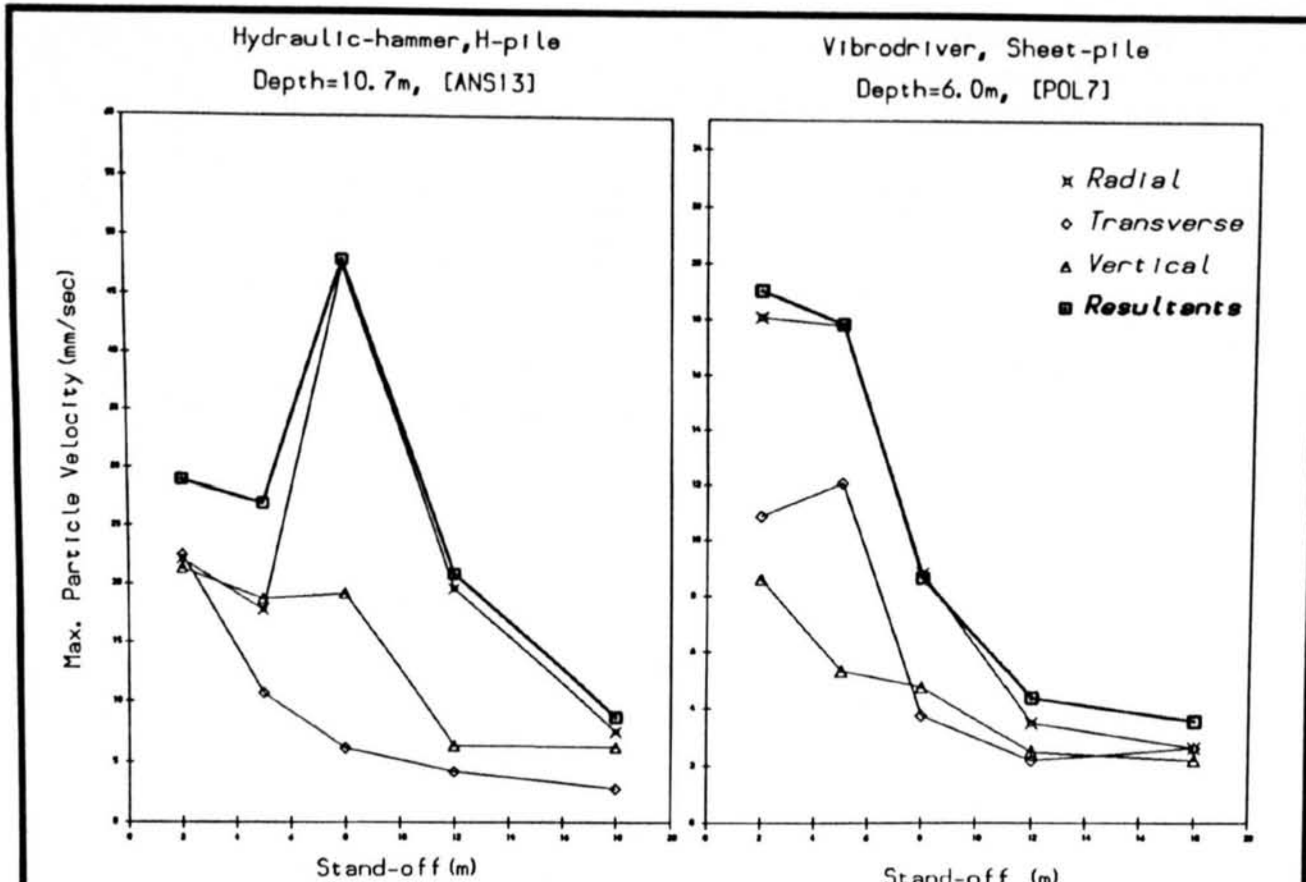
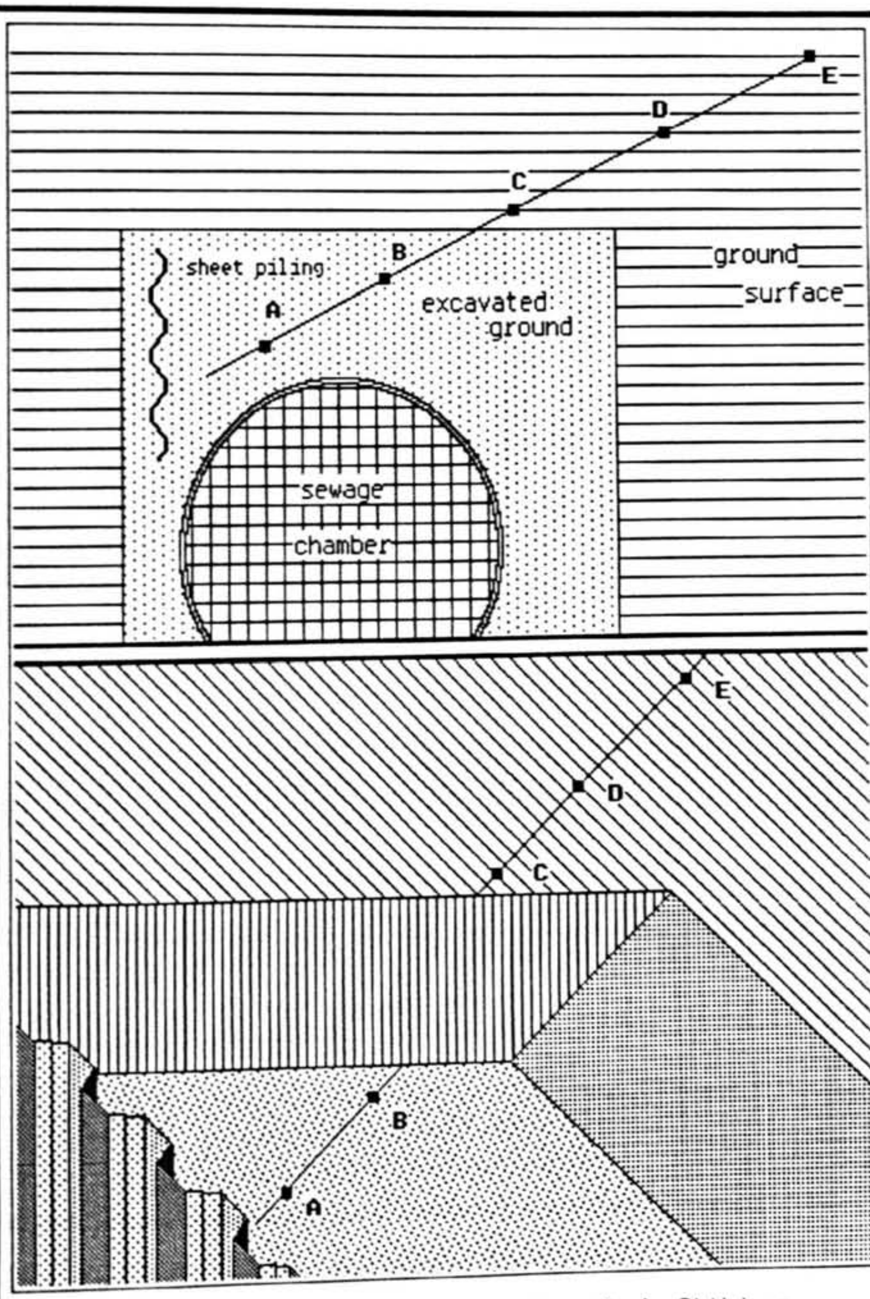


Figure (5.86) Attenuation of vibration with distance

St.Annes, Sheet-pile, Different driving hammers



Figure(5.89) Layout of the construction site in St.Helens

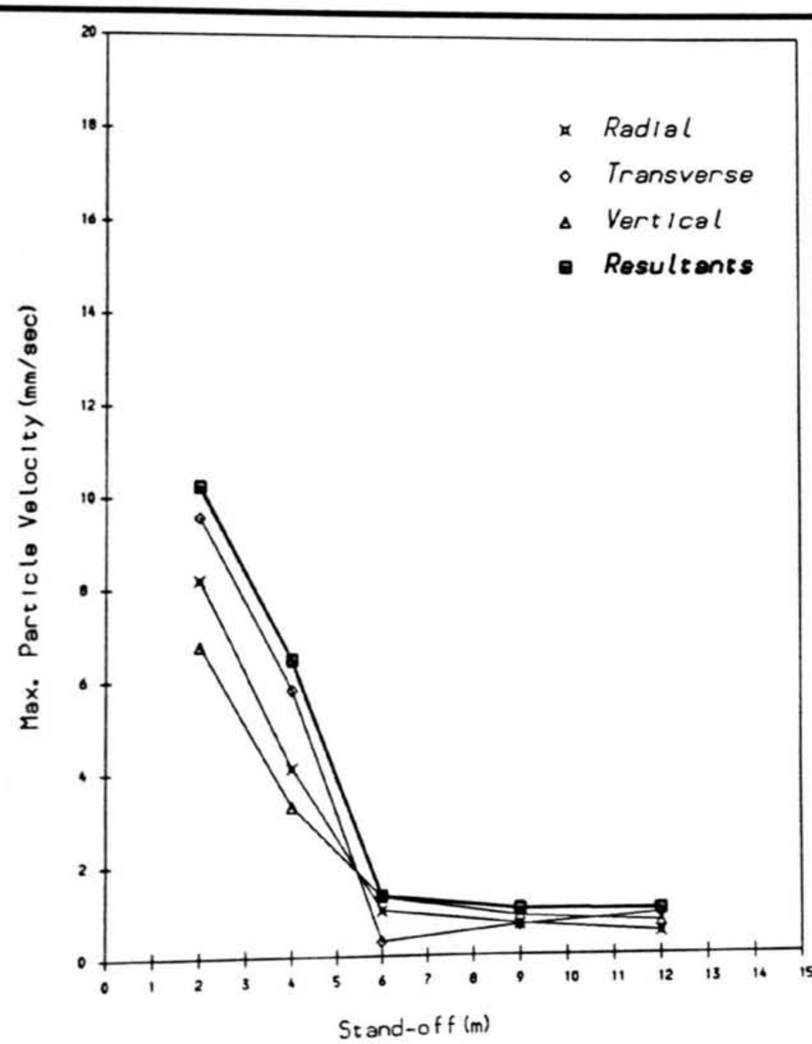


Figure (5.90) Attenuation of vibration with distance

St.Helens, Air-hammer(BSP-700N), Sheet-pile

toe-depth=3.0m, file-name (SSA-4)

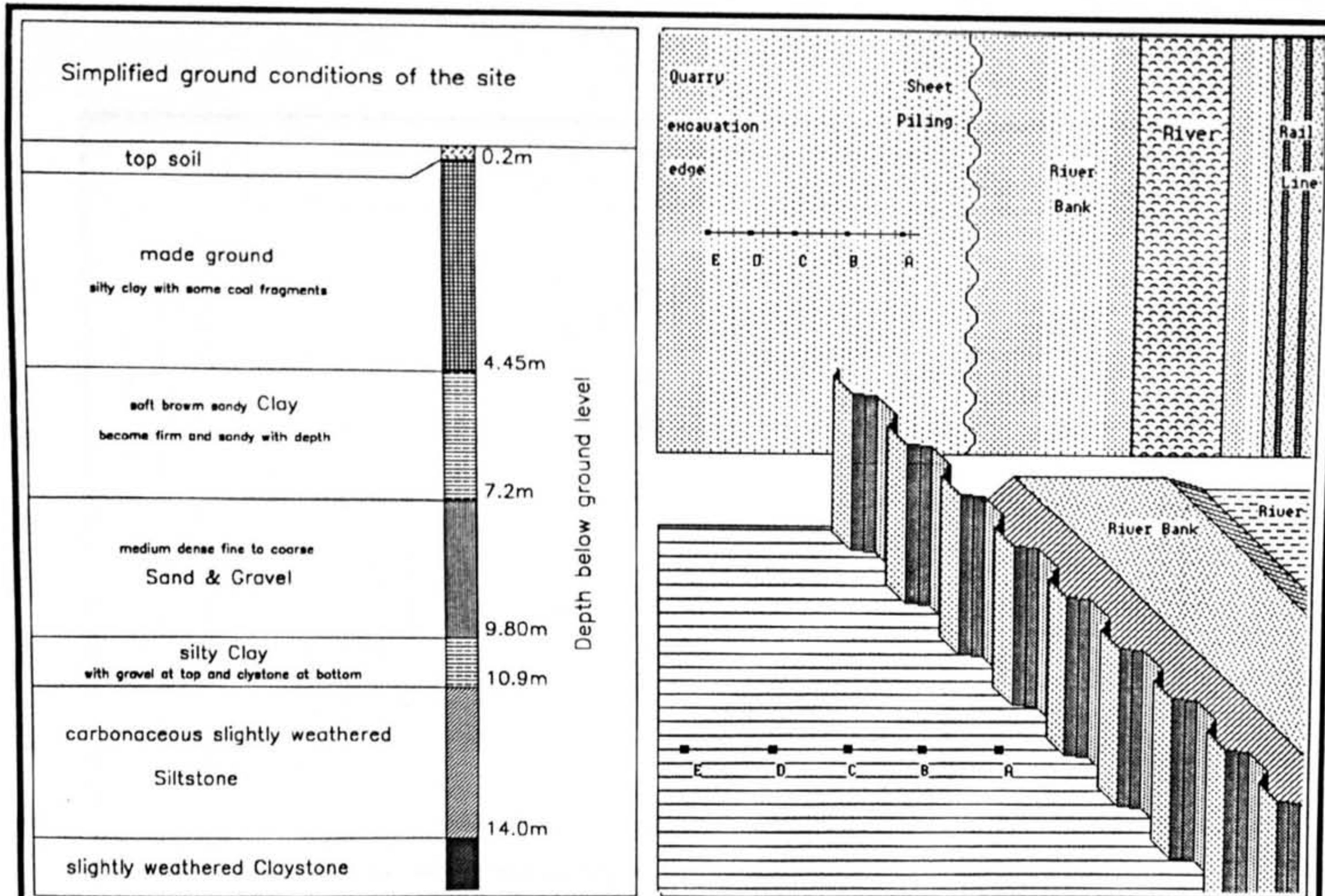


Figure (5.92) A schematic layout and the ground conditions display of Swillington site

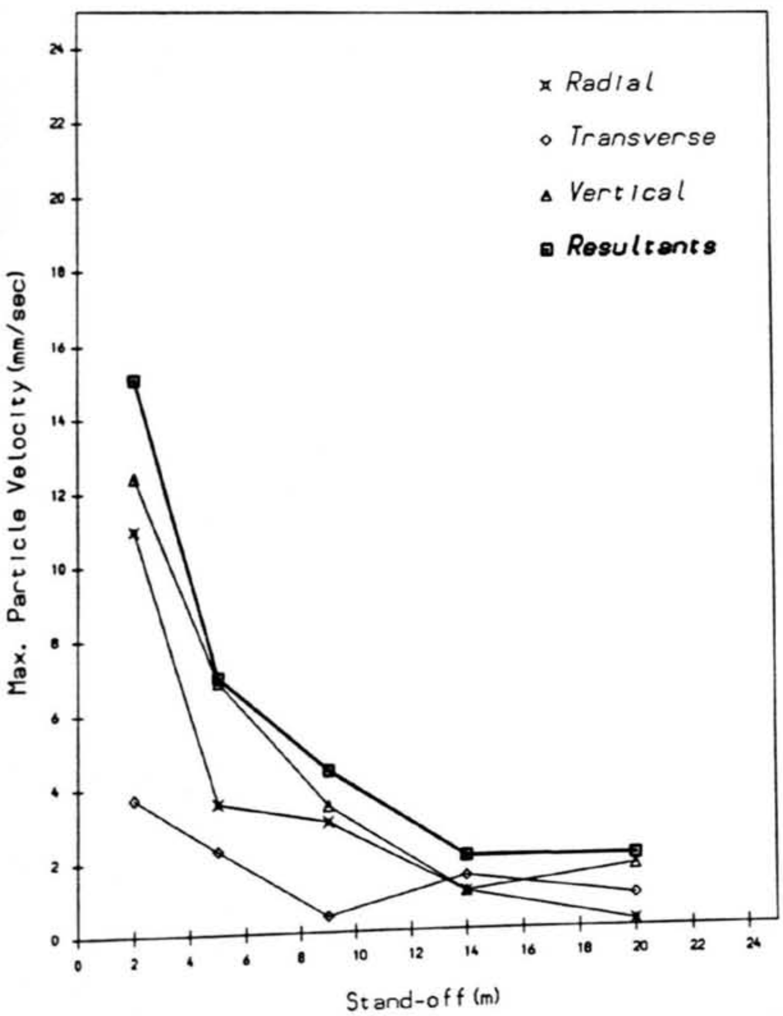


Figure (5.93) Attenuation of vibration with distance
Swillington, Vibrodriver (Muller MS-25H), Sheet-pile
toe-depth=4.8m, file-name (SSV-1)

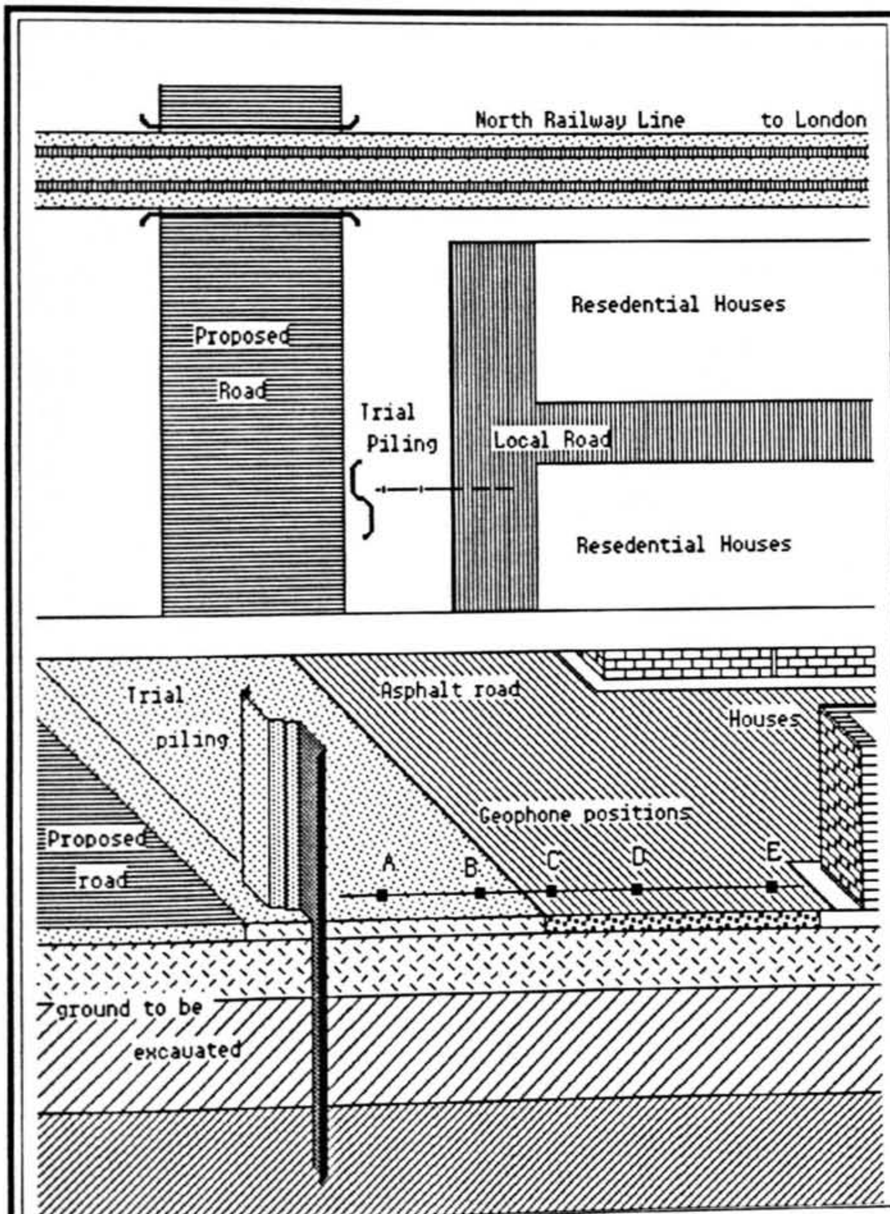


Figure (5.95) Schematic layout of pile driving site in Waltham Cross during driving sheet-piles using hydraulic-hammer (BSP357)

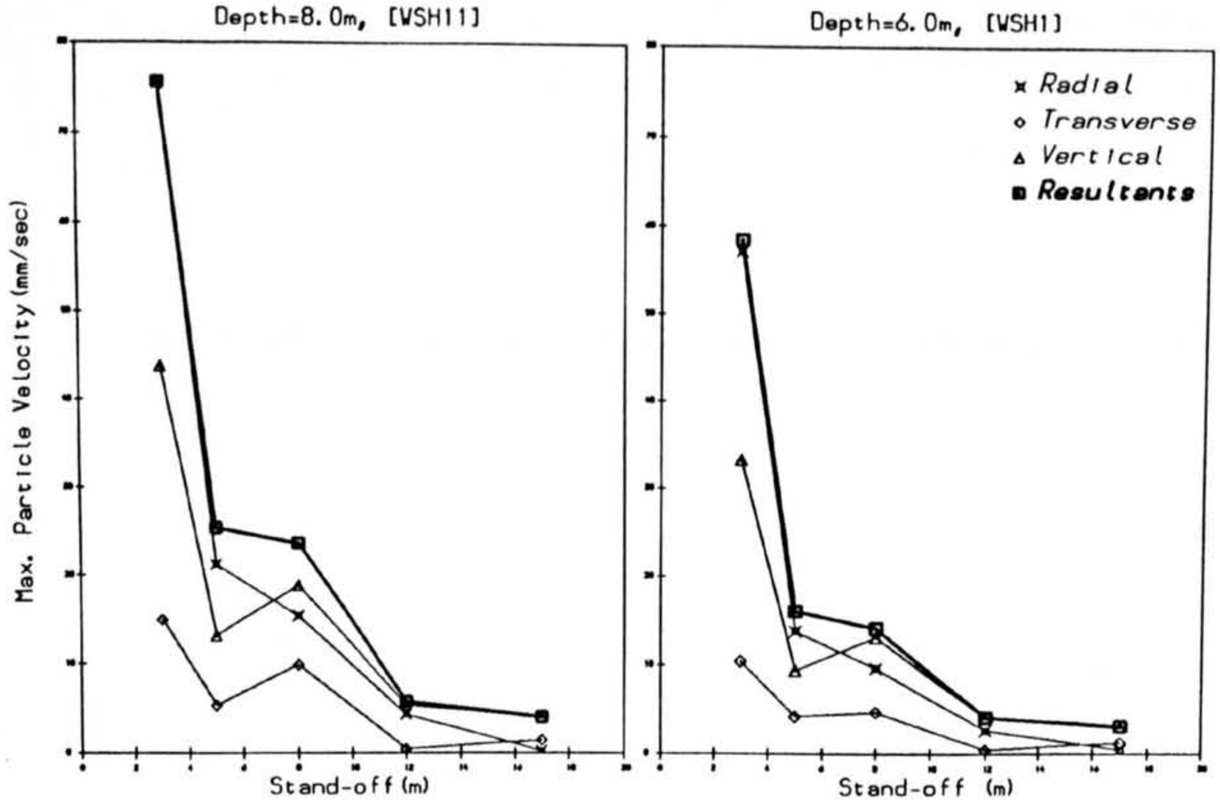


Figure (5.96) Attenuation of vibration with distance

Waltham Cross, Hydraulic-hammer, Sheet-pile, Different toe-depths

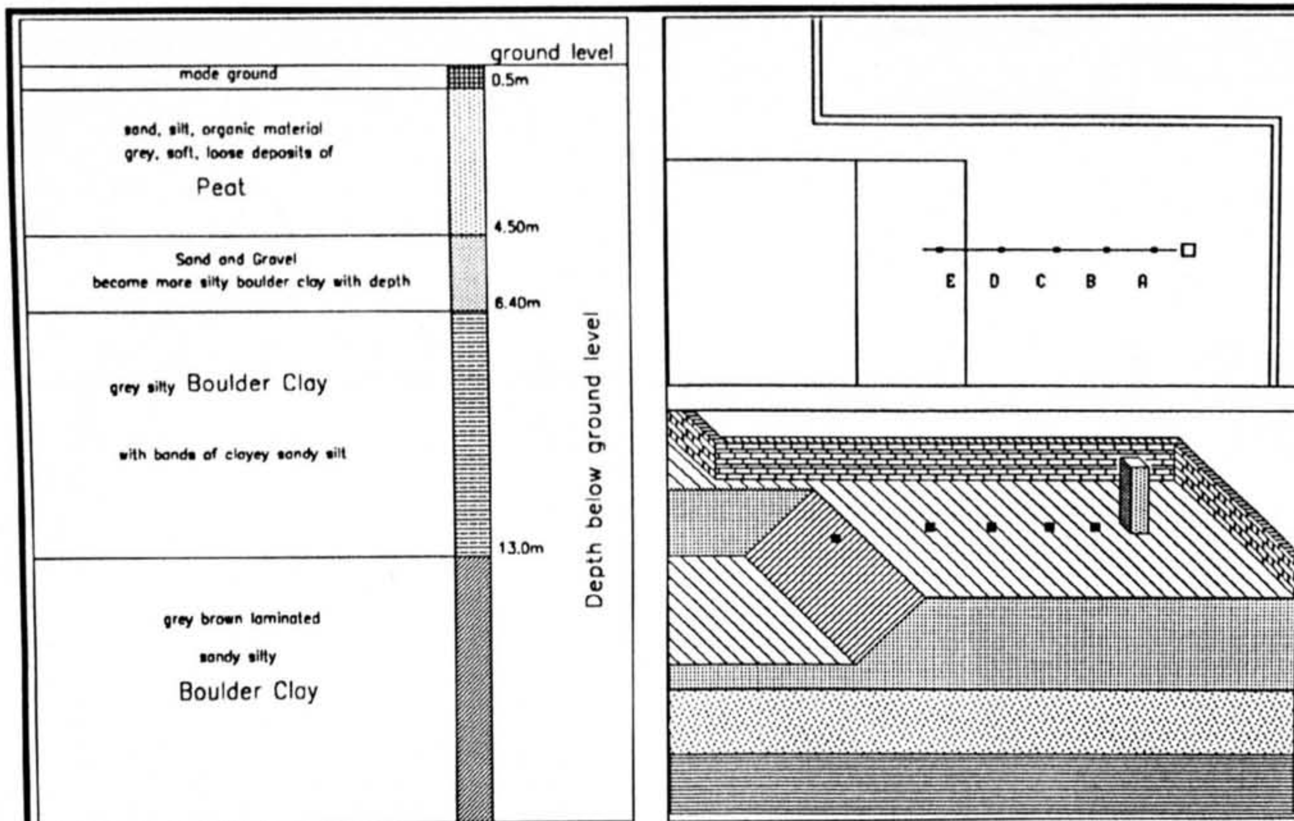


Figure (5.98) A simplified display of the ground conditions and plan of Whalley site

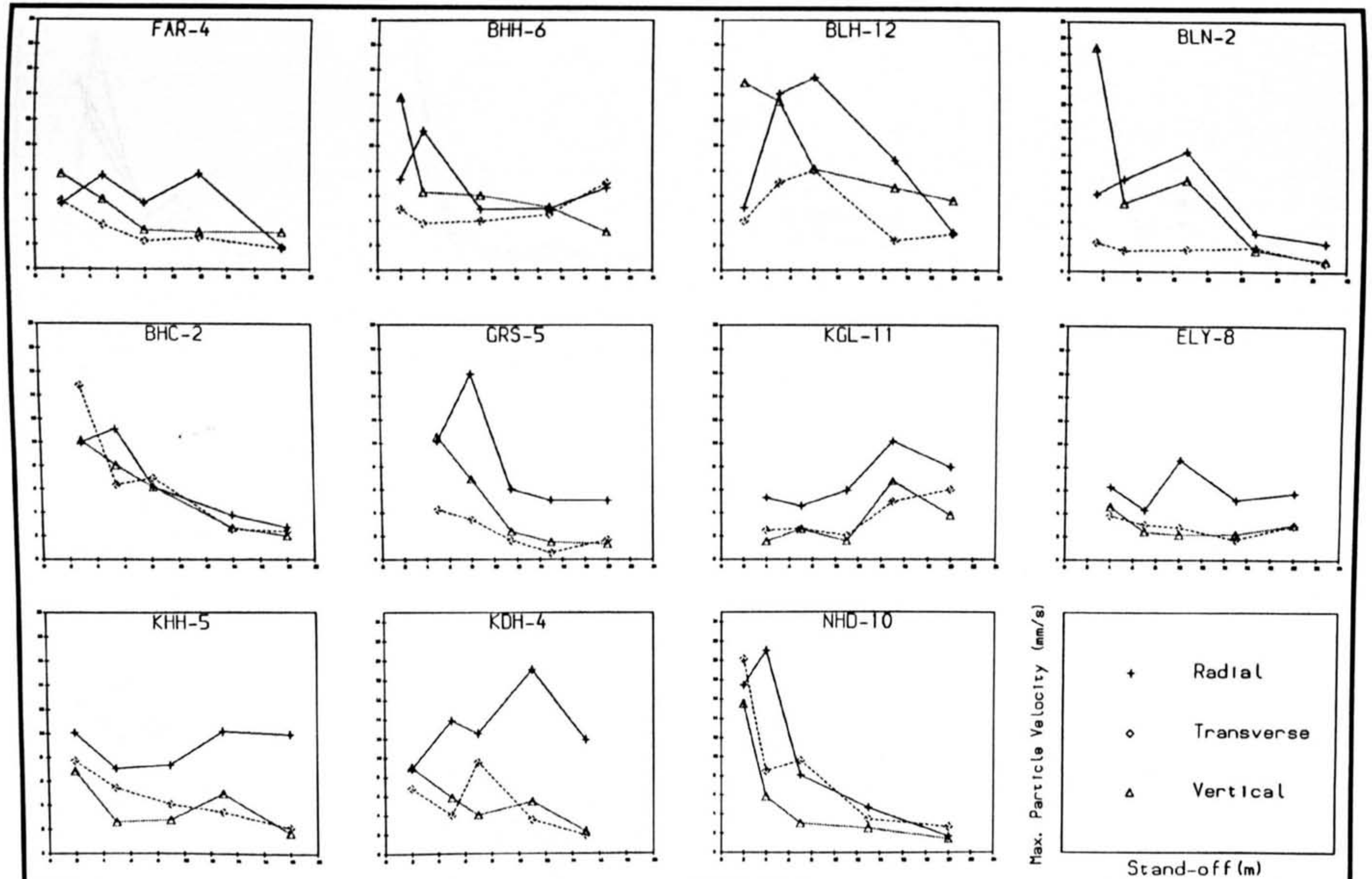


Figure (5.100) Attenuation of ground vibration with distance recorded from the operation of IMPACT—HAMMERS

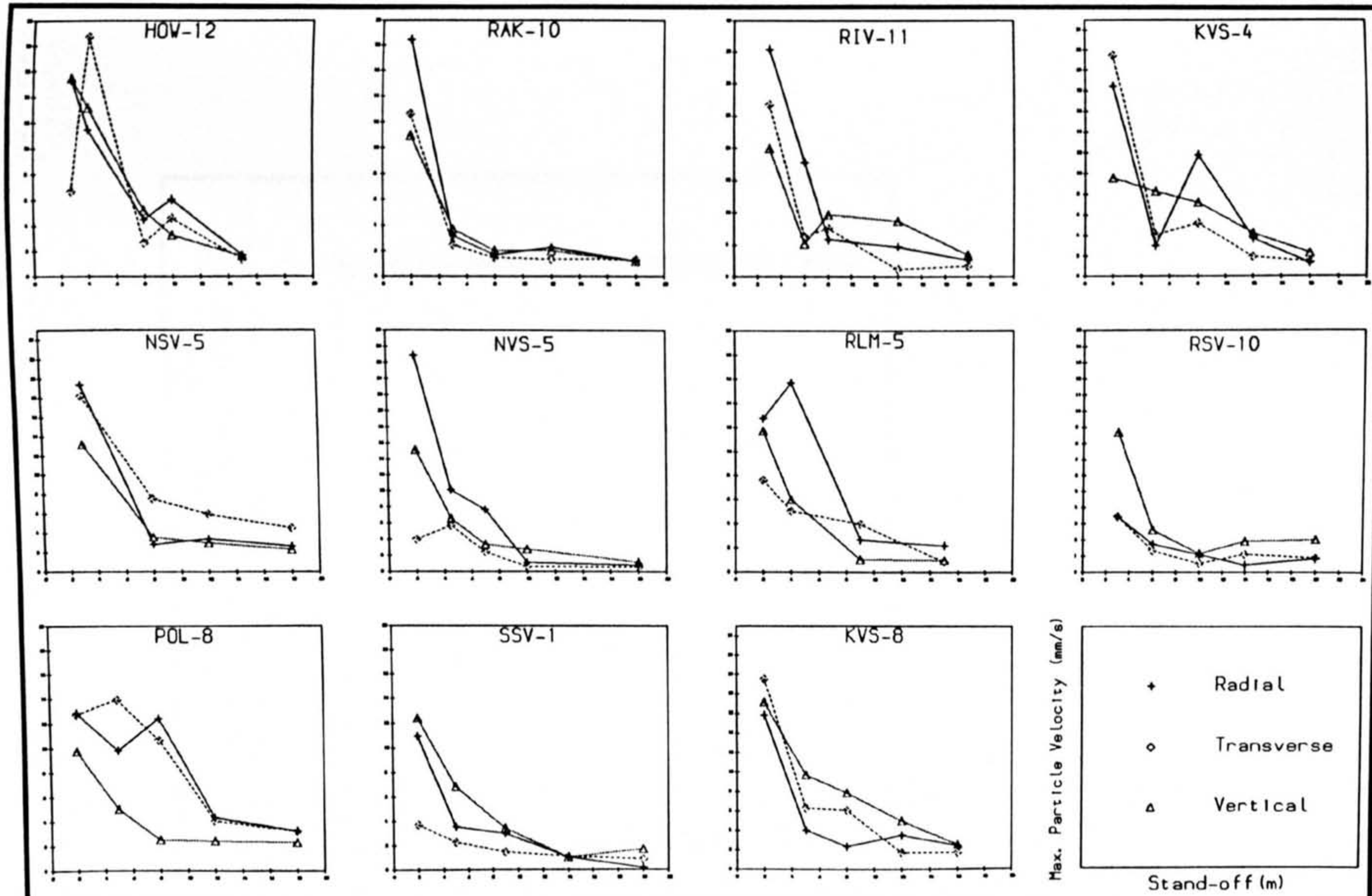


Figure (5.101) Attenuation of ground vibration with distance recorded from the operation of VIBRODRIVERS

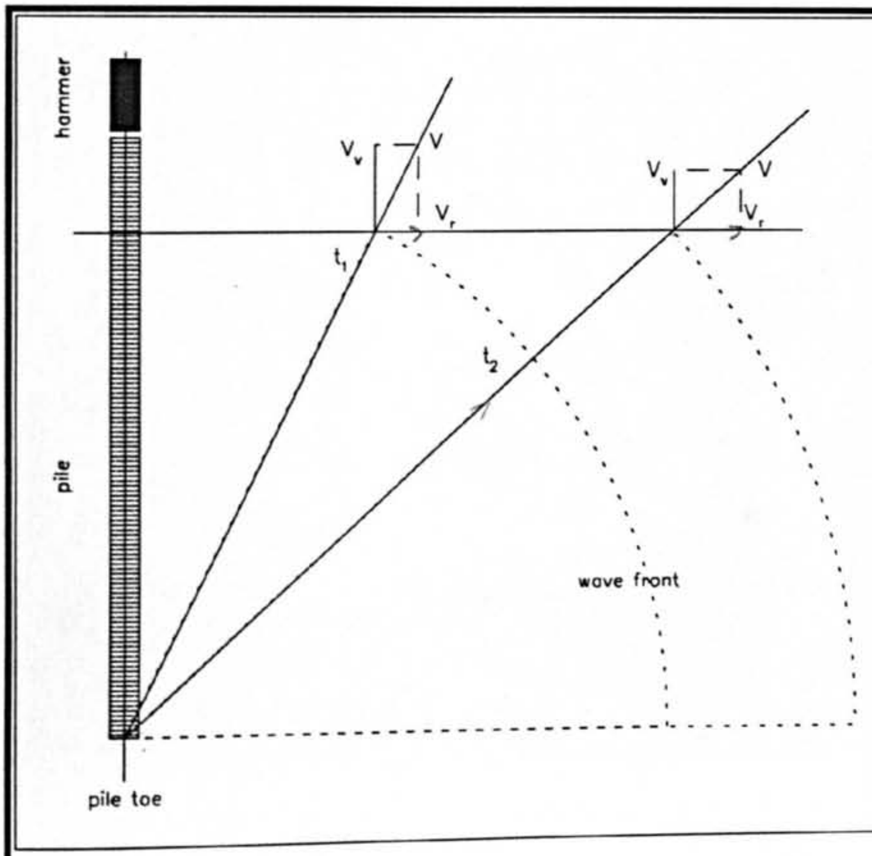


Figure (5.102) Differentiation of body wave at the ground surface to vertical and radial waves

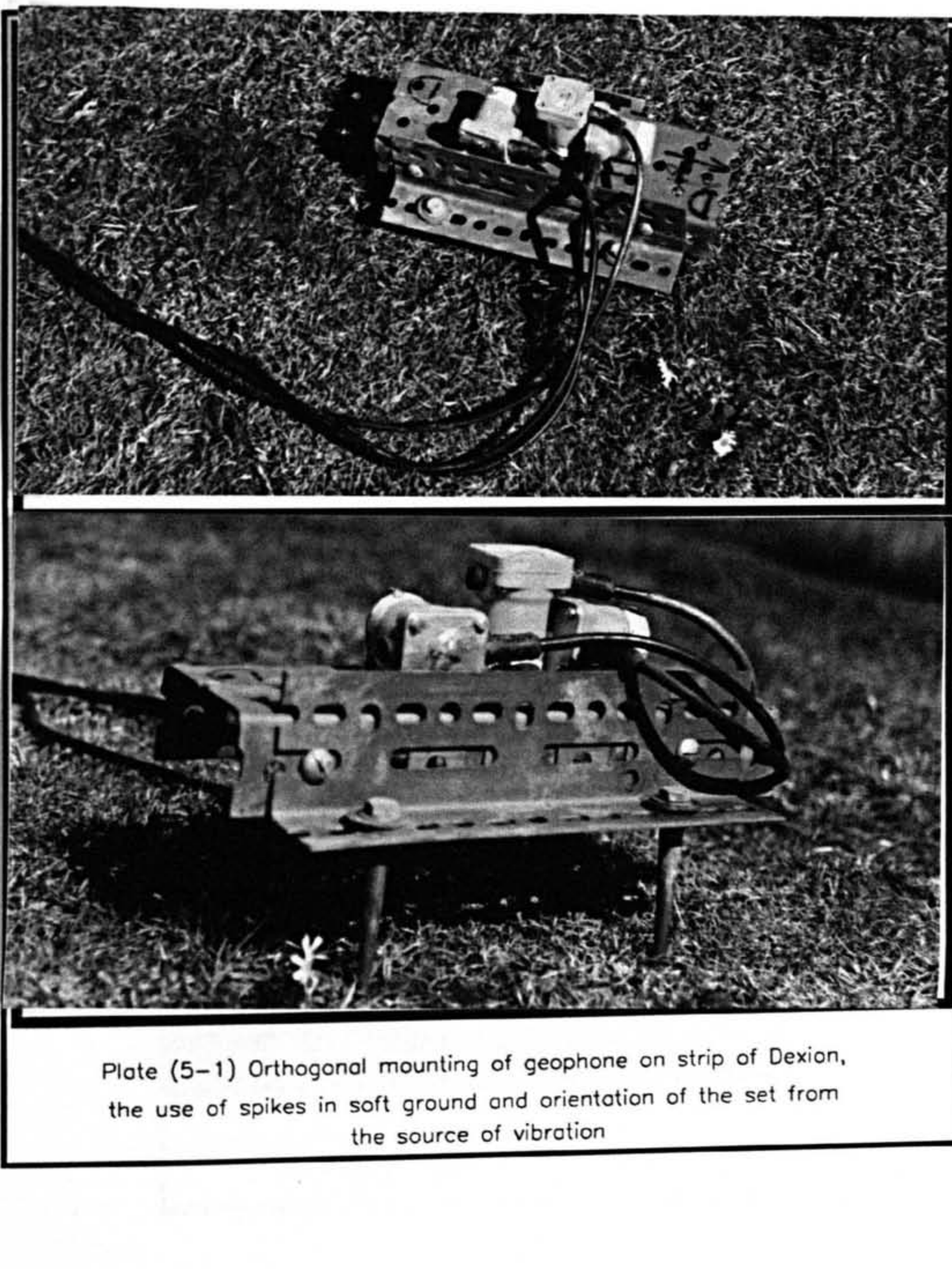


Plate (5-1) Orthogonal mounting of geophone on strip of Dexion, the use of spikes in soft ground and orientation of the set from the source of vibration

Plate (5-2) Driving H-pile by Hydraulic-hammer in Blaydon Using a 40m long crane

Plate (5–3) Location of cofferdam and sheet–pile in Blaydon

Plate (5-4)
Driving tubular pile by a vibrodriver as part of construction of defence wall along the River Yare *Great Yarmouth*

Plate (5–5) Driving sheet–pile by air hammer during the process of trial drivng, Grimsby

Plate (5–6)

Driving a tubular pile by a hydraulic–hammer (IHC.S–70).

Immingham

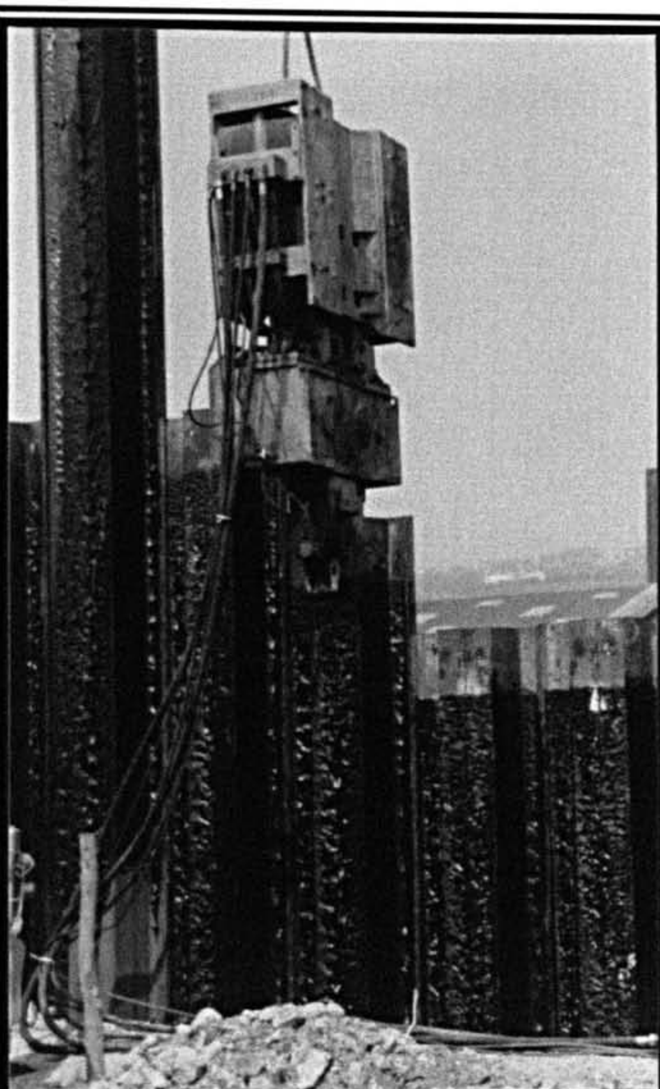


Plate (5-7) Driving Frodingham pile(3N) by vibrodriver(MS25H), Keighley, area-1

Plate (5-8) Location of pile-driving in an excavated ground, Keighley, area-2

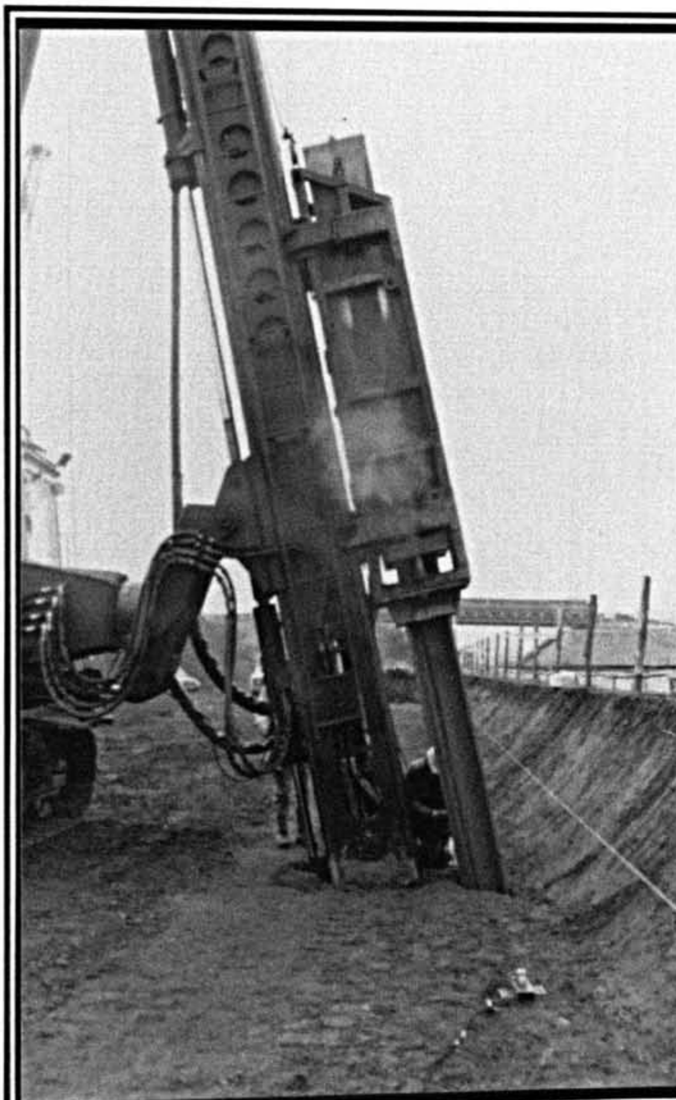


Plate (5-9) Driving an H-pile in a rake of 1:6
by a drop-hammer in Newark

Plate (5–10)

The use of air–hammer in driving of sheet–piles *Scarborough*

Plate (5-11)

Driving a raking H-pile by a diesel-hammer, Sheffield,

note the location of the pile in the excavated ground and the geophones on the ground surface

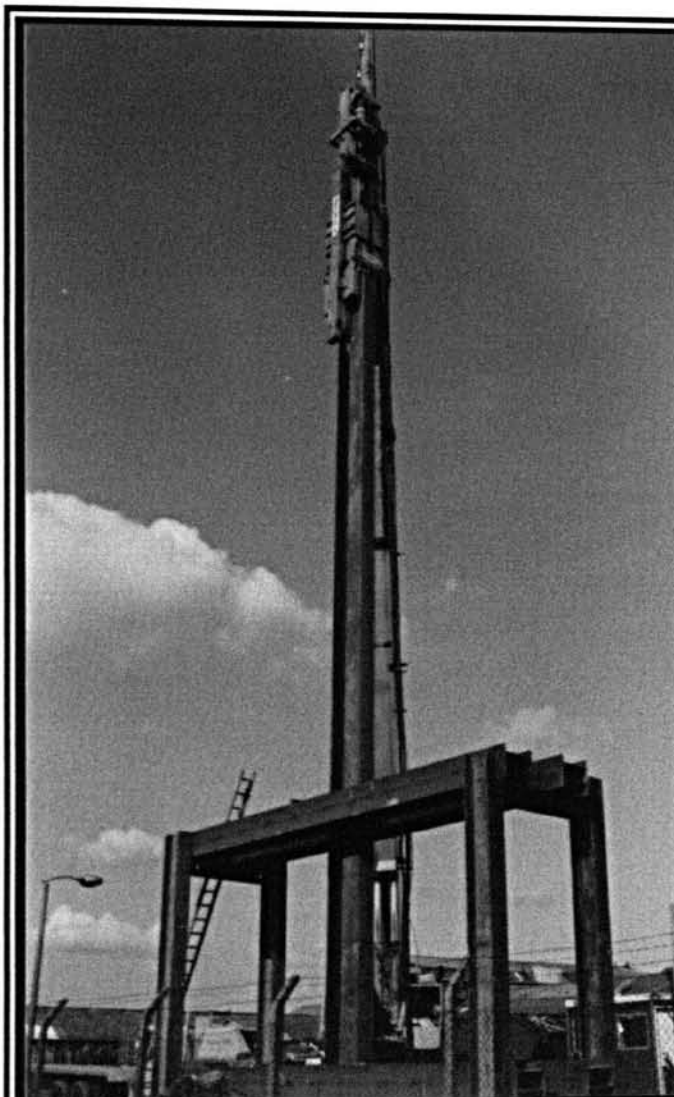


Plate (5-12) trial pile driving of pairs of sheet-pile by hydraulic-hammer, Waltham.Cross, London

Plate (5–13) Driving concrete–pile using drop–hammer
for construction of flats foundation, Whalley