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LANDFILL DESIGN, CONSTRUCTION AND NON-INVASIVE MONITORING

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LANDFILL DESIGN, CONSTRUCTION AND NON-INVASIVE MONITORING

Three techniques are investigated in order to assess their applicability for use in landfill design, construction and monitoring. Firstly, an assessment is made of QA procedures during liner construction through the detailed evaluation of two case studies. Construction QA procedures on-site are compared to available guidelines. The research illustrates the requirement for standardised, regulated QA procedures on landfill sites in order to provide a recognised framework for construction control. The Moisture Condition Value Test (MCV) is evaluated for use as a method of monitoring the placement of compacted clay landfill liners. London Clay and Mercia Mudstone, collected from the QA case study sites, are tested in terms of their suitability as engineered clay liners. Although, London Clay is the most acceptable it is this material which exhibits the poorest results in the MCV testing. This is due to seepage from the apparatus at high moisture contents. The research highlights the problems with the interpretation of the protocol for the testing and the differences between the Scottish and English Road Research Laboratory guidelines (Green & Hawkins, 1987). Thirdly, two airborne remote sensing techniques (ATM and CASI) are appraised as methods of monitoring landfill gas, or possibly leachate migration, from two case study landfill sites in South West England. Vegetation stress can be linked to landfill gas migration (Flower *et al.*, 1981) and this stress can be detected as a deviation from normal spectral reflectances in vegetation (Horler *et al.*, 1983a). Anomalies are identified on-site through remote sensing but they cannot be directly attributed to the landfills. This research emphasises the effects of contamination from other sources. It also requires the use of a simultaneous ground survey to collate data from boreholes with measurements of soil and vegetation types. Essentially, the QA case studies and the remote sensing show potential for future use and suggestions are made in this thesis for further research. The MCV technique provides a method for assessing the controlling parameters of compaction. With further development of aspects outlined in this investigation there is the potential for specified use of these techniques in landfill engineering and monitoring.

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LIST OF ABBREVIATIONS

ALK	Alkalinity
AOD	Above Ordnance Datum
ASTM	American Society of Testing Materials
ATM	Airborne Thematic Mapper
BATNEEC	Best Available Technology Not Entailing Excessive Cost
BES	Bentonite Enhanced Soils
BOD	Biochemical Oxygen Demand
BPEO	Best Practical Environmental Option
CAD	Computer Aided Design
CASI	Compact Airborne Spectrographic Imager
CEC	Cation Exchange Capacity
CCL	Compacted Clay Liner
COD	Chemical Oxygen Demand
CoPA	Control of Pollution Act
CQA	Construction Quality Assurance
CQC	Construction Quality Control
DN	Digital Number
DO	Dissolved Oxygen
DoE	Department of the Environment (now DETR)
DWM	Devon Waste Management
EA	Environment Agency
EIA	Environmental Impact Assessment
EM	Electromagnetic Spectrum
EPA	Environmental Protection Act
EU	European Union
FML	Flexible Membrane Liner
GCL	Geocomposite Liner
GIS	Geographical Information System
HDPE	High Density Polyethylene
HMIP	Her Majesty's Inspectorate of Pollution
IFOV	Instantaneous Field of View
LAWDC	Local Authority Waste Disposal Company
LCS	Leachate Collection System
LDPE	Low Density Polyethylene

LFG	Landfill Gas
LTP	Leachate Treatment Plant
LWRA	London Waste Regulation Authority
MCV	Moisture Condition Value
MW	Mega Watts
NERC	Natural Environment Research Council
NRA	National Rivers Authority
OMC	Optimum Moisture Content
PI	Plasticity Index
QA	Quality Assurance
QC	Quality Control
SISG	Site Investigation Steering Group
TOC	Total Organic Carbon
TON	Total Organic Nitrogen
TRRL	Transport and Road Research Laboratory (now TRL)
USEPA	United States Environmental Protection Agency
UV	Ultra Violet
VDU	Visual Display Unit
V:H	Vertical : Horizontal
VLDPE	Very Low Density Polyethylene
VOC	Volatile Organic Compound
WDA	Waste Disposal Authority
WRA	Waste Regulation Authority

$E_I(\lambda)$	Incident Energy
$E_T(\lambda)$	Transmitted Energy
$E_A(\lambda)$	Absorbed Energy
$E_R(\lambda)$	Reflected Energy
K	Hydraulic Conductivity
γ_d	Dry Density
γ_b	Bulk Density
γ_{dmax}	Maximum Dry Density
ω	Moisture Content
ω_l	Liquid Limit
ω_p	Plastic Limit
λ	Wavelength

λ_{re}	Red Edge Wavelength
$\rho\lambda$	Spectral Reflectance
$m^3\ t^{-1}$	Cubic metres per tonne
$mg\ l^{-1}$	Milligrams per litre
$\mu g\ l^{-1}$	Micrograms per litre
ppm	Parts per million
Meq/100g	Milliequivalents per 100 grams
$m\ s^{-1}$	Metres per second
MT	Million Tonnes
Km	Kilometres
m	metres
nm	Nanometers
µm	Micrometers

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AUTHORS DECLARATION

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PUBLICATIONS

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PRESENTATIONS AND CONFERENCES ATTENDED

- Symposium 'Protecting the Environment, Analysis for Landfill. Is it all a Waste of Time?' 28 Nov. Royal Society of Chemistry, London.
- 'Contaminated Land Course' at Camborne School of Mines, November 1995.
- Public inquiry for Haul Wastes proposed site at Uffculme, Somerset, May 1995.
- The Geological Society Geosynthetics Forum, May 1996.
- 'Progeo' Conference July 1997. Exeter.
- Institute of Waste Management (IWM) Annual Conference and Exhibition, June 1995,96,97 and workshops on *'Future possibilities for landfill in the UK'* and *'Careers in Waste Management'*.
- Presented research at the IWM South West AGM, Exeter, April 1996.
- Presented research at the Technology and Foresight in Science Conference, Dept Trade and Industry, Government Office South West. Taunton, March 1996.
- Presentation for the Usshers Annual Conference. Exeter, Jan. 1997.
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1.0 INTRODUCTION

1.1 INTRODUCTION

An integrated waste management system has been adopted in the United Kingdom (UK) as the main approach to the solution of the problem of waste disposal (DoE, 1995a). Waste management strategies have had to be adapted over time in order to keep pace with an increase in waste arisings. Landfill is one generally accepted solution and, indeed, is a requirement comprising a strategic element of current, overall waste management practice (DoE, 1995a). Landfill design, development and management have each been subjected to rigorous change over the past two decades in order to encourage safe, environmentally sound and sustainable waste disposal practice throughout the operational lifetime of a landfill site and into the future.

Historically, landfilling has been the most popular method of waste disposal since it has been a relatively cheap and 'efficient' option. However, attitudes to landfilling have changed. In the UK, landfilling is now index linked to financial taxation (DoE 1996a), the objective of which is to reduce the volume of waste deposited. More importantly, it has now been unquestionably proven that, unless controlled effectively, landfills can damage the environment in both the long and short term (Hart & Davy, 1996). Uncontrolled landfilling was merely a means to store waste, although it was recognised that it would create problems in future (Swinnerton, 1984). Consequently, the appearance of problems, such as contamination of groundwater, has led to the incorporation of landfilling within the sphere of modern environmental legislation. Current policy (DoE, 1995a) ensures that landfilling may be an acceptable practice and that the construction and operation of sites meet the latest legislation and controls.

1.2 WASTE MANAGEMENT ISSUES

There are five fundamental elements within a total waste management strategy:

- Production of waste;
- Reduction and minimisation of waste generated;
- Transportation;
- Recovery potential in the form of reuse and recycling;
- Disposal.

Waste Type	% Produced (1989-90)	Annual Arisings (MT*)
Agricultural	18	80
Mining & Quarrying	25	92
Industrial	16	69
Dredged Spoil	8	30
Sewage Sludge	8	33
Demolition & Construction	16	32
Household	5	20
Commercial	3	15
TOTAL	99%	371

*MT – Million Tonnes

Table 1.1 Estimated Waste Production (DoE, 1998a & DoE, 1995a).

Table 1.1 represents a break down of waste arisings in the UK. It illustrates the nature and scale of the waste disposal problem since there are over 370 Million Tonnes (MT) produced each year. The waste management industry must address the concept of environmental sustainability within the bounds of cost effectiveness, since, as global population increases, so too will waste production. The aim of a waste management strategy is to integrate effectiveness, in terms of long term disposal, with cost efficiency, to attain the best outcome in terms of the effects on the environment.

The reliance on landfilling within the current, complete waste management strategy is illustrated in Table 1.2. Landfill far outweighs any other current means of waste disposal. The proportion of recycling is higher than that of incineration (Table 1.2), highlighting the significance of recycling within the waste management hierarchy, particularly in the construction industry.

Waste Type	Landfill %	Incineration %	Recycled %	Other %
Household	90	5	5	0
Commercial	85	7.5	7.5	0
Construction & Demolition	30	0	63	7
Other Industrial	73	1	18	6
All Controlled	70	2	21	7

Table 1.2 Controlled Waste Disposal Routes (DoE, 1995a)

Landfilling is so heavily relied upon in the UK, that if an effective alternative were to be found, it would require many years of restructuring and re-education to make the change. The present UK waste management strategy (DoE 1995a) emphasises recovery. This policy anticipates limiting the increase in waste generation industrially, commercially and domestically. This in turn should result in a reduction in waste disposal to landfill. However, the strategy will still require a degree of landfill activity as a method of final disposal. There are limits to both recovery and recycling which are set by the nature of the materials and the economics of the programmes. Within current technology, certain materials cannot be recycled economically, whilst, in the case of others, recycling cannot always guarantee a perfect, uncontaminated final product outcome. Properties of recycled materials may in general be poorer than the original products from which they are derived, e.g., paper and glass. As a result, there is always a requirement for landfills.

1.3 LANDFILL DESIGN PHILOSOPHY

A principal factor for the achievement of safe and environmentally sound disposal of waste, lies in the design and engineering of an individual landfill site. Most landfills were, until the early 1980's unlined i.e., 'attenuate and disperse' sites (as described by Swinnerton 1984 in relation to the Wessex Region, and Bonney, 1984). Unlined sites are those based essentially upon the principles of attenuation as leachate seeps out of the site. The toxicity of the leachate seepage is stabilised through attenuation processes in the zone beneath the landfill, thus minimising risk to the environment. Originally, the nature of these attenuation effects was unknown, as indicated by Woodward (1906). However, research by Griffin *et al.* (1976) and Campbell *et al.* (1983), provided evidence of the attenuating capacity of clays in general and sand in the Lower Greensand respectively.

Lined, containment landfills require further controls for specific waste types. These lined landfills have engineered collection facilities in place for the control of the products resulting from the waste; leachates and landfill gases (LFGs). The objective of the lining system is to eliminate leakage. In practice this is not a straightforward task. Research into more environmentally sound and cost effective landfilling is essential. This is because there will always be a requirement for an improved final waste disposal method which poses the least environmental risk. An investigation into the practical realities of liner construction is illustrated through the case studies at Sites Alpha and Beta (Chapter Four).

1.4 SCOPE OF RESEARCH

1.4.1 Background

Landfill regulations and guidelines (e.g., DoE, 1986 & NWWDO, 1995) have assisted in the provision of a framework for the creation of fully designed and engineered landfill sites. This is to reduce the potential for pollution of the atmosphere, aquifers and surface waters. The extent and concentration of possible contamination is dependent upon a range of factors that impact upon landfill design, engineering and operation. These factors are investigated in detail in this thesis.

As background, this thesis investigates the changes in landfill philosophy over the past two decades and explores the reasons for this. The type of landfill design is fundamentally linked to the type of waste to be deposited and the ground conditions (IWM, 1998). Both regulatory and legislative frameworks have been examined in the light of the movement towards containment landfilling.

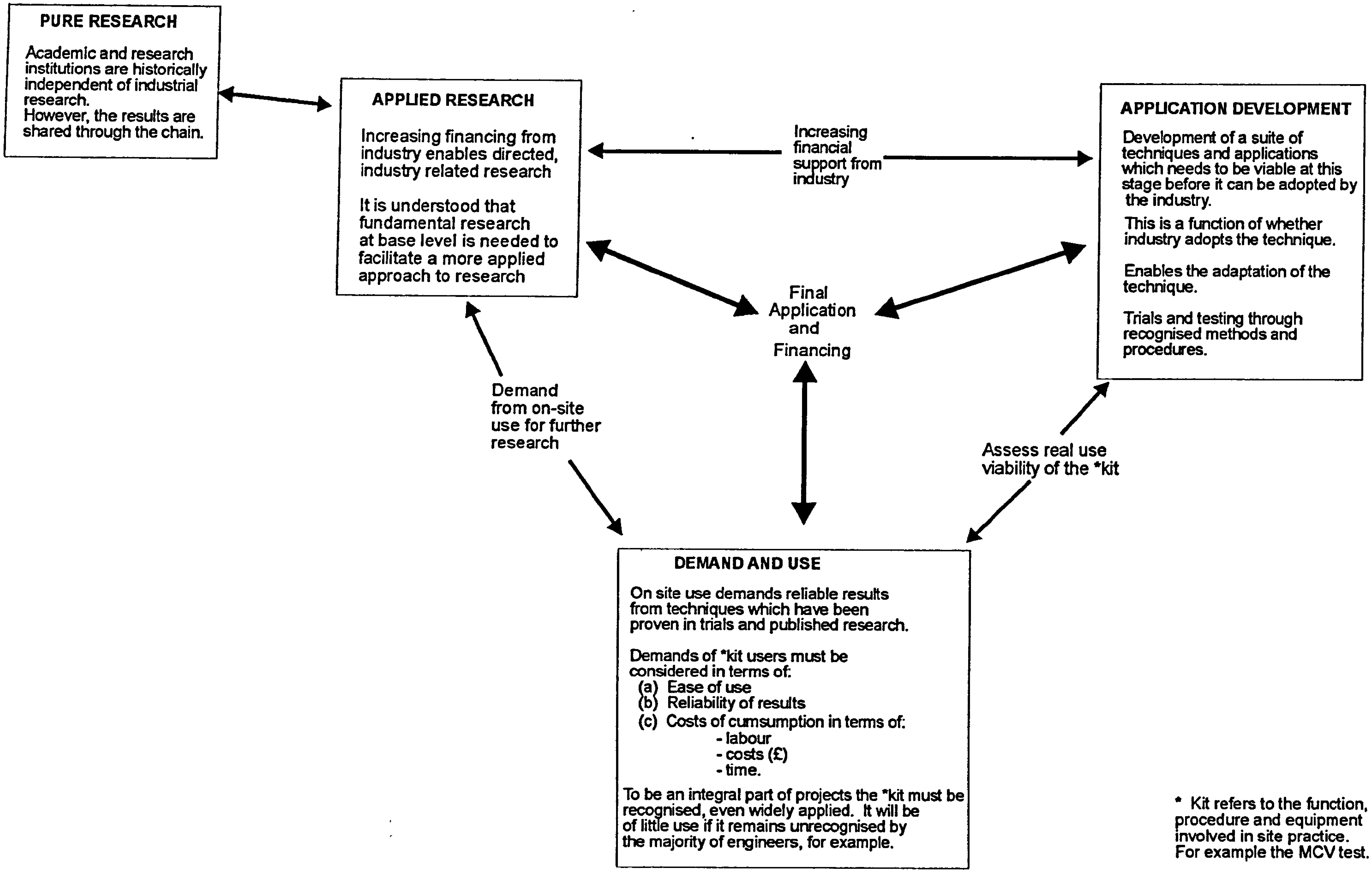
It is critical to consider the influence of legislation and Codes of Practice relating to landfill. Essentially, this will provide an understanding of how landfill technology has been directed by the experiences in the UK and Europe. Advances in landfill technology during the past two decades, have resulted in changes to existing policies and the instigation of new legislation and regulatory Codes of Practice (Bonney, 1984 and Cairncross, 1993). Indeed, the proposed European Commission Directive on the 'Landfilling of Waste' (EC, 1997), in its attempt to create a common European approach to waste disposal, (as early as 1991), acknowledges the rapid developments in the waste management industry. It is important to recognise this evolution since there are currently new laws and research which have been adopted in order to govern and regulate the field of landfilling (DoE, 1995a, 1995b, 1995c & 1994, for example). These are described in detail in Chapter Two.

Additionally, the achievement of a sustainable landfill design and management strategies aimed at safeguarding the environment is critical. The thesis puts this into context with regard to the current situation of landfilling in the UK. The provision of sections on landfill design, in Chapter Three, aim to illustrate the changing nature of strategies which are directly linked to other techniques researched for this thesis.

The three techniques presented in this thesis are the Quality Assurance (QA) of landfill construction, the Moisture Condition Value (MCV) Test and multispectral airborne remote sensing. These techniques have been developed for different purposes, although, the route to their final application by the landfill industry and the difficulties encountered in their acceptance as valid procedures are related. This investigation aims to explore the applicability of these three techniques to landfill site construction and monitoring.

The process for the development of a technique is illustrated through the use of Figure 1.1. It provides a model for the relationship between research, development, demand and use, in the evolutionary design and refinement of an application. This model has been developed to evaluate the use of these three particular applications in the landfill industry.

Problematic conditions arising during on-site work are usually the result of inadequate investigations conducted prior to commencement of earthworks and construction. This may be true in the macroscale, i.e. in broad terms, on all sites where investigation techniques are sufficient and have been applied appropriately. However, on the mesocale, i.e. specific to an individual site, unexpected ground conditions are most likely to be encountered to a certain extent. On-site problems arising in the latter case will be site specific and in most cases, could not have been predicted during the initial phases of site investigation. A combination of site, or even structure specific variables, may further culminate in necessary changes to construction, and construction monitoring techniques, after work has begun. Clearly, it is imperative that research is carried out in order to verify this. An opportunity to investigate the integrity of the site after earthworks and liner construction is then potentially available through the processes of Quality Assurance (QA). An investigation into the application of QA to address the issue of differences between guidelines and practical reality is described in the



* Kit refers to the function, procedure and equipment involved in site practice. For example the MCV test.

Figure 1.1 Relationship Between Research, Application Development and Demand following research carried out at two sites as described in Chapter Four. It is necessary to use case study landfill sites in order to acquire an appropriate knowledge foundation for this study.

On-site experience was seen as a pivotal point for this investigation, enabling an insight into landfilling in order to understand issues arising during the construction of a landfill site. It enables an understanding of the on-site restrictions and the differences between theoretical and laboratory conditions. For example, 'real' events that clearly need to be investigated and that one would anticipate to be important *a priori* include material standards; personnel management; financing and costings; operational and planning restraints and material delivery problems. Each of these is influential in the day to day running of a construction project, thus affecting the overall efficiency of its operation. Thus, the primary objective has been to achieve an understanding of landfill construction through experience, in order to provide a comparison with design and construction stipulations and regulations.

1.4.2 QA Case Studies

Quality Assurance programmes are increasingly influencing the effectiveness of the design and construction of a landfill lining system (Jessberger, 1994). In order to appraise the effectiveness of landfill QA, an investigation must be completed into its effectiveness on-site throughout construction phases. This is completed through the use of two contrasting landfill case studies, Sites Alpha and Beta. Design and construction issues are addressed, concerning:

- The choice of barrier system;
- The placement and Quality Assurance of clay and composite lining systems;
- Material suitability.

1.4.3 Moisture Condition Value (MCV) Testing

The importance of material suitability in the construction of landfill liners, as highlighted in Chapter Three, is assessed in this thesis. The Moisture Condition Value (MCV) technique was chosen for assessing clay suitability for landfill lining material taken from Sites Alpha and Beta. In order to determine suitability, it is essential to complete engineering tests, such as Atterberg testing (NWWRO, 1996), as outlined in Chapter Five. The MCV technique is investigated in its potential to monitor the placement of clays for lining landfill sites. It is chosen as a technique for use in this particular application due to its previous effective use for testing engineered fill (Parsons, 1979). The MCV testing for this investigation is conducted under laboratory conditions and its methodology is researched in order to compare with its potential use on-site.

1.4.4 Non-Invasive Airborne Remote Sensing

Monitoring is an integral part of the design, construction and management of a landfill site. Engineered, operational systems must now be provided throughout the lifetime of the site and into the future. The requirement for new systems which are fast and effective, whilst also being non-invasive, is examined with respect to the provision of a remote sensing technique. This thesis investigates the use of multispectral airborne remote sensing in the form of Airborne Thematic Mapper (ATM) and Compact Airborne Spectrographic Imager (CASI) for deployment in non-invasive landfill monitoring.

Multispectral remote sensing is evaluated as a method for monitoring landfill gas (LFG) and, possibly leachate migration using two contrasting case study landfills in the South West of England. The data is collected without ground survey information in order to assess the importance and validity of the results without ground referencing. It is thought that this would enable a faster monitoring process. The rapidity of data collection and manipulation and eventual sharing of the results with the site operators was to be appraised. Early on in the investigation, previous work indicated that stressed vegetation can be used as an indicator of landfill gas migration (Flower *et al.*, 1981) and that damaged vegetation has a different spectral signature to that of normal vegetation (Horler, 1983a, Rock *et al.* 1988). In combination, these observations could provide an effective monitoring tool which is investigated in Chapter Six.

1.5 OUTLINE AND SUMMARY OF OBJECTIVES

The thesis thus provides a detailed account of the current situation of landfilling in the UK together with research into QA procedures, the MCV and airbome remote sensing. The construction QA case studies indicate a requirement for alternative techniques to those currently available for landfill liner monitoring and contaminant monitoring. In terms of describing new development techniques, this thesis illustrates alternative construction monitoring and non-invasive contaminant monitoring methods available to the landfill industry. It is after all, the overriding responsibility of all parties involved in a landfill project, based upon current knowledge, to construct and manage a site which poses the least environmental risk throughout time.

Landfill satisfies the basic requirement for waste disposal. However, a question remains with regard to its suitability. Landfill must be judged in relation to current issues including: environmental impact, land availability and aesthetic effects which are present in both the short and the long term. The methods proposed by this investigation aim to assist in the provision of a landfill site which is both cost effective as well as offering minimal environmental impact in the long term.

The objectives therefore are:

- To provide a detailed account of the influential legislation and Codes of Practice relating to landfill;
- To outline the current situation in terms of landfill design and management strategies which can also be applied a basis for the landfill construction case studies;
- To investigate the construction QA procedures which are employed on-site through the use of case studies. To assess the requirement for a regulated QA on landfill sites;
- To evaluate the MCV technique in its use as a method for monitoring the placement of compacted clay landfill liners;
- To appraise the use of airborne remote sensing (ATM and CASI) as a method for monitoring landfill gas or leachate migration from the landfill.

2.0 LANDFILL LEGISLATION AND GUIDANCE

2.1 INTRODUCTION

The controls placed upon landfilling practices in the UK have been strengthened in the past two decades primarily due to environmental enlightenment of the effects of landfilling (Montgomery, 1992), increased policing by the NRA (now Environment Agency (EA)) and new European Union (EU) legislation (such as EC, 1991). The UK had originally been generally reliant upon attenuation landfills and, as other countries' policies changed, was increasingly influenced by 'successful' experiences in the US and Germany. This culminated in the implementation of the Groundwater Directive (EC, 1991) which required heavier controls to prevent any control of contamination of groundwaters. Environmental protection had become an issue of paramount importance, influenced by the general consensus of support from the public.

Due to changes in landfill design philosophies, alterations to legislation (DoE 1995c) have been accompanied by new guidelines issued by Government sources (1995a & 1995c for example) which are also affected by European Directives (EC 1997, 1994 & 1991). The guidelines reflect current thinking on landfilling operations whilst also considering the effects of other environmental policies, an important example being sustainability (DoE, 1995b). They must encourage the Best Practical Environmental Option (BPEO) for all landfills, with the current knowledge and available technology. The BPEO is the result of decision making and consultation processes which stress environmental protection and conservation in order to provide the most benefit or least damage (DoE, 1995a). Thus, guidelines must constantly evolve, in accordance with results from research, in order to provide the best environmental solution for waste disposal at any one time.

2.2 LEGISLATION

2.2.1 Legislation and Regulation

The role of landfill legislation and regulation is primarily to encourage protection of the human population and the environment into the future through pollution control, protection of health and safety and organised land management (DoE, 1996b). The responsibility for this falls mainly upon the Government in its legislative capacities. As a result, sites operating within the current prescribed standards should pose minimal risk. However, these standards cannot be imposed retroactively.

Cairncross (1993) states that UK legislation has addressed the issues of air and water pollution before those of solid waste landfilling. For example, the Clean Air Act (DoE, 1956) recognised the threat of air pollution and instigated measures to address it, twenty years before the formulation of any waste management legislation. This might be explained by the fact that waste is usually hidden underground and degrades over time, delaying the onset of any easily detectable problems until long in the future. Air and water pollution is generally visible and, if inhaled or imbibed, can be detrimental to public health. Waste confinement in specified areas minimises pollution however, the early landfill sites were clearly not as tightly controlled compared to their modern counterparts. Over the course of time, it has been seen that even controlled sites exhibit signs of pollution of groundwater, surface waters, soils although more frequently, the air in the immediate vicinity. Case study evidence of this is provided in IWM (1998b) in the case of gas migration from partially controlled sites.

This section addresses past and present legislative procedures impacting upon landfilling in the UK. Such explanation cannot be attempted without considering the wider European view, as the UK has developed and constantly has to reflect its legislative, economic and financial links with the EU. It is not feasible to overlook the importance of general environmental legislation, in terms of environmental protection, policies and governmental guidance. In particular, the National Rivers Authority Policy and Practice for the Protection of Groundwater (NRA, 1992), the EU Groundwater Directive (80/68/EEC) (EC, 1991), the Hazardous Waste Directive (EC, 1994) the Government White Paper 'This Common Inheritance' (DoE, 1990a), Special Waste Regulations (DoE, 1996c), and the Government instigated Waste Management Papers (Nos. 26 A (DoE, 1994) B (DoE, 1995b), D (DoE, 1998b), E (DoE, 1996b) and F (DoE, 1998c) which have been crucial to the formulation of UK policy. These clearly show that UK waste legislation and regulations are now mainly aimed at the protection of both ground and surface waters, as well as to air quality.

2.2.2 Legislative Terminology

Legislative terminology in this field aims to distinguish clearly between types of waste and their capabilities for contamination. For the purposes of this investigation, it is appropriate to outline the following definitions as used by the UK Government (DoE, 1995a) and the EU (EC, 1997):

'Waste' implies *'any substance or object ... which the producer or the person in possession of it discards or intends or is required to discard'*;

'Inert waste' implies that which does *'not undergo any significant physical, chemical or biological transformations. Inert waste will not dissolve, burn or otherwise physically or chemically react, biodegrade or adversely affect other matter with which it comes into contact in a way likely to give rise to environmental pollution or harm human health. The total leachability and pollutant content of the waste and the ecotoxicity of the leachate must be insignificant'*;

'Municipal solid waste' (MSW, domestic or putrescible) shall mean *'waste from households, as well as commercial, industrial, institutional and other waste which, because of its nature or composition, is similar to waste from households'*;

'Controlled waste' is the term used to imply household, industrial or commercial wastes solely, or in combination.
Other waste types include hazardous and non-hazardous wastes. This investigation is not directly concerned with these types of waste which require specific handling and treatment.

Ball & Bell (1997) describe the principle of gradualism in relation to pollution controls. This principle states that such controls should be adaptable according to economic climate, scientific attainments and the goodwill of producers. Therefore, any legislative and regulatory changes deemed appropriate should only be completed if the scientific basis is suitably reliable and supports the case for change. In this way, scientifically proven results of investigations and research projects influence regulatory and legislative procedures to a high degree. As explained in the next section, this has resulted in a delayed approach to waste management legislation and, possibly, system fragmentation.

2.2.3 Legislative Background

Environmental legislation specifically aimed at landfilling is a relatively new concept, having originated through the Deposit of Poisonous Wastes Act (DoE, 1972) (Ball & Bell, 1997), as a direct response to environmental disasters which had already occurred particularly, contamination in mining areas. As a result, waste management legislation originates in a reactive process, i.e. measures were initially only taken to protect the environment where failure had already occurred.

The 1972 Act was closely followed by a real attempt to address future problems in the form of the Control of Pollution Act 1974 (CoPA) (DoE, 1974). This proved to be a skeletal form of legislation. It soon became apparent that the CoPA (DoE, 1974) was insufficient to cope with the demands placed upon it by rapidly advancing technologies in waste disposal.

In the long term, one of the foremost drawbacks of the system laid out by CoPA (DoE, 1974) was the creation of Waste Disposal Authorities (WDAs). These were County Council run organisations in England, but District Councils in Wales, totalling 79 individual bodies. The WDAs were responsible for a licensing scheme for new waste disposal sites comprising mainly landfills or incinerators. Gronow (1993) states that it soon became apparent that CoPA (DoE, 1974) was insufficient, since the WDAs were able to operate their own sites in a county, and were responsible for the regulation of these as well as other, privately run, sites. Regulation of waste disposal sites was completed through the county organised Waste Regulation Authorities (WRAs), causing a conflict of interest.

Another shortcoming of this early legislation could be found in the new licensing scheme. For example, under CoPA (DoE, 1974), the licence holder had the right to hand back the site to the WRA at any stage during, or even prior, to completion. This ultimately meant that the WRA could be made responsible for a highly problematic site costing thousands of pounds to complete or remediate. Hence, the polluters were relatively easily able to renounce their responsibilities.

CoPA (DoE, 1974) also failed by not addressing other issues involving storage, transportation and treatment of waste. It was mainly concerned with the actual deposit of waste, which alone proved to be too restrictive. It became clear that it would be necessary to create regulations which would protect the environment, both the atmosphere and the lithosphere, in a more holistic fashion.

2.2.4 Recent Legislation

Waste disposal sites in the UK have always been required to obtain planning permission, even before the inception of CoPA (DoE, 1974). Prior to CoPA (DoE, 1974), it was covered in the Town and Country Planning Acts (Ball & Bell, 1997). Today, these Acts, the Town and Country Planning Act (DoE, 1990b) and the Planning and Compensation Act (DoE, 1991a), partially cover planning requirements. However, for the most part, the requirements, such as the need for an Environmental Impact Assessment (EIA), are dealt with under the umbrella of the Town and Country Planning Regulations Number 1199 (DoE, 1988).

The Environmental Protection Act (EPA), (DoE, 1990c) was a direct attempt by the Government to address and resolve the issues which had arisen since the introduction of CoPA (DoE, 1974). The EPA (DoE, 1990c) addresses issues such as waste regulation and licence surrendering, presenting them in a clearer fashion. This Act was strongly influenced by the advances made by both the German and US legal systems in environmental protection. Furthermore, it is arguable that the UK's legal system was inevitably also influenced by pressure groups and public opinion due to a rapid escalation in general awareness of environmental issues.

The EPA, Part 2 (DoE, 1990c) includes the 'Duty of Care' and 'Registration of Carriers' in an attempt to clarify responsibilities for waste. The Duty of Care places a legal responsibility for the waste on the producer who is responsible for the waste from the moment of its creation to the point of its disposal. The onus is now on the producer of controlled wastes through which it is hoped to discourage illegal (fly tipping) and unsustainable waste disposal.

In 1992 the Government outlined the possibility of creating an Environment Agency (EA) which was compared to that of the Environmental Protection Agency in the USA (USEPA). This organisation was to embody the Government organisations which operated separately and included: the NRA, the WRA's and Her Majesty's Inspectorate of Pollution (HMIP). It was hoped that through amalgamation, the existing interest overlap would be minimised, leading to a single, more efficient authority directed from one source. Thus, in

1994 the EA was born in England and Wales (SEPA in Scotland) with resultant reorganisation.

Under the EPA (DoE, 1990c), a landfill still requires a site licence from the EA as well as planning permission. In 1994 the Waste Management Licensing Regulations, (Part II of the EPA) were introduced. These regulations implement part of the EU Groundwater Directive (80/68/EEC) (EC, 1991) in order to protect groundwater quality (Rukin & Walker, 1998). Even at this early stage of the process, a large amount of detailed information is required. For example, statutory consultees must be consulted about the location and impact of a landfill, in both the short and long term. The process is then opened for public consultation, which itself necessitates close liaison between the main parties involved in a project: the statutory consultees, the landfill designer and the operator. Section 74 EPA (DoE, 1990c) sets out the requirements of a 'Fit and Proper Person' to hold a waste management licence. This requirement is applicable to all aspects of waste management and the body which applies for the licence and operates the site must now demonstrate it has achieved these requirements.

An applicant for a landfill licence is required to produce a document to account for the financial costs involved throughout all stages of landfilling. Once the landfill owner has proved that the landfill no longer has a capacity to pollute, the site may secure a 'Certificate of Completion' and the license surrendered. Owners are no longer able to surrender their licences at any point up to completion, indeed, they must prove that there are sufficient funds available to operate, restore and also to complete long term monitoring. In the draft compliance cost assessment published by the DoE, a polluting lifetime of a landfill site was limited to 30 years. Research (Lee & Jones, 1992b) has shown that processes of degradation may still be in operation within a site even after this period has elapsed. Any leachates and gases which had migrated within the attenuation layer still possess a polluting capacity, possibly up to 100 years after completion (Estrin &

Rowe, 1997).

It is, therefore, in the best legal interests of the engineer to ensure that minimum risk is a concept encapsulated in each landfill project. Estrin & Rowe (1997) highlight the importance of margin of safety measures which are adopted by the UK in the Engineering Council Code of Practice. These measures facilitate the reduction of the environmental risk posed by landfills, thus also diminishing the responsibility of the landfill engineer through the deployment of containment facilities based on the latest technological developments.

2.3 UK GOVERNMENT POLICIES

The Waste Strategy for England and Wales (DoE, 1995a) aimed to outline the main waste sources and the options available for their disposal. It states the policy for waste disposal in England and Wales, outlining the main aim which is waste reduction. The UK Government is now progressively committed to a recycling and waste minimisation policy, through which it is hoped to reduce the amount of waste going to landfill and, therefore, protect the environment for future generations. In this respect, the policy is based on principles of sustainability, encouraging an increased environmental efficiency of landfill operation.

A waste hierarchy has now been outlined comprising Reduction, Re-use and Recovery prior to waste disposal which is described as the *'least attractive option'* (DoE, 1995a). These options achieve a direct reduction in the amount of waste to be disposed of finally to landfill. Government policy states that there is no gain to be achieved from final disposal although, as illustrated in Chapter Three, LFG can be used to produce electricity. Landfilling of waste causes problems over a longer period of time in comparison with reduction, re-use and recovery which may be achieved and managed effectively with relative ease. The latter options have the ability to be more economical both in terms of the financial cost and the re-use of materials. Recycling currently perhaps has the highest profile, and is aimed at achieving a goal of 25 % reduction in the amount of biodegradable waste to landfill by 2006 and 65 % by 2016 from 1995 levels (Pearce, 1998). In line with this are targets for the Packaging Waste Directive which aims to achieve 50 to 65 % recovery by 2001 (DoE, 1995a). Thus, the Government is firmly committed to the reduction of waste disposal through landfill or incineration. Landfill, however, is the only waste management process to be described as final disposal. Incineration, for example, still produces waste, in the form of a cake, which must be disposed of to landfill.

In 1996 a tax (DoE 1996a) was imposed on waste going to landfill at £7 per ton of hazardous wastes and £2 per ton of inert which in April 1999 is to be increased to £10 for the former (Pearce, 1998 and IWM, 1998a). This acted towards promoting recovery and reducing landfilling, the price of disposal to landfill reflecting the environmental costs (DoE, 1995a). In this respect the 'polluter pays' mechanism was enacted. Ball & Bell (1997) state that the EC (European Community) had always included this principle within its policy framework (Economic Commission Article 130R(2)). It implies that the producer of goods should be responsible for the costs of preventing or dealing with any of the polluting processes it causes. Thus, the costs of landfilling should be attributed to the waste producers in order to provide a financial incentive to reduce waste production.

2.4 EUROPEAN UNION DIRECTIVES

The EC Landfill Directive (97/0085 (SYN)) (EC, 1997) is currently progressing through the European Parliament and once implemented will have extensive implications for UK practice. It will affect the type and quantity of wastes which are currently sent to landfill whilst also stipulating stricter controls on current regulatory and operational management strategies.

The EC Landfill Directive (EC, 1997) has stipulated the collection and treatment of leachates through the employment of contained landfill which will result in attenuate and disperse sites eventually being phased out. The latter are still currently used in the UK and are monitored closely but still rely on the *proviso* that the migrating contaminants will be attenuated in the unsaturated zone under natural conditions.

Bradley (1997) states that in the drive to commit to policies of sustainable development, the EU has been able to promote the reduction of waste and pre-treatment prior to landfilling. A main objective of EU policies is to encourage the reduction of the organic content in wastes disposed of to landfill through pre-treatment. This has resulted in pressure on the industry in the UK to do the same.

2.5 GROUNDWATER PROTECTION

Groundwater protection is a prime concern throughout the landfilling process. Mather (1992) notes that in England and Wales, 32 to 70 % of public water supplies are derived from groundwater sources. Therefore, protection of these potable sources must be prevalent in the environmental protection legislation. Lee & Jones (1992b) indicate that of the 75,000 landfills in the USA, approximately 75 % are polluting groundwaters, compared to 1 in 60 in the UK (Roche, 1996). The importance of recognising the potential impact on groundwaters is seen by Waste Management Paper 26B (DoE, 1995b) which advocates the use of risk assessment as a method for quantitative analysis.

Groundwater is defined by the Groundwater Directive (EC, 1991) as the *'liquid in the zone below the uppermost level of the water table'*. Conversely, the Water Resources Act (DoE, 1991b) includes all water in underground strata (Hart & Davy, 1996). Both of these are used as legal definitions under the term 'controlled waters' (DoE, 1991b) to enable the protection of all groundwaters from point or diffuse pollution sources.

The Policy and Practice for the Protection of Groundwater (NRA, 1992) provides a framework for the protection of groundwaters in the UK. It enables the recognition of the aquifer protection policy and classification of vulnerable zones, which, in turn, denotes areas of acceptability and unacceptability for landfill sites. Engineering requirements for landfill design must encompass the minimisation of contamination. Stringent monitoring requirements are, however, still stipulated for all sites. Thus, as a direct result, attenuate and disperse sites are being phased out, especially in potable water zones, and replaced by engineered containment sites to prevent aquifer contamination. There is currently an on going debate into the effectiveness of attenuate and disperse sites with respect to the protection of groundwaters. Concern for the protection of existing groundwater reserves has led to the encouragement of containment sites, however, the potential for these sites to operate at 100% efficiently is questioned in Chapter Three.

2.6 GUIDELINES FOR LANDFILL PRACTICE

It is obviously in the best interest of the landfill operator to adhere to guidelines. The role of the landfill designer and engineer is to liaise with the regulatory authority in order to produce a design, specific to the site, which poses the least risk, complies with guidelines and enables the achievement of a profit margin. In addition, this must ensure the use of Best Available Technology Not Entailing Excessive Cost (BATNEEC) (DoE, 1995b).

The document 'Guidance on Good Practice for Landfill Engineering' (DoE, 1996b) aims to offer a basis for the achievement of 'environmentally safe' landfills. It is possible that these initial types of independent guidelines can be used to provide the framework for future Department of the Environment, Trade and Regions (DETR) regulations and legislation.

Estrin & Rowe (1997) note that most regulatory agencies outline prescriptive standards for landfill sites as opposed to performance based ones, which could improve the operation of the sites, i.e. based upon a liner permeability of no more than 1 x 10^{-9} ms^{-1} and a 1 m leachate head. This is especially seen in the details of minimum standards for landfill liners and was defined in Waste Management Paper No. 26 (DoE, 1986), which as Rukin & Walker (1998) state, was preceded in the requirements of the North West Waste Regulation Authority (NWWRA) in 1979. However, these are standards implemented without prior investigation into the level of control which is required by an individual site. Full implications in terms of costs, both operational and outlay, and long term environmental impact of the site are therefore generally ignored through this method. Interestingly, Rukin & Walker (1998) highlight that in most cases the landfill operator will accept the conditions outlined by the overseeing EA office without challenge. This inevitably hastens the planning process but does not necessarily permit the most suitable approach. Therefore, the use of a risk assessment for the proposed site remains underestimated by both parties. The importance of the relationship between the EA and the designer is vital to the success of the project but compromise is not always easy. The current state of the reorganisation of management and policies has caused a 'lack of policy consistency' resulting in different approaches being implemented across the country (Rukin & Walker, 1998).

Estrin & Rowe (1997) indicate that the timescale for concern about a landfill site is generally limited. Sites in the UK were deemed to be potentially problematic for a period of 30 to 50 years following completion. Today, however, a landfill site is deemed to be a potential polluter until the owner can prove, using monitoring applications, that the site is no longer producing dangerous levels of leachates or gases. This period therefore cannot necessarily be defined with precision given the unknown quantities of waste degradation, water influx and leachate quantity and quality.

2.6.1 Design Regulations

Estrin & Rowe (1997) compare the regulatory designs of the USA, Germany and the EC Directive (EC, 1997) (Table 2.1). The German standard is immediately noticeable since it has a minimum of 3.75 m attenuation layer (including Compacted Clay Liner (CCL)) in total, in comparison with the 1 m of the EC and 0.6 m of USA. Calculations by Estrin & Rowe (1997) revealed that the seepage of highest quantities would occur through the US liner, to reach the aquifer below. Based upon specified premises of retardation in the attenuation layer, concentration and diffusivity, results indicated that after 14 years the maximum acceptable concentration (50 $\mu g\ l^{-1}$ of organic carbon) would be attained and it would peak at approximately four times this level after 44 years. In comparison, the

Minimum Design	Geomembrane	Compacted Clay Layer (CCL)	Attenuation Layer
USA (EPA)	1.5 mm HDPE	0.6 m CCL $K \leq 10^{-9}\ ms^{-1}$	N/A
EC Directive	Geomembrane	N/A	1 m attenuation layer $K \leq 10^{-9}\ ms^{-1}$
Germany	2.5 mm geomembrane	0.75 m CCL $K \leq 5 \times 10^{-9}\ ms^{-1}$	3 m geological barrier $K \leq 10^{-7}\ ms^{-1}$

Table 2.1 Minimum Design Requirements for Landfill Liners (Estrin & Rowe, 1997)

German liner gave a maximum of 0.2 $\mu g l^{-1}$ organic carbon in the aquifer at 150 years. The EC approach resulted in a peak at 70 years. These results give an idea of the effects of variation within standards in current operation in different countries. The EC proposals must consider the strategies of those countries, such as the UK which employ less strict guidelines for sites, whilst also attempting to include more complex approaches, such as those in Germany. They remain, however, merely guidelines and it is up to the regulators and the site designers to achieve the best environmental option for each individual site.

A further point of interest is associated with the stipulated maximum head of leachate. In most cases this is 1 m and is incorporated within the design strategy. However, basal lining has reduced the need for this, since the approach is now to encourage waste degradation which necessitates wet conditions to increase the rate of stabilisation.

The primary aim of the EC policy, the Council Directive (EC, 1997) on the Landfill of Waste (EC, 1997), is to homogenise the approach to landfilling carried out by all the member states. The Environment Act (DoE, 1995c) states that the EU as a whole will *'become self-sufficient in waste disposal'* which will be completed through individual plans implemented by the Member States. It has been illustrated that there are differing philosophies in operation at present which could inevitably lead to future problems.

General basic requirements, as outlined in the EC Directive (EC, 1997), are already largely in use. However, municipal waste landfills are now required to be situated 0.5 km from urban sites or waterbodies and 2 km distance in the case of hazardous sites. This may lead to difficulties involving landfill siting in the UK, which does not appear to have the availability of locations respecting such requirements. This was only a minor change in comparison with the aim to phase out co-disposal and to enforce lining for all sites.

Waste Type	**Liner Permeability**	**Liner Thickness**
Inert	$K \leq 1 \times 10^{-7}$ ms^{-1}	≥ 1 m
Non-hazardous	$K \leq 1 \times 10^{-9}$ ms^{-1}	≥ 1 m
Hazardous	$K \leq 1 \times 10^{-9}$ ms^{-1}	≥ 5 m

Table 2.2 Landfill Liner Minimum Standards (EC, 1997).

Table 2.2 gives the EC standard landfill liner stipulations according to waste type. In circumstances where the geological barrier does not naturally achieve these specifications it must be engineered to a minimum thickness of 0.5 m. Attenuation processes below the landfill liner are therefore still relied upon, although the policy is one of engineered containment. A suitable geological barrier must be provided in order to prevent or at least reduce the risk to groundwater and soils in the environs.

2.6.2 Landfill Guidelines

In the UK there are several bodies which have set guidelines for the landfill engineer. These include the papers in the Waste Management series, North West Waste Regulation Officers Sub-Group Technical Reports (NWWRO, 1995 & 1996) and Guidance on Good Practice for Landfill Engineering (DoE, 1996b). These are based upon input from researchers in the field and landfill engineers, operators and regulators. They provide sources of reference but do not act as Codes of Practice.

The main Codes of Practice related to landfilling include the British Standards for Site Investigation BS 5930 (1981), Soils Testing BS 1377 (BSI, 1990) and for Earthworks (BS 6091) (BSI, 1981). The Department of Transport Specification for Highway Works Series 600 (DoT, 1991) is also relevant to landfilling and its application is explained in further detail in Chapter Five. These are derived predominantly from civil engineering and at present there are no Codes of Practice in use specifically related to landfill construction. However, there are stipulated standards for drilling of landfills given by the British Drilling Association 'Guidelines for the Safe Investigation by Drilling of Landfills and Contaminated Land' (1988), DD 175 (BDA, 1992) and Site Investigation in Construction (SISG, 1993 a & b). Drilling guidelines are necessary in order to install boreholes in a completed landfill for proactive monitoring purposes. In addition, Waste Management Papers (DoE, 1998c, 1996b, 1996d, 1995a & 1994) provide guidelines for construction.

The guidelines published by the NWWRO (1995 & 1996) aim to provide a reference base for the landfill engineer since many changes have occurred in the design and construction of landfills in recent years. These are not intended to be specifications for landfill construction, in the way the Earthworks Specifications (DoT, 1991) are regarded in Engineering practice. However, it is necessary to comprehend the complete changes experienced in this field and therefore guidance notes of just a few years ago will today be completely outdated. The field continues to advance rapidly, which is reflected in these guidelines. DoE (1996b) gives additional information about the processes of site investigation, liner choice and construction, quality assurance and monitoring.

2.7 DISCUSSION

This Chapter has outlined the main legislative and regulatory requirements for landfilling in the UK at the present day. This is a continually evolving process, that is closely linked to available technologies and current research into understanding the processes involved within the waste mass and environs of the landfill. Changes in the philosophy of landfilling have necessitated the adoption of new guidelines and regulations. This has outlined a common framework for the design, construction and operation of landfills.

In the past, environmental legislation took a reactive form, but this has now been superseded by a more proactive approach. Measures are now designed within the framework to assist in the prevention of environmental disasters rather than merely dealing with the problems created after an incident has occurred. However, it should be recognised that with even the most efficient controls, regulations and legislation in place, difficulties cannot always be averted. For example, the general problems of controlling leachates and gases within a confined site give rise to engineering construction and operational problems to enable their permanent control.

The landfill legislative system in the UK has inevitably become highly influenced by

European practice. The UK is now influenced (or restricted) by events elsewhere, perhaps because of the reactive nature of its early legislative procedures. For example, the possibility for the removal of the co-disposal landfilling practice from waste disposal routes in the UK, as stipulated in EC proposals. However, the process of building a comprehensive European framework is not yet complete and, to date it has not been harmonious.

This chapter has also attempted to illustrate the nature of some of the discrepancies within current procedures. The fragmentation of the governing system appears to have been inevitable considering the nature of the origins of legislation and regulations. Furthermore, both of these must be put into practice in order to reveal their shortcomings and problematic areas. With regard to the design and construction of landfill sites, legislation can only provide a minimum standard, which is to be inevitably questioned in the light of future research and experience. The most widely recognised requirement is to acknowledge and assess the potential risk posed by a landfill site on the environment, with a final aim of complete risk reduction.

Regulatory processes can stipulate certain routes to the achievement of the best environmental option, however, the parties involved need to liaise in order to construct and operate a site. It is hoped that through this liaison, the most suitable approach will be achieved, although situations may still arise involving disagreements between parties.

This chapter has provided a review of the main legislative procedures currently in operation in the UK. Emphasis has been placed upon the changes which new European led legislation and regulations will have upon landfilling practice. It is now hoped that with the presence of one general body, the EA, consultation for new landfills and the licensing and regulation of operating sites will be greatly improved. The almost total reliance upon landfilling within the current waste management strategy will in the future be reduced by recovery of waste. This being a main objective in the UK's waste management strategy outlined in the Waste Strategy for England and Wales (DoE, 1995a) and enacted by the Environment Act (DoE, 1995c) Section 12, Schedule 12.

2.8 SUMMARY

- Landfill legislation and guidance aim to provide the framework for landfilling which poses the least environmental risk and which encompasses the implications of sustainability concepts.

- There is a requirement for a new legislative framework to address and resolve problems arising from waste management issues. Individual Government legislation must adhere to the trends of European policies and legislation relating to waste management.

- A changing emphasis on the Codes of Practice in the UK for modem landfilling techniques has been influenced by American and German practices and advances in technology and materials science.

- Legislation and guidance provides minimum prescriptive standards for landfill design and practice (as opposed to performance based ones), although their shortcomings are not usually recognised until the system is realised and operational.

- Waste management legislation and regulations relating to landfill operations have an opportunity to achieve uniformity across Europe through the EC Landfill Directive. However, Codes of Practice relating to design requirements are still relatively varied between countries.

3.0 LANDFILL SYSTEMS

3.1 INTRODUCTION

An important theme throughout this thesis is the growing concern regarding the anthropogenic effects of landfilling on the environment. In converse to the understanding of Geological Time (i.e. the present is the key to the past), it could be said of landfilling that it is the practice of the past which may be a key to the present, and indeed, the future. Old landfill sites now provide a basis for studies about the effects of decomposing waste on the environment. These original sites were completed without guidance in terms of design, construction and monitoring indicated as early as Woodward (1906).

This chapter provides a discussion of the philosophies behind and components involved in landfill design and the environmental and engineering management techniques for landfill sites. It attempts to provide a basis for an understanding of the fundamental aspects of landfilling design in the UK. Changes in design have facilitated the use of new materials for construction and operation. Little is known about the long term effects upon these, however, they are highly dependent upon understanding the active processes in operation within the waste mass. Due to the inhomogeneous nature of wastes, areas of this understanding are fairly convoluted.

Landfill practice in the UK has been strongly influenced by the waste management criteria imposed in other countries, predominantly Germany and the USA (Chapter Two). Landfills now involve complex engineering structures and, as discussed later, landfill engineers are required to be knowledgeable over a very broad spectrum of ideas and technologies.

3.2 LEACHATE AND LANDFILL GAS

The degradation of wastes over time within a landfill system produces secondary aqueous and gaseous products, leachates and landfill gases (LFGs). Experiments by Jones and Owen (1932), as discussed in Mather (1992), revealed that decaying wastes produced gases, although, at that time, the consequences were not fully understood. Both leachate and LFG have since proved their potential to exhibit extremely hazardous properties and demonstrated their ability to migrate from the site should conditions allow. The probability of the latter ultimately lies with the geological and geochemical properties of the surrounding rock strata of the site and the nature of the contaminants themselves.

The inception of the total containment principle, i.e. the inclusion of a provision for management schemes for leachates and LFGs, has facilitated some control on their production. In addition, it may become necessary to consider the development of possible on-site works for their treatment. The latter has thus become a part of waste management in itself (Christensen *et al.*, 1992). Therefore, in order to evolve complementary treatment practices, it is critical to understand the generation and composition of both leachates and LFGs. For example, the estimation of flow regimes through the waste is important in order to comprehend rates of generation and to plan appropriate engineered environmental management schemes.

3.2.1 Leachate Generation and Composition

Leachate is the solution produced by the decomposition of the wastes in the landfill in combination with rainfall which is intercepted by the waste body. The decomposition mechanisms encompass the degradation of organic matter and the leaching and dissolution of readily soluble constituents within the waste. Rainfall is a highly influential factor in the quantity and quality of leachate generated, thus making it variable and therefore individual to each site (Ham & Bookter, 1982). The composition and rate of flow may be subject to seasonal variations to the point that during summer months, leachate production may cease altogether (Robinson & Maris, 1983). Chemical composition is also importantly affected by waste composition, pH, redox potential (Eh) and landfill age

Parameter	Range
COD (mg l^{-1})	150-100 000
BOD (mg l^{-1})	100-90 000
Ph	5.3-8.5
Alkalinity (mg$CaCO_3$ l^{-1})	300-11 500
Hardness (mg$CaCO_3$ l^{-1})	500-8900
NH_4 (mg l^{-1})	1-1500
N_{org}(mg l^{-1})	1-2000
N (mg l^{-1})	50-5000
NO_3 (mg l^{-1})	0.1-50
NO_2 (mg l^{-1})	0-25
P (mg l^{-1})	0.1-30
PO_4 (mg l^{-1})	0.3-25
Ca (mg l^{-1})	10-2500
Mg (mg l^{-1})	50-1150
Na (mg l^{-1})	50-4000
K (mg l^{-1})	10-2500
SO_4 (mg l^{-1})	10-1200
Cl (mg l^{-1})	30-4000
Fe (mg l^{-1})	0.4-2200
Zn (mg l^{-1})	0.05-170
Mn (mg l^{-1})	0.4-50
CN (mg l^{-1})	0.04-90
AOX[a] (µg Cl l^{-1})	320-3500
Phenol (mg l^{-1})	0.04-44
As (µg l^{-1})	5-1600
Cd (µg l^{-1})	0.5-140
Co (µg l^{-1})	4-950
Ni (µg l^{-1})	20-2050
Pb (µg l^{-1})	8-1020
Cr (µg l^{-1})	30-1600
Cu (µg l^{-1})	4-1400
Hg (µg l^{-1})	0.2-50

[a] Adsorbable Organic Halogen
COD Chemical Oxygen Demand
BOD Biochemical Oxygen Demand

Table 3.1 Typical Leachate Composition (Andreolotta & Cannas, 1992).

(Andreolotta & Cannas, 1992). Thus, there can be little possibility for identical leachates, only common components which are found typically to comprise the solutions (Table 3.1).Phillips *et al.* (1994) have identified five stages of chemical transformation that are operational within a landfill site. These are predominantly based upon the work of Farquar & Rovers (1973), which is detailed later:

1. Waste emplacement, moisture accumulation and site closure.
2. Anaerobic microbial activity increases as oxygen is depleted; reducing conditions form; biological activity produces volatile carboxylic acids which dissolve to form leachate.
3. Shorter chain carboxylic acids are produced which further lowers the pH; waste metals form complexes; esters are produced; the leachate has a high organic content.
4. Methane is produced; consumption of carboxylic acids as pH increases; metals precipitate; leachate decreases in organic content.
5. Oxygen slowly reappears; methane production ceases; humic-like substances complex with heavy metals.

This can be fitted to the diagram of Farquar & Rover's work on LFGs in Figure 3.1. The composition and generation of landfill leachate is thus seen to be highly complex, therefore research completed on one site may only be indicative of that particular site. However, in a broader sense, the main recognised processes in operation and their relative timing within production and generation processes may be recognised between sites.

3.2.2 Landfill Gases

The decomposition of waste through volatisation processes and chemical reactions of

WASTE CHARACTERISTICS	***MANAGEMENT FACTORS***	***PHYSICAL AND CLIMATIC FACTORS***	***KEY GAS GENERATION FACTORS***
Placement method e.g. area, trench	Waste compaction	Air temperature	Oxygen - Aeration
Composition	Form e.g. bales	Precipitation	Moisture
Density	Depth of fill	Atmospheric Pressures	Nutrients
Moisture content	Area of waste fill	Land form	pH
Age	Daily cover; thickness, absorbing and Adsorbing capabilities	Hydrogeology	Eh
Drainage		Ground permeability	Temperature
Cover e.g. final or Intermediate		Topography	Toxicity

Table 3.2 Factors Affecting Landfill Gas Generation.

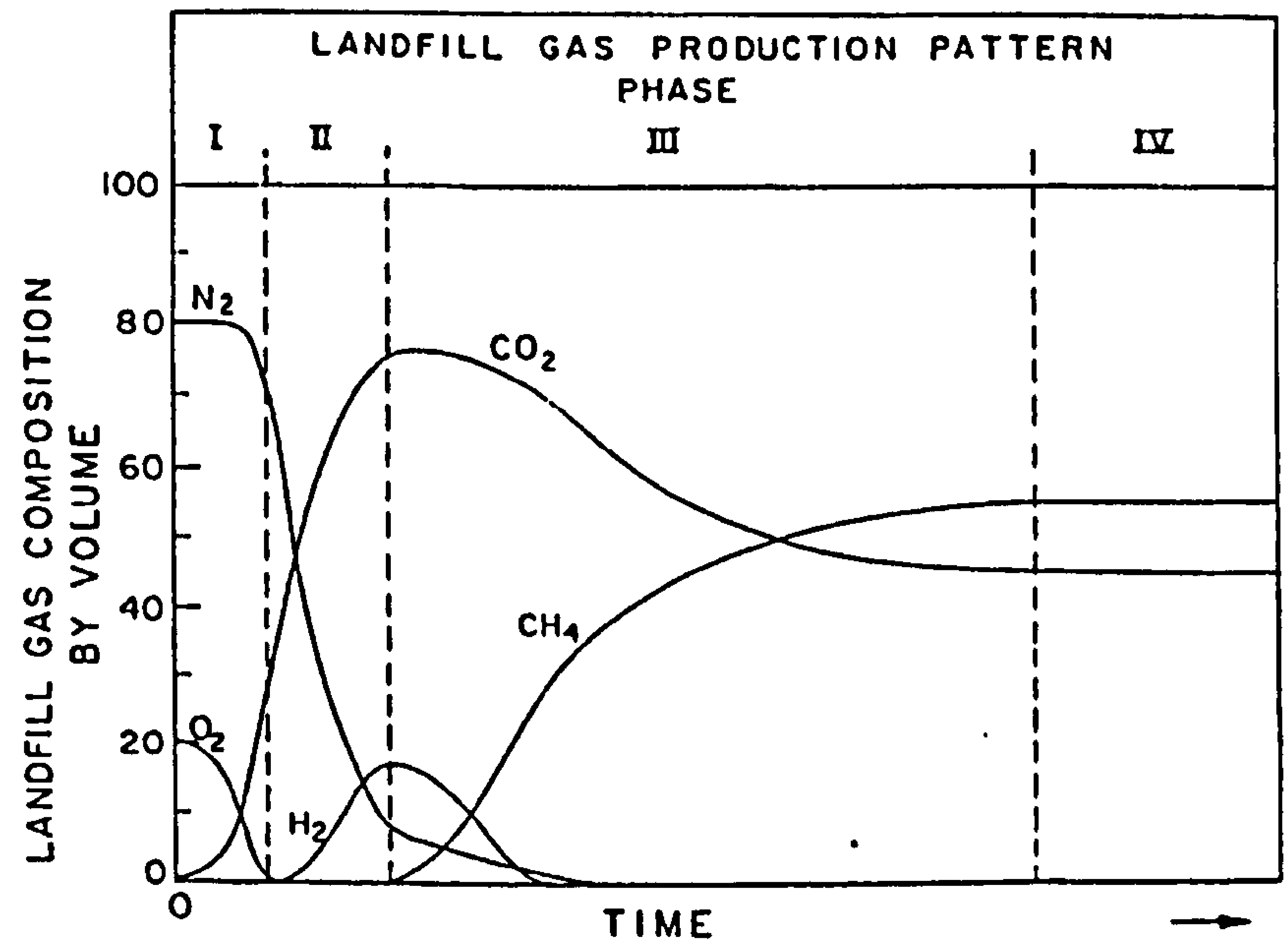
Adapted from Campbell, (1985) and Farquar & Rovers, (1973).

micro-organisms under aerobic conditions generates a variety of LFGs, for example, methane (CH_4), carbon dioxide (CO_2) (Cemuschi & Giugliano, 1989 and Senior, 1984). Gas generation therefore depends upon the characteristics and parameters as outlined in Table 3.2. Gas generation will begin from approximately 6 to 12 months after the first stages of waste inception, (i.e. during the operational stage of the landfill), possibly through decades after completion (Falzon, 1997). In order to design a landfill site which can control the generation and release of these gases, it is important to understand the nature of the gases and their properties and thus estimate the length of time the landfill will take to reach a steady state equilibrium.

Although the presence of landfill gases has always been acknowledged, until relatively recently (post 1986), there was a limited awareness of the need for their monitoring and control measures, hence the latter were not originally incorporated into site design. Indeed, Campbell (1989a) indicates that this may be due to *'a lack of understanding of the basic nature and composition of the gases; potential production rates and yields'.* This changed with *'a realisation of the potential adverse environmental impacts resulting from the uncontrolled release of gas'* (Campbell, 1989a). The problems incurred by the production of gases (for example Loscoe, Section 3.2.7) have, however, been exacerbated by landfill practices today coupled with increasing public awareness of environmental protection. Research into gas production from landfill sites has revealed that there is indeed a danger due to the quantities produced and the properties of the gas, namely its high combustibility (Jarre *et al.*, 1997), which are both predominantly related to the composition of the wastes.

3.2.3 Landfill Gas Generation

The pioneering study by Farquhar & Rovers (1973) is the main source of reference on the production of LFGs throughout the stages of waste degradation. The study identified four stages in the decomposition of the waste which affected the gas production. Figure 3.1 illustrates the composition of the gas by volume in terms of the four identified phases. Prior to this influential research, the mechanism for the production and estimation of the quantities of these gases had not been identified, since, before the 1960's, there was very little published evidence (Campbell, 1989a). Researchers still attempt to recreate such an explanatory model in relation to the production of leachate. To date, this has not been achieved as effectively, but in the event, it would provide an interesting focus in order to attempt integration with the work of Farquar & Rovers (1973). The alternative



Phase I: Aerobic

Consumption of the oxygen occurs predominantly at the time of waste placement.

Phase II: Anaerobic Non-Methanogenic

Carbon dioxide bloom and some hydrogen production.

Phase III: Anaerobic Methanogenic Unsteady

Increase in methane concentration to some 'relatively constant terminal value' and reduction of carbon dioxide and nitrogen to terminal levels.

Phase IV: Anaerobic Methanogenic Steady

Phase V Steady production rates achieved. Abrupt changes in the gas composition at this stage may illustrate changes in environmental conditions.

Over the long term methane formation becomes negligible. Solid organic carbon oxidised to form CO_2. Rates of the processes begin to reach those in the 'active soil' so the LFG starts to resemble soil air (IWM, 1998b)

Figure 3.1 Sanitary Landfill Gas Production Pattern (Farquar & Rovers, 1973).

solution, which is currently in use, is to attempt to fit the production of leachate within the structure of the Farquar & Rovers (1973) model.

Farquar & Rovers' research (1973) noted that, although the above explanation is typical, there may be changes in relation to differing conditions at individual landfills which is to be expected with consideration to variations in the type of waste (Willumsen, 1996). These conditions are generally the same as those that affect the production of leachates in the waste body, as discussed earlier. This is to be a repetitive theme throughout this investigation, underlining the proposition that landfills are site specific and that their chemical and biological behaviour depends upon varying circumstances experienced at each individual landfill site.

3.2.4 LFG Composition and Rates of Production

LFG composition and production rates are a function of the nature of the organic matter of the wastes, its biodegradability and the moisture content and temperature within the system. Table 3.3 illustrates the typical composition of landfill gases, indicating their diverse nature and the resultant problems which may occur.

The rates of gas generation decrease over time with the maximum being phases II and IV in Farquar & Rover's (1973) model. Theoretical yields may be in the region of 400 - 550 $m^3 t^{-1}$ over a 10 - 30 year period (Campbell, 1989a). Cossu *et al.* (1996) give a breakdown of the reported LFG generation yields (Phase III) which vary from 40- 50 $m^3 t^{-1}$ Municipal Solid Waste (MSW) by Bowerman *et al.* (1977) to as much as 400 $m^3 t^{-1}$ MSW.

Methane is the largest contributor to LFG composition, while approximately half as much carbon dioxide is produced based on typical values (Table 3.2). Willumsen (1996)

COMPONENT	Typical value[∂] (mature refuse) % by volume	Observed maximum[∂] % by volume	Stage of Production	Properties
Methane*	68.2	77.1	Anaerobic methanogenic unsteady	Combustible
Carbon Dioxide	33.6	89.3	Anaerobic non-methanogenic	Acidification of groundwater and displacement of O_2 in soil.
Oxygen	0.16	20.9	Aerobic	Odourless
Nitrogen	2.4	80.3	Anaerobic	Inert but combines with H^+ to form ammonia
Hydrogen	< 0.05	21.1	Anaerobic non-methanogenic	Combustible
Hydrogen Sulphide	0.00002	0.0014	Anaerobic	Poisonous Odorous Weak acid in solution
Halogenated compounds	0.0002	0.032	Minute quantities throughout LFG production	Some are potentially poisonous
Gaseous hydrocarbons e.g. ethane C_2H_6	0.005 (saturated) 0.009 (unsaturated)	0.074 (sat) 0.048 (unsat)		Ethane is colourless And odourless
Organosulphur compounds	< 0.00001	0.028		Minimal production
Alcohols	< 0.00001	0.127		Odourless
Others	0.00005	0.023		-

* The lower flammability limit of methane is 5 - 15 % in air (Campbell, 1985)

∂ For notes to these figures see Campbell (1989a)

Table 3.2 Typical Landfill Gas Composition.

Adapted from Farquhar & Rovers (1973), Attewell (1993), Campbell (1989a) and Cemuschi & Giugliano (1989).

illustrates that methane production rates are in the range of 0.5 to 10 m^3 methane per ton of waste per annum (typically, 2.5 m^3). The EU Directive on the Landfilling of Waste states that 32 % of the total methane production can be attributed to waste disposal, mainly landfilling, methane being the second most common contributor to the greenhouse effect (EC, 1997).

3.2.5 Potential LFG Hazards.

Both leachate and LFG have the potential to be hazardous, a feature which increases if neither are diluted or diffused. The combination of gases may be capable of causing the following, (although this is not necessarily applicable to all landfills):

1. Increasing gas pressures in the landfill enable, and may encourage, vertical or lateral migration from the site;
2. Since LFG is highly flammable, it is a potential fire and explosion hazard;
3. LFGs commonly possess an odorous nature, which mainly derives from trace components, for example, Hydrogen Sulphide (H_2S). Odour is one of the main causes of complaints from local landowners and inhabitants as it is directly noticeable;
4. Vegetation damage on the landfill itself and areas affected by migrating pollutants. Further details of this are explained in Chapter Six.

3.2.6 Landfill Gas Migration

The possibility and extent of gas migration from a landfill is dependent upon parameters, including the design of the landfill, i.e. whether it is lined, geological characteristics and barometric pressures.

Gases will migrate through a permeable geological medium if the pressure within the site is sufficient to drive out the gas. The possibilities for migration include flow through macrostructures such as fractures, joints, bedding and fault planes (Williams & Aitkenhead, 1991), although the type of strata will also have a direct affect. Migration through porous rocks may occur as molecular diffusion, due to the concentration gradient or flow as a result of the pressure gradient. Higher permeability may exist in harder crystalline rocks which exhibit these features, as opposed to mudstones which tend to have closed fissures. It is also understood that the potential for migration can be enhanced by the existence of processes such as, periglacial frost-heave, landslipping or cambering which can create additional features through shearing and unloading.

3.2.7 The Loscoe Disaster (1986)

The Loscoe explosion of March 1986 is probably the best documented case in the UK illustrating the adverse environmental impacts of landfill gas. It was possibly the turning point in the assessment of the potential of landfill gas in terms of its migrational characteristics. The enquiry into the explosion that occurred reported that *'it is fair to say however, that the possibility of lateral migration of landfill gas was not a subject of widespread knowledge until about 1986'*, a learning curve in terms of landfill gas management having begun around 1980 (WEPC, 1995).

The Loscoe Brick pit, which had been worked for clay, provided the void for the landfill which accepted 'agreed material' until an adjacent housing development was completed in 1973, when inert waste was also deposited. Later in 1973, a licence was issued for the site to begin accepting domestic wastes, and, upon completion in 1982, a clay capping layer was applied (Williams & Aitkenhead, 1991). Warning signs from the landfill were apparent, such as reports from local residents of odours and vegetation die back, which, in hindsight, is characteristic of the build up of gases.

The explosion was attributed to the landfill as a consequence of the investigation of gas samples taken from the site. An investigation revealed that the gas comprised 60 % methane and 40 % carbon dioxide (Williams & Aitkenhead, 1991), i.e. a typical LFG. The presence of low permeability mudstones and seatearths, and surface deposits of head and glacial till, served to reduce vertical migration, but lateral migration remained unchecked. The surrounding geology of the site had, therefore, unintentionally provided a migrational pathway for the gases from the landfill.

3.3 LANDFILL DESIGN PHILOSOPHY

The design of a landfill site is fundamentally dependent upon the type of wastes to be deposited, local geology, hydrology and hydrogeology, potential contaminant production and locality of pollution targets in the direct vicinity of the proposed site (DoE, 1996d & 1995b). As a result, landfill design and construction is site specific. The ensuing sections describe the types of landfill currently in operation in the UK today.

There are primarily two influential philosophies in landfill design which are dependent upon opposing parameters. Historically, the most widely used design relied upon natural attenuation processes in the strata surrounding the waste to reduce the capacity for leachate contamination, i.e. an unlined, self diluting site. More recently, the increase of environmentally sensitive legislation, regulations and Codes of Practice (as illustrated in Chapter Two), have resulted in the instigation of engineered landfill liners employing the most recent technology in order to encourage complete containment of aqueous and gaseous emissions (Seymour, 1992 and Street, 1993).

The more recent decision to landfill using encapsulation techniques depends upon the type of waste to be landfilled. For example, domestic wastes, which have a greater potential to create polluting compounds, are now limited to contained sites. Unlined sites, if licensed today, would only be able to accept the less polluting inert wastes (for example, construction wastes) which would have already been sorted. This is further illustrated by the case studies in the following chapter.

3.4 DILUTE AND ATTENUATE LANDFILL

Attenuation is the minimisation of concentrations of chemical species in leachate or groundwater as the species move through the subsurface unsaturated or saturated zones (Rowe *et al.*, 1995 and Christensen *et al.*, 1994). Dilute and attenuate landfills are unlined and thus encourage egress of solutions and gases from within the site (Figure 3.2). Gray *et al.* (1974) defined these landfills as sites which allow *'leachates to move from the landfill at such a rate that natural chemical and biological processes such as absorption and dilution, have rendered such leachates innocuous by the time they reach active or potentially active groundwater abstraction zones'.* These biochemical and geochemical mechanisms are not only at work on the leachate but also have the ability to stabilise some components of the landfill gases. For example, the carbon dioxide content may be reduced by dissolution in porewaters to produce weak carbonic acid (HCO_3^-) and hydrogen (H^+) ions.

Since there are no basal or side barriers, the base of the waste abuts the top of the *in situ* deposits, above the level of the water table. A detailed example of this type of site is given by Hopper (1994). A pit, in Runfold, Surrey was licensed for the extraction of high quality sands alongside the deposition of inert wastes (although there will always be a small percentage of organic waste within this) as illustrated by Plate 8.1. There was no form of liner or leachate control employed by the site and there was approximately 5 m depth of unsaturated zone. The landfill gases diffuse through pathways of higher permeability to the edges of the site, although they are mainly extracted from one location.

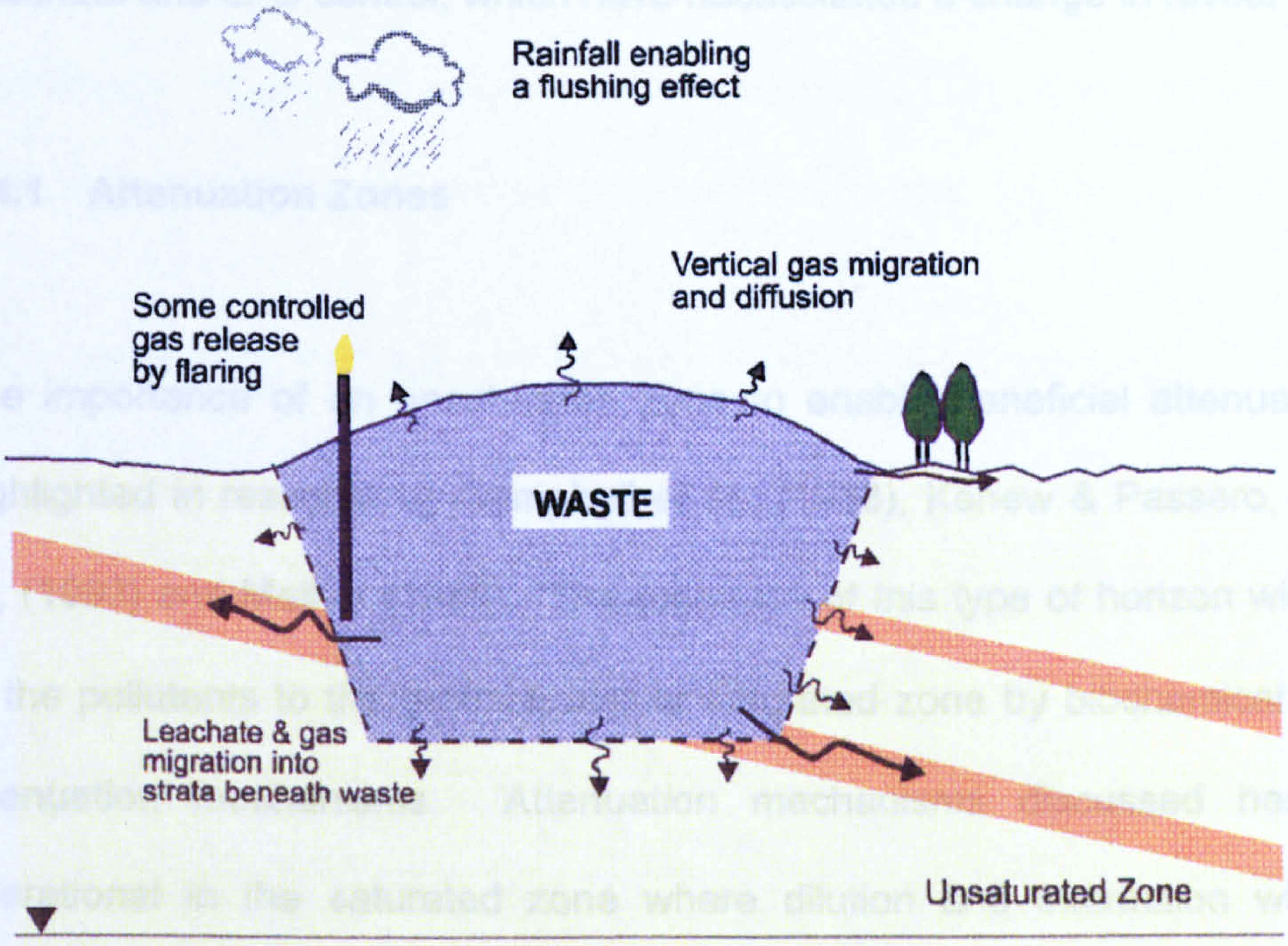


Figure 3.2 A Typical Attenuate and Disperse Landfill.

Adapted from Swinnerton, (1984).

The assessment for site suitability as an attenuate and disperse landfill requires the combination of results from an environmental risk assessment in a design protocol in order to monitor and control the rate of discharge and composition of the pollutant. The DoE (1996d) research report states that this assessment requires *'considerable skill'* to achieve effectively, since huge amounts of site specific monitoring data are required over prolonged periods. Complete reliance is placed upon the natural attenuation mechanisms in the vicinity of the site which must be monitored closely to prevent pollution of the saturated zone. Rouse & Pyrih (1993) describe the choice of unlined sites as a technically sound approach to landfilling, an assessment based on research into the existence and effective operation of attenuation mechanisms. Rouse & Pyrih (1993) state that it is the regulatory reliance upon certain design parameters, for example, Leachate and LFG control, which have necessitated a change in favour of liners.

3.4.1 Attenuation Zones

The importance of an unsaturated zone to enable beneficial attenuation processes is highlighted in research by Campbell *et al.*, (1983), Kehew & Passero, (1990), Blakey *et al.*, (1993) and Mather (1989). The presence of this type of horizon will delay the arrival of the pollutants to the groundwater or saturated zone by biochemical and geochemical attenuation mechanisms. Attenuation mechanisms discussed here may also be operational in the saturated zone where dilution and interaction will occur with the groundwaters.

Attenuation is dependent upon the travel time of the leachate and, importantly, the mineralogy of the substrata, predominantly the carbonate content (Mather, 1989, Blakey *et al.*, 1993 & Campbell *et al.*, 1983). Mather (1989) highlights the importance of the type of material which constitutes the unsaturated zone. This research implies that the highly acidic conditions found in some strata, for example, many Permo-Triassic Sandstones, are not conducive to attenuation mechanisms. Rouse & Pyrih (1993) give the most active pH range for attenuation mechanisms as between 5 - 8. A high buffering capacity of the attenuator is required to increase the pH of the predominantly acidic leachate permeant. This buffering process constitutes the dominant attenuation mechanism.

Although research has proved the relative efficiency of the attenuative mechanisms, the method has never since been employed fully in landfill design. This is due mainly to the NRA groundwater protection policy (1992), EA regulations and those stipulations increasingly imposed by the EU. Campbell *et al.* (1983) advocate the use of attenuation (in the unsaturated zone) for groundwater protection from landfill pollutant migration. Alone, however, this is an unacceptable approach under current national and international policies of environmental protection. The characteristics in favour of and against the facilitation of attenuation are given in Table 3.4.

FOR	AGAINST
Deep unsaturated zone	Shallow unsaturated zone
Intergranular flows	Preferential fissure flow pathways
Fine grained	Coarse grained underlying strata
Mixed mineralogy (CEC)	Monomineralic unsaturated zone
High buffering capacity i.e. significant carbonate content	Low buffering capacity (pH)
Steady flows through the zone	High flow variation, especially rapid, high concentration flows
Balanced 'nutrient' leachate produced by the waste	Leachate containing persistent compounds, namely high NH_4, Cl & Total Organic Carbon (TOC) levels.

Table 3.4 Factors of High Influence on Attenuation Mechanisms.

Adapted from Blakey *et al.*, (1993).

These sites are now generally considered to be environmentally unacceptable and would probably no longer be licensed, unless a liner is employed. The risk of polluting the sensitive and valuable groundwater reserves is too great, especially considering public awareness of environmentally sensitive issues.

3.4.2 Attenuation Mechanisms

Attenuation mechanisms have been known to exist for some years, although, until the early 1990's, considerably little research had been completed on the subject. Robinson & Gronow (1992) state that biological mechanisms had been identified as being mainly responsible for attenuation. Nicholson *et al.* (1983) indicate that the main processes in occurrence are chemical reactions, dispersion and dilution with movement of the contaminant plume. These processes include anion and cation exchange with clays, adsorption of anions and cations onto hydrous oxides of iron and manganese, sorption on organic matter, precipitation of ions in solution, co-precipitation by adsorption, volatilisation and biodegradation (Rouse & Pyrih, 1993). These processes are dependent upon suitable conditions within the attenuating layer, some of which are portrayed in Table 3.4.

Cation exchange results in the storage of some cations and the release of others to solution, i.e. into leachates. Natural clays possess Ca^{2+} and Mg^{2+} ions which can be exchanged by Na^{+}, K^{+} and NH_4^{+} present in leachate, through processes of advection and diffusion. For example, Rowe *et al.* (1995) illustrate that, as it takes two Na^{+} to exchange one Ca^{2+} in clays, the permeability of the material will be reduced. This is particularly beneficial to discourage migration in unlined sites, but will also decrease permeability in engineered clay liners. Matrix diffusion, i.e. the movement of contaminants from fractures into the adjacent matrix thus restricting migration provides a further example and is well documented in its role as an attenuator (Freeze & Cherry, 1979).

The Cation Exchange Capacity (CEC) may be determined for the geological components and, therefore enabling an estimation of their suitability as attenuators. This is rather a complex process, given the variety and quantity of possible cations involved, Mg^{2+}, Fe^{2+}, Mn^{2+}, Ca^{2+}, K^{+}, & Na^{+}, for example. Research completed on the attenuation mechanisms of a sandy aquifer (Nicholson *et al.*, 1983), illustrated that cation exchange can be responsible for the release of calcium and subsequent precipitation of calcite. Griffin *et al.* (1976) completed some of the inaugural work in this area and showed that '*attenuation was a direct function of the CEC of the clay mineral*'. Heavy metals (Pb, Cd, Zn) were the easiest to be attenuated, whereas Cl and Na were the poorest. Within this framework, intermediate attenuation of K, NH_4, Mg, Si and Fe was also achieved.

Attenuation mechanisms are therefore diverse and highly dependent upon the strata underlying the landfill and that in the vicinity of the contaminant plume. Research has proved their existence under field and laboratory conditions. Indeed, it has even proved that they decrease permeabilities of clays, which would support a proposal for a form of engineered leakage.

3.5 ENGINEERED CONTAINMENT

3.5.1 Philosophy

The landfill design philosophy of *Dilute and Attenuate* has gradually been superseded by the practice of *Engineered Containment*, which is also reliant upon attenuation to a certain extent. Containment may be defined as the total isolation of wastes from the environment through entombment and instigation of measures to control the products of the waste mass. In theory, it is the most effective approach to the management of wastes. However, in practice on-site, real situations have meant that total containment is unachievable, as acknowledged by Giroud & Bonaparte (1989), Blakey *et al.* (1993) and importantly, more recently by the proposed EC Landfill Directive (1997). As a result, it might be true to state that most sites are, in the long term, a form of engineered leakage. In landfills situated above the water table leachate leakage can be reduced by lowering the head of leachate. For those below the water table, the head is reduced to a level below that of the piezometric level thus creating a hydraulically contained site (Rukin & Walker, 1998), as illustrated by the Site Alpha case study in Chapter Four.

Figure 3.3 portrays the main components of an engineered landfill, illustrating the potential complexity of the system. An engineered site requires both basal and side liners (Figure 3.4) and also a capping system. These components must function independently of one another, in case of failure in part of the system. Ultimately, however, this is not the case, owing to the complex interactive relationships between individual parts of the system. For example, failure in a geomembrane liner would result in increasing pressure on the attenuating liner and subgrade. Since the attenuating layer was not designed to operate alone, it may be only a thin layer, resulting in limited attenuation and eventually, possible groundwater contamination.

3.5.2 'Bioreactor' or 'Wet Cell' Landfills

'Bioreactor' or 'Wet Cell' landfills are a variation upon the entombment of wastes concept. These landfills are based on the same premises as the contained sites, although, instead of the removal of leachates to create 'dry tombs' (Lee & Jones, 1992a & b), leachates are actively recirculated within the waste, the main aim being to encourage an increase in the rate of degradation.

The recirculation of leachate increases the microbial activity in the site. This results in the transfer of the organic load from its aqueous to its gaseous producing phase (according

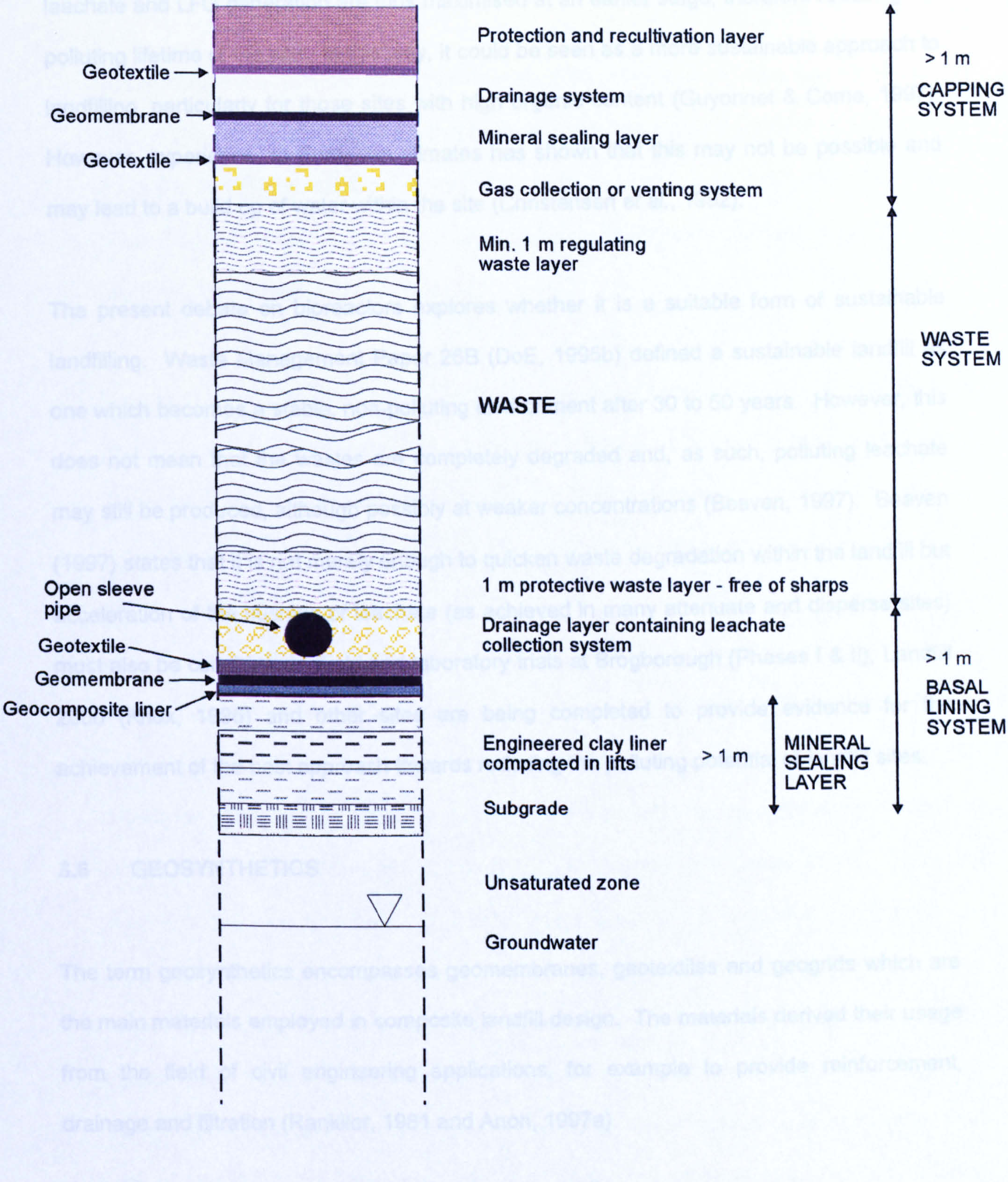


Figure 3.3 Typical Components of a Landfill System (Adapted from Jessberger, 1994)

to Farquar & Rovers, 1973) over a faster period (Blakey *et al.*, 1997). The rates of both leachate and LFG generation are thus maximised at an earlier stage, therefore reducing the polluting lifetime of the site. In this way, it could be seen as a more sustainable approach to landfilling, particularly for those sites with high organic content (Guyonnet & Come, 1997). However, experience in European climates has shown that this may not be possible and may lead to a build up of water within the site (Christensen *et al.*, 1992).

The present debate on bioreactors explores whether it is a suitable form of sustainable landfilling. Waste Management Paper 26B (DoE, 1995b) defined a sustainable landfill as one which becomes a stable, non-polluting environment after 30 to 50 years. However, this does not mean that the wastes are completely degraded and, as such, polluting leachate may still be produced, although possibly at weaker concentrations (Beaven, 1997). Beaven (1997) states that it is not merely enough to quicken waste degradation within the landfill but acceleration of the flushing of leachate (as achieved in many attenuate and disperse sites) must also be considered. Field and laboratory trials at Brogborough (Phases I & II), Landfill 2000 (Knox, 1996) and other sites are being completed to provide evidence for the achievement of the best approach towards reducing the polluting potential of landfill sites.

3.6 GEOSYNTHETICS

The term geosynthetics encompasses geomembranes, geotextiles and geogrids which are the main materials employed in composite landfill design. The materials derived their usage from the field of civil engineering applications, for example to provide reinforcement, drainage and filtration (Rankilor, 1981 and Anon, 1997a).

3.6.1 Geomembranes

Geomembranes or Flexible Membrane Liners (FMLs) have been employed since around 1982 in the US, when the US Environmental Protection Agency (USEPA) adopted them within the regulatory structure of landfill design. It stated that *'prevention (via FMLs), rather than minimisation (via clay liners), of leachate migration similarly produces better environmental results'* (Page, 1994).

Geomembranes comprise mainly High Density Polyethylene (HDPE), 2 mm thick or greater, Low Density Polyethylene (LDPE) and Very Low Density Polyethylene (VLDPE). Within these groups there are also variations in the structure of the material, for example, Hyper-elastic liners and textured sheet lining. HDPE includes polyethylenes in the range 0.935 - 0.97 g cm^{-3} in density and LDPE covers 0.915 - 0.935 g cm^{-3} (Cadwallader & Barker, 1994). On most occasions in the UK, HDPE is used as the lining material for landfill. HDPE is composed typically 97 % polyethylene resin, a single polymer, with the remaining 3 % comprising carbon black, which is used to enhance Ultra Violet (UV) resistance. This type of geomembrane is fairly durable throughout site construction and initial phases of landfilling and it has a high resistance to chemical attack. Table 3.5 illustrates the typical values for HDPE lining material as produced by Gundle, an American manufacturer which was one of the first in the market and who has encouraged further development in the lining field. These parameters are typically tested during the installation of the liner, in order to assure its integrity. Most factors remain the same with an increase in material thickness and an increase in tear resistance is noticeable. It is also more difficult to handle and installation times may be increased. For landfill lining, the liner thickness generally used is between 2 and 2.5 mm.

Typical Properties	Test Method	Gauge (Nominal)		
		40 mil (1 mm)	80 mil (2 mm)	100 mil (2.5 mm)
Density (g cc^{-1}) (Minimum)	ASTM D1505	0.94	0.94	0.94
Melt Flow index (g $minutes^{-10}$) (Max.)	ASTM D1238	0.3	0.3	0.3
Tensile strength	ASTM D638			
Strength at break lbs $inch^{-1}$ width		160	320	400
Elongation at break %		700	700	700
Elongation at yield %		13	13	13
Low temp brittleness (°F)	ASTM D746	-112	-112	-112
Environmental stress crack (Hrs) (Minimum)	ASTM D1693	1500	1500	1500
Puncture resistance (lbs)	FTMS 101	22.7	47.6	59

Unless specified, figures are typical values for test results.

Table 3.5 Properties of High Density Polyethylene (Gundle, 1991)

The factors portrayed in Table 3.5, can, however, be altered over time with exposure to leachate (Peggs, 1994). Research by Rollin *et al.* (1994) showed that over a relatively short period of time (7 years), leachate had specifically affected the basal lining as opposed to side and top covers. HDPE liner degradation is, therefore, a relatively large area of interest for current research, which needs also to address the issues of longer term durability and the effects of more aggressive leachates.

These types of material generally provide an extremely low permeability barrier, although, if their integrity is damaged through a tear or puncture, leakage at significant rates can be recorded. Chapter Four details the use of Construction Quality Assurance (CQA) for the reduction of such rates. Specific HDPE liner CQA can be based on the premises as in the following guidelines (DoE, 1995b);

Very good CQA	2 to 3 holes ha^{-1}
Average CQA	10 to 20 holes ha^{-1}
Poor CQA	30 to 50 holes ha^{-1}

The order of permeability (K) under laboratory conditions for HDPE is approximately 1×10^{-15} m s^{-1} (Mollard *et al.*, 1996) but this will be increased through inevitable construction problems and possibly even degradation during operational phases. Table 3.6 gives the gas transmission rates in HDPE compared to LDPE, which, although measured at different temperatures, show significant differences. Thus, HDPE would be the preferred liner, but, due to its thickness, may experience limitations in its use.

Synthetic Membrane	Gas Transmission Rate Ml (*stp*) m^{-2} d^{-1} atm^{-1}	
	CO_2	CH_4
HDPE 0.61 mm thick	729	138
HDPE 0.86 mm thick	467	104
LDPE 0.25 mm thick	6180#	1340#

stp Standard temperature and pressure

\# Measured at 30 °C.

Table 3.6 Gas Transmission Rates (Adapted from Haxo & Haxo, 1994).

Geomembranes have lower permeabilities (both aqueous and gaseous) than engineered mineral liners if deployed correctly and therefore would be the preferred choice of liner. However, geomembranes also have a variety of disadvantages:

- Handling difficulties which increase with greater liner thickness;
- Construction and installation problems including folded wrinkles, damage

to liner from protruding stones in the subgrade, excessive grinding during seaming, overheated seams;

- Susceptibility to mechanical stresses causing cracking or creep;
- Low frictional (shear) resistance with soils and other geosynthetics;
- Susceptibility to UV damage and chemical stresses to cause polymer degradation;
- Minor break down by attack from biological agents, micro-organisms and birds;
- As yet undetermined long term behaviour.

(Adapted from Haxo & Haxo, 1988, Peggs, 1994, & Seymour, 1992).

In order to provide assurance of their integrity at the time of installation, continual monitoring (Quality Assurance) of materials, installation procedures etc. is required, this is explained in detail in Chapter Four. After inception of the wastes, assurance of the liner integrity is minimised, since direct access to them is difficult. As with clay liners, even if leakage is known to occur, the point and rate of discharge still remain to be determined.

As yet, there are no British Standards for geosynthetics liners, therefore manufacturers employ American Standards from the American Society of Testing Materials (ASTM), (ASTM, 1998) which until recently had not included tests specifically for materials employed in landfill design.

3.6.2 Geocomposite Liners (GCLs)

Geocomposite Liners (GCLs) comprise thin layers of FMLs (usually HDPE) covered with dried sodium bentonite and fixed together with an adhesive to a complete thickness of 10 mm. The hydraulic conductivity (K) of this type of material is low at approximately

1 to 5 x 10^{-11} m s^{-1} (Daniel, 1997). The HDPE backing has the same properties as those used in single liners (Table 3.7) although the strength is considerably reduced since the material is thinner.

Standard Construction	
Gundline HD membrane backing	0.5 mm (20 mil)
Roll width	5.3 m
Roll Length	60 m
Roll weight	1792 kg
Typical Properties	
Bentonite loading	0.0488243 kg cm^{-2}
Effective hydraulic conductivity	No measurable leakage
Permeability coefficient of membrane (ASTM E96)	2.7 x 10^{-13} cm s^{-1}
Bentonite hydraulic conductivity	3.7 x 10^{-10} cm s^{-1}

Table 3.7 Gundseal (HDPE / Bentonite Composite Liner) Properties.

Adapted from Gundle, (1991).

GCLs possess advantages over engineered clay barriers:

- Low volume;
- Fast and simple deployment and low cost in comparison with clay liners;
- Deployment by relatively light weight plant;
- Self-healing abilities;
- Ability to withstand significant tensile strain without loss of hydraulic integrity;
- No *in situ* density or moisture content monitoring is necessary since they are manufactured to a consistent and guaranteed quality.

However, they possess a high vulnerability in terms of puncture, chemical alteration and low shear strength properties of the hydrated bentonite. Table 3.8 indicates some of the GCL types available and the differences in properties which can be found with varying materials currently available. Choice of GCL will influence engineering design of the liner and placement:

- To reduce the possibility of liner slippage at point of contact with the subgrade;
- To create sufficient friction between liner components to prevent this.

GCL type	Effective cohesion (kPa)	Effective angle of internal friction (°)
Gundseal®	8	8
Claymax	4	9
Bentomat®	30	26

®Trade name

Table 3.8 Shear Strength Parameters for GCL (Daniel, 1993).

Water height (m)	Q_{GCL} $K = 1 \times 10^{-11}$ ms^{-1}	Q_{GCL} $K = 5 \times 10^{-11}$ ms^{-1}	Q_{CCL} $K = 1 \times 10^{-9}$ ms^{-1}	Q_{CCL} $K = 1 \times 10^{-7}$ ms^{-1}
0.1	0.01	0.05	0.10	9.50
0.3	0.03	0.13	0.11	11.23
1.0	0.09	0.44	0.17	17.28

Q_{GCL} Seepage in l day^{-1} through 1 m^2 Geocomposite Clay Liner (10 mm thick).
Q_{CCL} Seepage in l day^{-1} through 1 m^2 Compacted Clay Liner (1 m thick).

Table 3.9 Seepage Rates Through a GCL and Compacted Clay Liners (CCL). (Naismith, 1997).

GCLs are widely employed to provide an effective low permeability liner since their advantages significantly outweigh their disadvantages. Table 3.9 illustrates the effectiveness of a GCL at different permeabilities in comparison with a compacted clay liner (CCL). A combination of the GCL and CCL would produce an even lower hydraulic conductivity, if installed efficiently. However, as with most of the newer materials on the market at present (HDPE etc.), little is known about the long term properties of GCLs (Jaros, 1996).

3.6.3 Geotextiles

Geotextiles comprise synthetic fibres of polypropylene, polyester, polyethylene and polyamide. It is generally the first two which are most widely used (Cazzuffi *et al.*, 1994). Geomembranes will need protection from the drainage layer and waste components of the landfill. This is required in the short term due to continual trafficking during installation of the liner and in the long term from point loading by the gravel drainage layer. Protection for geotextiles generally comprises non-woven, needle punched materials which are resistant to chemical erosion from the effects of leachates. Fine particles from the aggregate layer may filtrate into the geotextile which could weaken its protective abilities. In addition, Seeger & Muller (1991) indicate that the components of the geotextile are affected by chemical activity throughout the waste degradation process. The effects of such activity cannot be reliably predicted due to the inability to define a standard leachate composition.

The geotextile layer has several fundamental roles:

1. To envelope the individual grains of aggregate comprising the drainage layer in order to absorb point loading effects and protect the underlying geomembrane.
2. To distribute the load from an individual aggregate grain, due to its tensile strength (Kirschner & Witte, 1991), and act as a reinforcement.
3. To act as a substrate for the deployment of the aggregate drainage layer (Seeger & Muller, 1996).

4. To act as a filter and drainage mechanism in the lining system (Rankilor, 1981).

These materials are known to clog, due to mechanical and biological mechanisms (Cazzuffi *et al.*, 1994). Research is being completed in this relatively new field, although interestingly, geotextiles are currently used for their known protective and reinforcing abilities.

3.7 LANDFILL LINERS

The objective of landfill liners is to maintain the highest possible retention of leachate and LFGs within the site. Liner requirements are prescriptive and an integral part of the landfill design. Requirements, as per DoE (1995b), include the control of leachate and LFG migration, groundwater ingress control and, finally, to achieve and maintain stability throughout the life of the site. Liners are now designed in the UK on a site specific basis determined by required prescriptive standards.

3.7.1 Objectives of Landfill Liners

Compliance of the liner with the assurance that waste has been disposed of in an environmentally sound manner is of fundamental importance in order to ensure:

- An assurance of the quality of underlying groundwaters;
- A guarantee of the integrity of the liner, should one be used;
- Restoration to an enhanced / improved and non-hazardous environment;
- The control of LFGs and leachates by collection or diffusion into the atmosphere.

Since it has been proved that attenuation processes in the unsaturated zone are beneficial to the reduction of the potential polluting capacity of migrating leachates, attenuation processes may also be employed in containment site design. The liner will reduce the capacity for migration from the site, but the insurance of an attenuation zone beneath the site will again reduce possibilities of groundwater contamination (Bright *et al.*, 1996). An example of this is provided in Chapter Four where case study Site Alpha is an engineered containment landfill, provided with a basal unsaturated depth of >30 m of London Clay in which attenuation will undoubtedly occur.

3.7.2 Single Liners

These comprise a primary barrier system, either clay or Bentonite Enhanced Soils (BES), overlying a prepared subgrade. If necessary a groundwater control system may be installed within the subgrade. Leachate Control Systems (LCS) overlie the barrier in order to contain and divert the solutions. The location of these components within the lining system is given in Figure 3.3. This type of liner is employed in situations involving inert materials due to the low degree of environmental protection provided. The most common primary barrier deployed is an engineered mineral layer, 1 m or greater in thickness.

3.7.2.1 Single mineral liners

Single mineral liners (Figure 3.4a) comprise engineered weathered mudrocks and clays which have the ability to achieve the specifications as set out in the prevalent guidelines and Codes of Practice. These are possibly the most common form of landfill liner employed in the UK for inert wastes. This is due to their:

- Known effectiveness in leachate attenuation;
- Widespread availability across the UK.

However, contrary to the above, they can be:

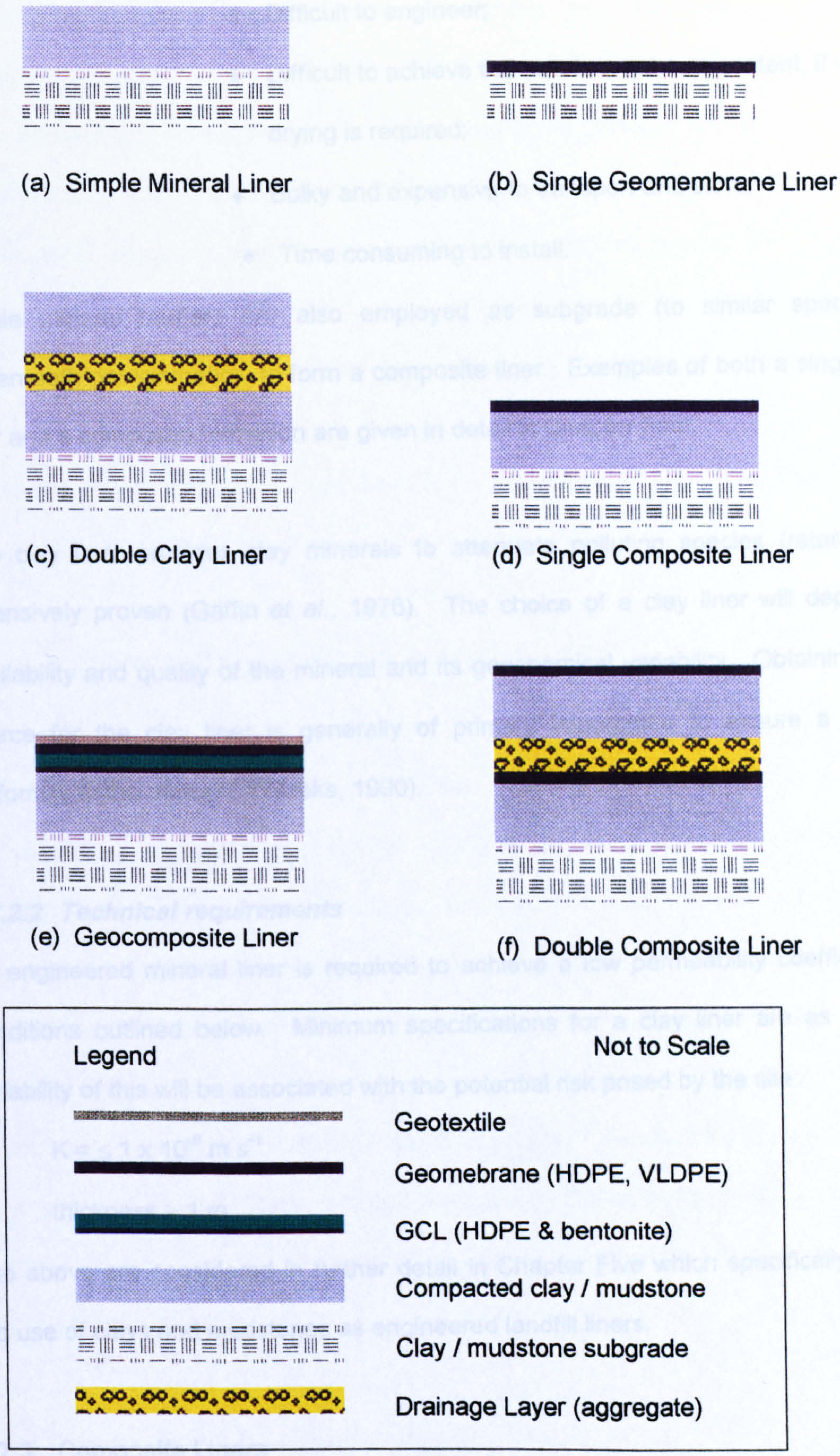


Figure 3.4 Simple Liner Systems

- Difficult to engineer;
- Difficult to achieve the suitable moisture content, if wetting or drying is required;
- Bulky and expensive to transport and store;
- Time consuming to install.

Single mineral barriers are also employed as subgrade (to similar specifications) underneath geosynthetics, to form a composite liner. Examples of both a single mineral liner and a composite formation are given in detail in Chapter Four.

The clay liner provides clay minerals to attenuate polluting species (retardation) as extensively proven (Griffin *et al.*, 1976). The choice of a clay liner will depend upon availability and quality of the mineral and its geochemical variability. Obtaining a single source for the clay liner is generally of primary importance to ensure a degree of uniformity in the material (Weeks, 1990).

3.7.2.2 Technical requirements

An engineered mineral liner is required to achieve a low permeability coefficient under conditions outlined below. Minimum specifications for a clay liner are as follows but variability of this will be associated with the potential risk posed by the site:

$K = \leq 1 \times 10^{-9}$ m s^{-1}

thickness ≥ 1 m

The above are considered in further detail in Chapter Five which specifically addresses the use of clays and mudstones as engineered landfill liners.

3.7.3 Composite Liners

The development of these types of liner (Figure 3.4 d to f) has occurred in parallel with technical advances in geosynthetics and plastics over the past 25 years. The geosynthetics provide several components of a composite liner. The design integrates geosynthetics with an engineered mineral sealing layer, the latter adheres to the previous technical specifications in terms of hydraulic conductivity. In this way, the combination of the material creates a landfill liner which has a reduced susceptibility for leakage. Possible leakage through the FML could be attenuated by the clay layer underneath. This type of liner is the most suitable for the containment of domestic wastes.

There are further variations to this strategy, including double composite liners and single sandwich composite liners as illustrated in Figure 3.4.

3.8 GEOSYNTHETIC INSTALLATION PROCEDURES

This section is intended to give a review of some of the methods available for geosynthetics placement and testing. This area of landfilling technology was until recently dominated by only a few companies (German and American) which developed equipment and set standards according to their own techniques. As a result, this is reflected in the literature and the techniques are set out in standard manuals, which differ between the companies according to their particular choice of lining material. In recent years, there has been an influx of other companies, mainly from Europe, which have developed alternative liners, albeit based upon similar components. A specialised engineer is required for geomembrane installation in order to ensure the highest performance of the liner.

3.8.1 Installation and Seaming Conditions

Geomembranes require specific weather conditions for installation, especially in the seaming stages of deployment, the practice of which is addressed in more detail in Chapter Four. However, all geosynthetics must be deployed under non-windy conditions, since even small gusts are able to pick up the liner and carry it some distance with force. GCLs must be laid under dry conditions in order to protect the integrity of the bentonite sealing layer. The same is recommended for the geotextile, since it has a huge capacity for absorbency, the weight of which inhibits rolling and placement. Indeed the Gundle Manual (1995) states that welding and placement of materials cannot take place during '*any precipitation, in the presence of excessive moisture, blowing dust, or in the presence of high winds (unless wind barriers are provided)*'. This will therefore place heavy timing restrictions upon countries with certain climatic conditions such as seasonal heavy rainfall.

3.8.2 Liner Placement

All these liners are anchored at the top of the landfill site's surrounding containment side slope, in 'anchor trenches', as illustrated in Figure 3.5 and Plate 8.2. This is in order to keep the liner in place throughout installation and operation of the cell. The GCL layer deployment is relatively straightforward, providing the conditions are correct. An overlap layer is required between each sheet which bonds on addition with solution. The geotextile solely requires heat bonding at the point of over lap for each seam. Figure 3.6

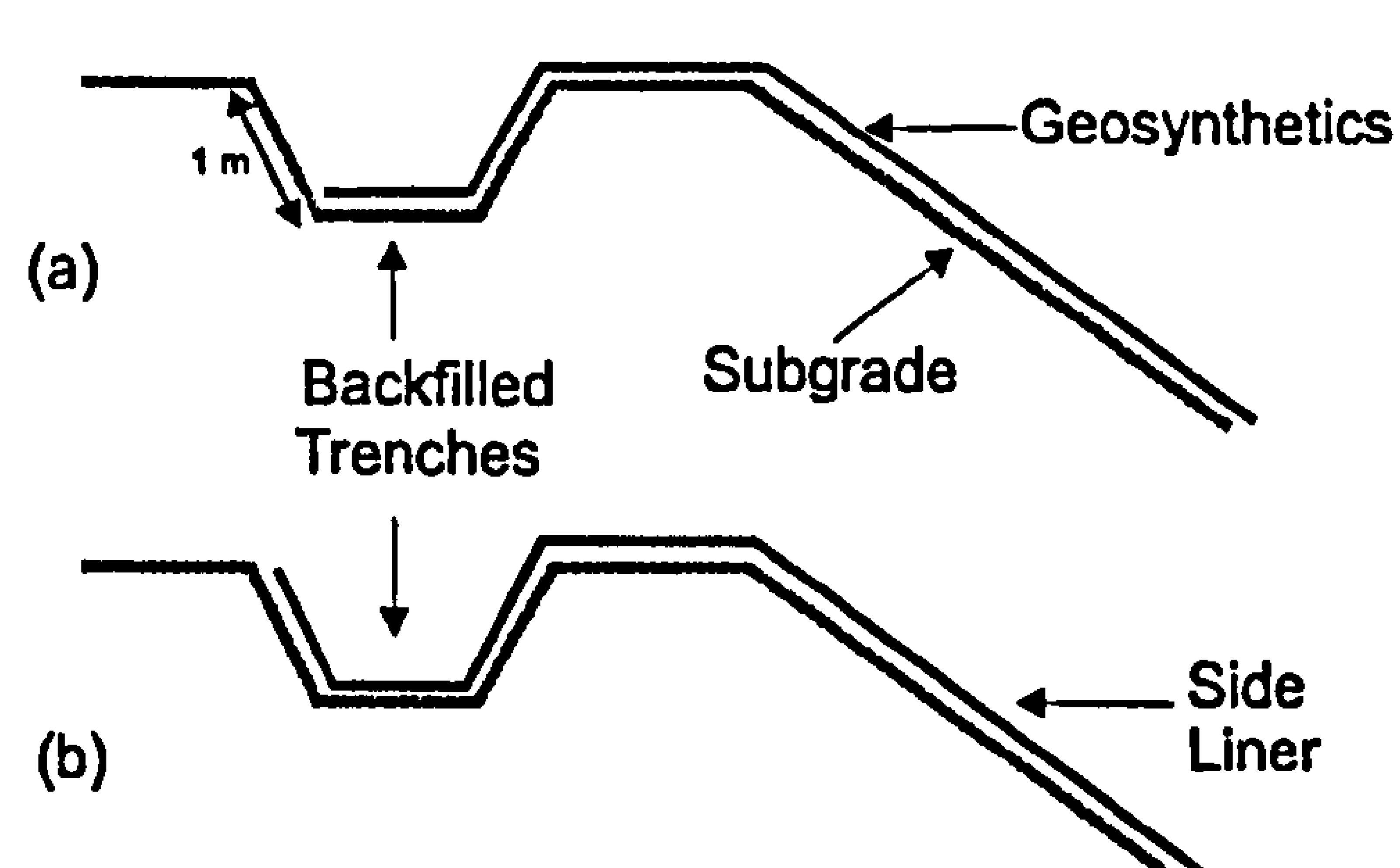


Figure 3.5 Possible Anchor Trenches for Composite Geosynthetic Liner Systems.

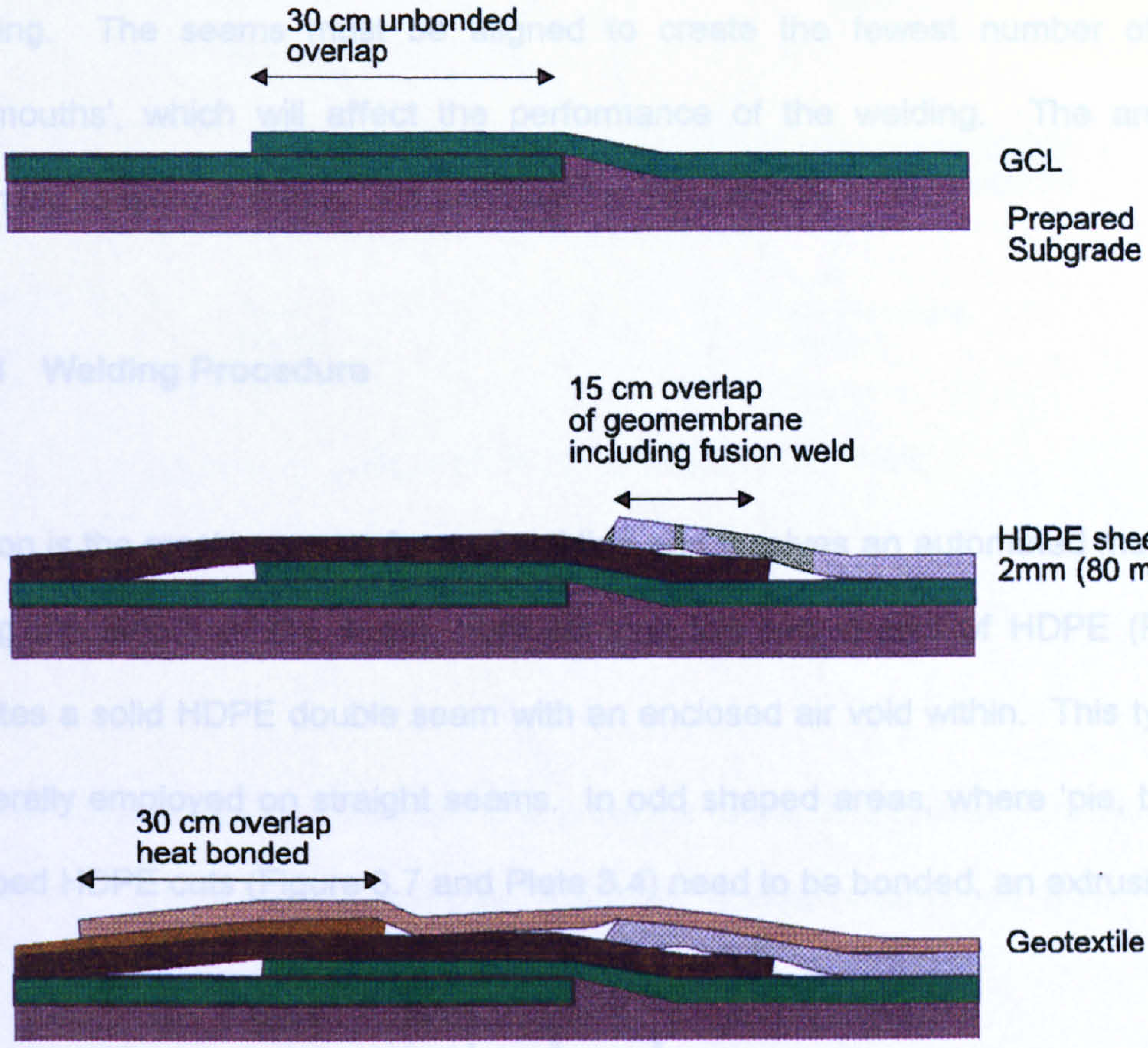


Figure 3.6 Composite Liner Overlap Detail. Adapted from details in Gundle, (1995).

illustrates the organisation of the overlap detail and standard required overlap distances.

The HDPE cannot be deployed in a simplistic fashion. Each sheet, cut to size and shape, is required to be heat bonded to prevent the immediate escape of leachates or LFGs. The HDPE is therefore rolled out with an overlap which is individually cut to enable bonding. There are two main methods of this, fusion and extrusion.

3.8.3 Seaming

In order to perform consistent and efficient seaming, the welder must attain a certain temperature and retain this throughout the procedure. Trial seams are completed on fragments of HDPE in order to assess the conditions at the start of the day, prior to welding. The seams must be aligned to create the fewest number of wrinkles or 'fishmouths', which will affect the performance of the welding. The areas must be cleansed to remove debris, oils and dust from the vicinity.

3.8.4 Welding Procedure

Fusion is the most common form of welding and involves an automated machine running along the length of the seam, heat bonding the two sheets of HDPE (Plate 8.3). It creates a solid HDPE double seam with an enclosed air void within. This type of weld is generally employed on straight seams. In odd shaped areas, where 'pie, boot and skirt' shaped HDPE cuts (Figure 3.7 and Plate 8.4) need to be bonded, an extrusion fillet weld

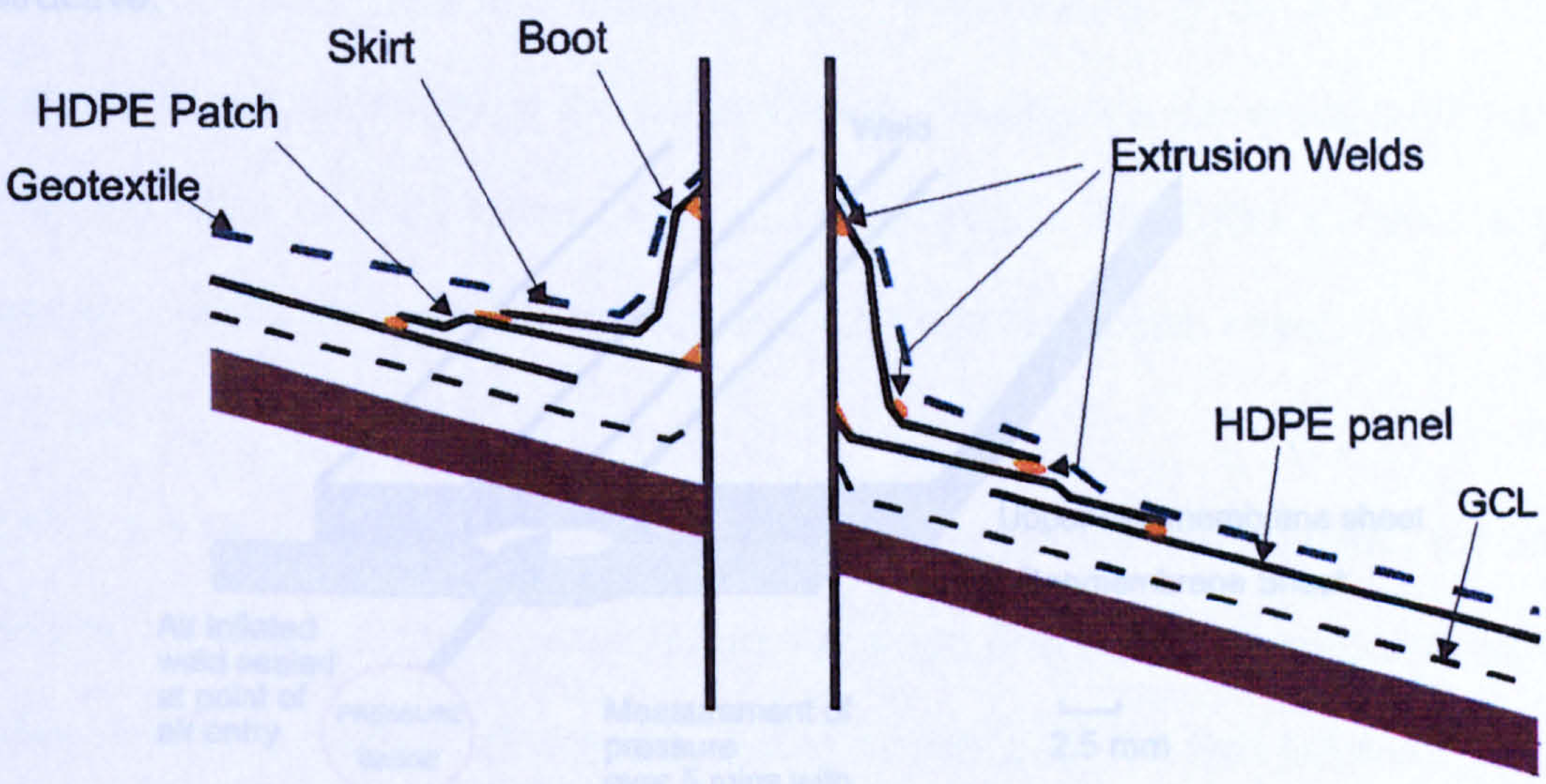


Figure 3.7 Typical Boot and Skirt Construction in HDPE.

is used as illustrated in Figure 3.8. This involves a hand held gun which heats HDPE cord and redistributes it around the seam (Plate 8.5). Prior to this, the seam edges are buffed and a thin liner of copper wire is placed at the join along their length.

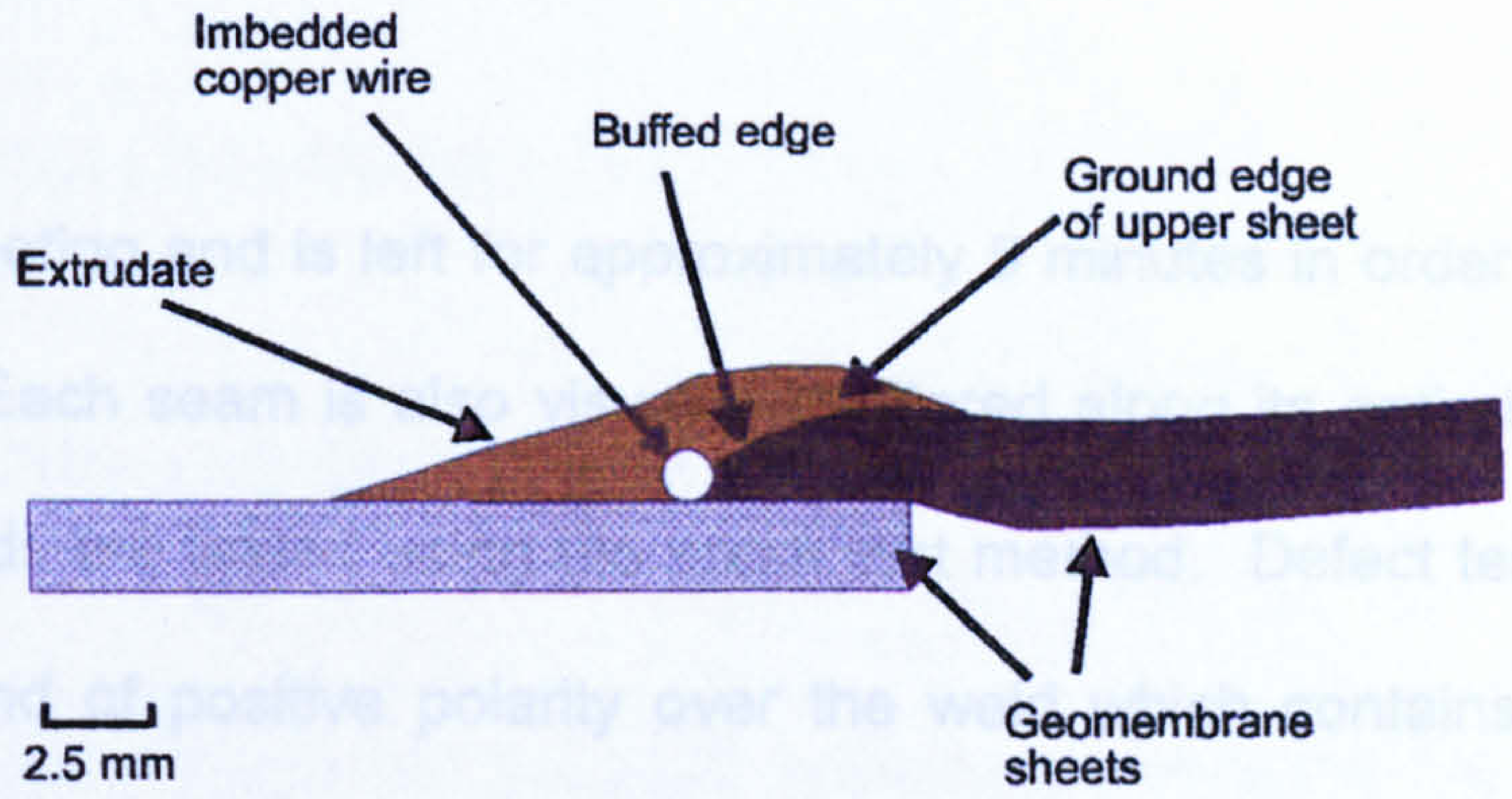


Figure 3.8 An Extrusion Fillet Weld

3.8.5 Seam Testing

In order to guarantee the integrity of the seams at the time of liner installation, they must be tested. There are generally two forms of testing procedures, non-destructive and destructive.

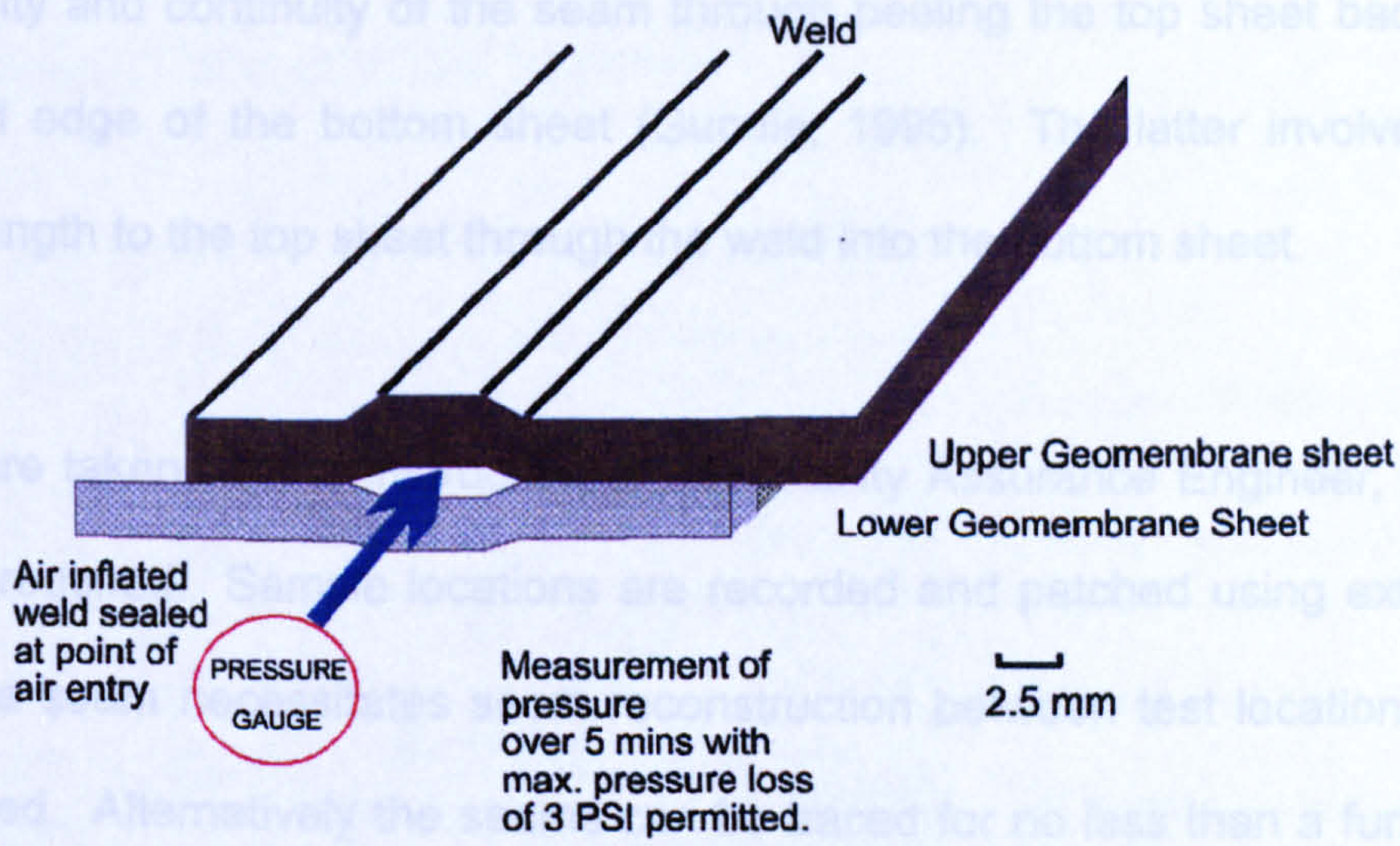


Figure 3.9 Air Pressure Testing Procedure.

Non-destructive testing usually involves a vacuum test unit or air pressure testing along the length of the individual seam. Figure 3.9 illustrates the set up for the procedure for the air pressure testing. The seam is 'inflated' through a needle which penetrates the top of the welded sheeting and is left for approximately 5 minutes in order to assess if there is any leakage. Each seam is also visually monitored along its entirety for any defects. The extruded welds are tested using the spark test method. Defect testing is completed by passing a wand of positive polarity over the weld which contains the copper wire. Voids in the weld allow the establishment of an electrical conductivity and therefore sparks are created at the point of weakness. The Gundle Manual (Gundle, 1995) states that the two must be in intimate contact to create a valid test since air is such a good insulator.

For destructive testing, samples are taken from the seams to evaluate strength and efficiency of bonding which in turn can be used to assess long term durability. This type of testing comprises peel and shear testing. Peel testing gives an indication of the homogeneity and continuity of the seam through peeling the top sheet back against the overlapped edge of the bottom sheet (Gundle, 1995). The latter involves applying a tensile strength to the top sheet through the weld into the bottom sheet.

Samples are taken, at the instruction of the Quality Assurance Engineer, for laboratory testing as required. Sample locations are recorded and patched using extrusion welds. Failure of a seam necessitates seam reconstruction between test locations which have been passed. Alternatively the seams can be traced for no less than a further 3 m from the point of failure and new tests carried out. Success of these tests results in rewelding of the area in-between. Additional failure demands further tests in closer proximity.

3.9 LEACHATE COLLECTION AND TREATMENT SYSTEMS

3.9.1 Leachate Collection System Design

Leachate Collection systems are generally embedded within the gravel drainage layers (Figure 3.10) and graded towards the point for extraction. Lechner (1994), however, has noted that this system has problems, due to silting and precipitation blocking the pipes, and also deformation of the pipe itself.

The pipes are most commonly HDPE, slotted pipes which are attached by collars. Pipe junctions are available to create herringbone arrangements for leachate drainage. Pipe arrangement will depend upon the location of the sump and the size and shape of the cell. Each cell will require an individual system, although collected leachate can be amalgamated for extraction and treatment.

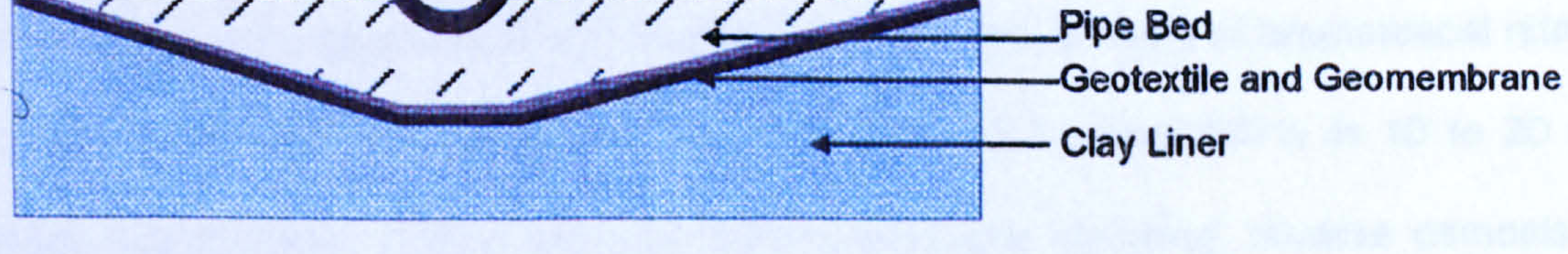


Figure 3.10 Typical Leachate Collection Pipe Design.

Leachate generation calculations are fundamental in order to supply adequate piping in correct locations to fulfil the requirements of the collection system. Research by Cossu *et al.* (1997) has indicated that the leachate flow regime will be affected by non-homogeneous waste characteristics, well clogging and damaging. To reduce the latter problems, pipe cleansing and monitoring after site completion are necessary.

3.9.2 Leachate Management and Treatment

The control of leachate is directly related to the waste in terms of its storativity, i.e. the capacity of the waste to hold solutions, and its permeability properties (Beaven, 1997). In order to understand the processes necessary for leachate treatment, scientists must first learn about the hydraulic properties of the waste mass. These can be likened to the flow regimes of *'bounded, multi-layer, aquifer systems with bulk mass and preferential pathway flow in confined, leaky and unconfined aquifers interbedded with aquitards and aquicludes'* (Burrows *et al.*, 1997).

Leachate can be managed by extraction through integrated drainage systems at the base of the waste, as well as vertical pumping wells. Robinson *et al.*, (1997) highlight the use of aeration schemes which are efficient in on-site leachate treatment, following extraction. The main problems associated with leachate are the high content of ammoniacal nitrogen and COD levels and these can be reduced effectively by over 90 % in 10 to 20 days through this strategy. Other systems include ammonia stripping, reverse osmosis and anaerobic methods.

3.10 LANDFILL GAS COLLECTION FACILITIES

LFGs may be collected in active systems or allowed to diffuse through passive systems within the landfill. The choice depends upon management strategies for the site and the anticipated environmental impact which in turn is related to the expected gas output.

LFG collection facilities are an integral part of the design of the site and must be completed throughout waste placement. However, some systems can be installed after site completion, although this is not generally recommended unless there are special conditions. For example, large completed sites may now want to utilise the gas produced.

3.11 LANDFILL CAPPING

Landfill capping is a requirement of a site licence (DoE, 1996d). Regulations of capping contribute towards ensuring the containment of waste and eventual integration of landfills with the environment (DoE, 1996d). There are two basic types of cover system, very low permeability and quasi-impermeable. The fundamental requirements are:

- To contain the gases and leachates in order that they can be controlled;
- To minimise precipitation infiltration and also control run-off;
- To allow for waste settlement and to cope with seasonal wetting and drying;
- To prevent migration of perched leachate through the side liners;
- To allow final landscape integration;
- To maintain a long term integrity.

Capping mechanisms have similar components to the landfill basal barriers i.e. compacted clay or composite (Figure 3.4). The most common components in landfill cap design, as portrayed in Figure 3.11, can be divided into the five phases as demonstrated (Daniel & Koerner, 1993). DoE (1996d) gives the minimum soil thicknesses for the capping layer which are dependent upon afteruse. For example, an inert site with an after use for grazing must have a minimum 0.5 m cap in contrast to the 1 m specified for sites accepting other types, for example, domestic wastes.

The cap can be profiled to the height and shape agreed in previous design stages. The general compliance is for progressive restoration to be completed as cells are filled. In order to reduce the effects of runoff, which cause minor erosion features such as rills, the final gradients and cover materials must be considered carefully. Problems are also incurred due to waste settlement, for example, cap failure by cracking or rupture, which will increase possibilities of infiltration, thus increasing leachate head levels within the completed landfill.

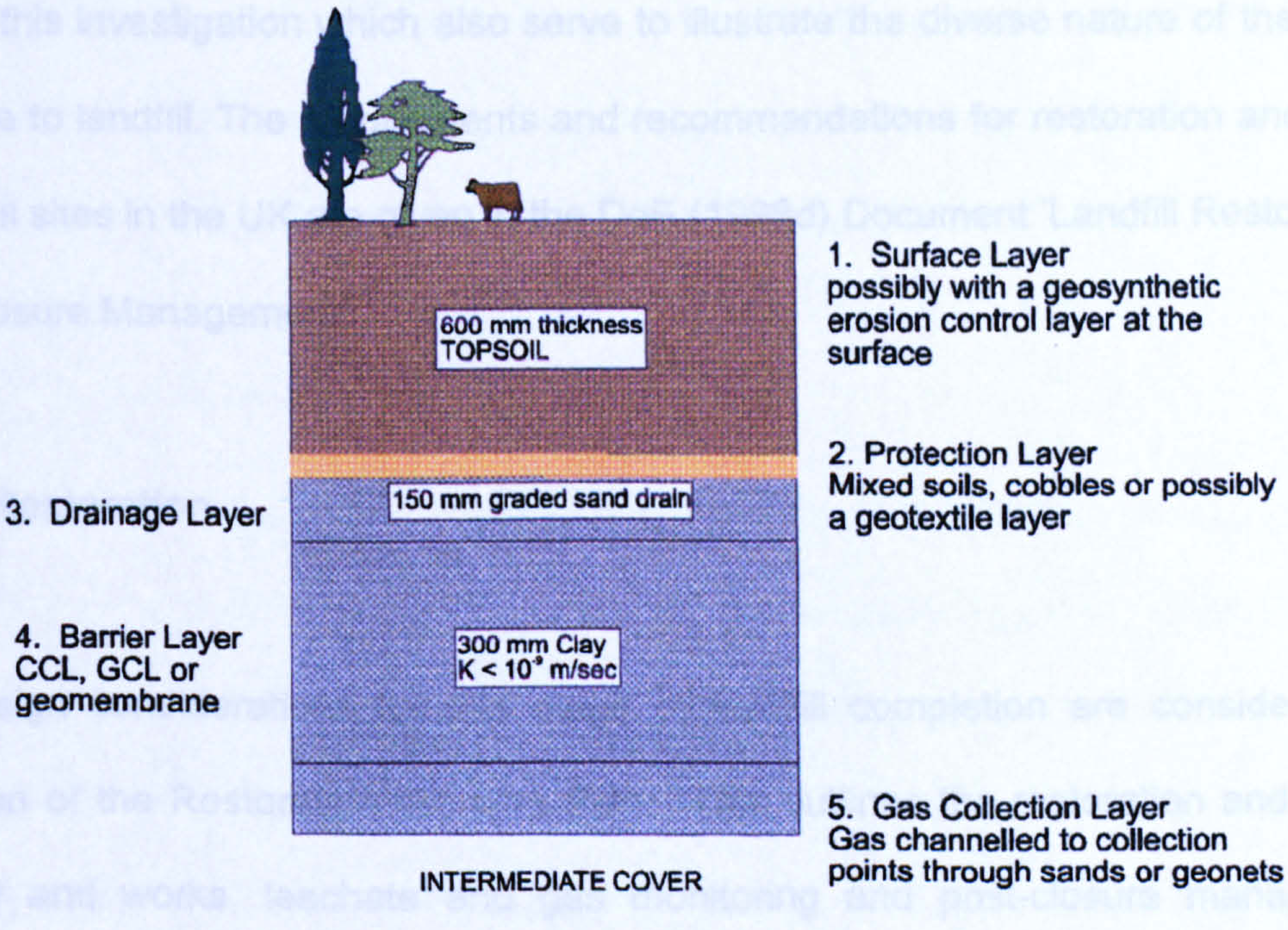


Figure 3.11 Possible Components of a Landfill Capping Design (Not to Scale).

The last layer of waste to be deposited is specified as inert in order to reduce polluting possibilities in the top layers. The final layers of the capping comprise sub soil and top soil. This is usually derived from the site prior to the landfilling process is begun or can be imported. The latter is less preferential since it may be inhomogeneous or of suspect provenance (DoE, 1996d). It could, however, be manufactured to specifications. Top soil is a particularly important layer in its ability to support indigenous and vigorous vegetation growth.

3.12 RESTORATION AND AFTERCARE

This is the process in which the completed landfill is integrated into the environment. The afteruse of a landfill site is now agreed at the design and licensing stage of landfilling so that restoration work can be completed accordingly. This is indicated by the case studies used in this investigation which also serve to illustrate the diverse nature of the end uses available to landfill. The requirements and recommendations for restoration and aftercare of landfill sites in the UK are given in the DoE (1996d) Document 'Landfill Restoration and Post Closure Management'.

3.12.1 Restoration

The design considerations for this stage of landfill completion are considered in the formation of the Restoration Working Plan. This outlines the restoration and after care strategy and works, leachate and gas monitoring and post-closure management of engineering systems (DoE, 1996d).

Alongside phased capping, phased restoration can be conducted, which is beneficial in terms of the following (Adapted from DoE, 1996d):

- Screening more recent phases with restored ones;

- Reducing the area which is to be worked at the completion of the operational phase;
- Returning land to its end use as soon as possible to create a more aesthetically pleasing feature;
- Reducing the amount of infiltration to completed areas of the site, thus keeping leachate heads to the minimum specified;
- Importantly, in order to test the effectiveness of control and monitoring systems while there is time available to change unfinished areas.

Drainage may be employed on the surface of landfills which are to be restored for an agricultural use. Surface drains are used to collect run-off and discharges from any operational underdrains. They may comprise open ditches, french drains and land drains, for example. Drainage designs are diverse and therefore, specifically dependent upon the choice of landfill design in terms of, angle of slope, estimated run off potential and finished cover material.

3.12.2 Aftercare

Landfill afteruse is the planned application for the use of the landfill site after completion of waste tipping and restoration. It is, however, reliant upon results of monitoring to show there are no immediate causes for concern regarding leachate or LFG migration. Afteruse is diverse, which highlights the possibilities now available for completed sites. In terms of the older completed sites, these may now be restored to agricultural use, nature conservation areas or locations of formal recreation with remediation.

Afteruse requires a specified level of monitoring in order to ensure the integrity of the site and that there is no contamination occurring. Integrated landfill systems must be protected in order to ensure that they fulfil their role in accordance with the requirements for the individual landfill site.

3.13 LANDFILL MONITORING

Landfill monitoring is an essential measure in order to reduce the risk of pollution occurring in operating and closed sites. Pollution can take many forms and will occur at varying concentrations. Costs of remediation treatment may be minimised by comprehensive monitoring systems employed at each site, such as those illustrated in Figure 3.12. A comprehensive monitoring strategy is required to encompass all stages of landfilling, even prior to waste placement.

Initially, monitoring serves two main purposes (Bagchi, 1990). These are:

1. To find out whether a landfill is performing as designed;
2. To ensure that the landfill meets its regulatory requirements.

However, although these may be the prime considerations, they are not the only aims associated with the operation of a holistic monitoring system. The North West Waste Regulation Officers Technical Sub-group (NWWDO, 1995) includes a further two purposes:

3. Ensuring an accurate level of flammable gas, oxygen and carbon dioxide is recorded at a given point. It should also enable gas flow rate and barometric pressure trends to be measured and representative samples of gas to be taken for further analysis.
4. Monitoring for gas and leachate migration plumes outside the waste boundary.

Specifically, it is the last of these points that is of direct relevance to this study. Chapter Six examines the possibility of airborne remote sensing for contaminant migration detection, which will invariably be lateral migration outwards from the entombed wastes.

Organisation of the types of monitoring in Figure 3.12 would only be able to determine the affected area within the scope of the equipment employed. Remote sensing can provide a more holistic method which enables detailed coverage of the vicinity of the landfill site.

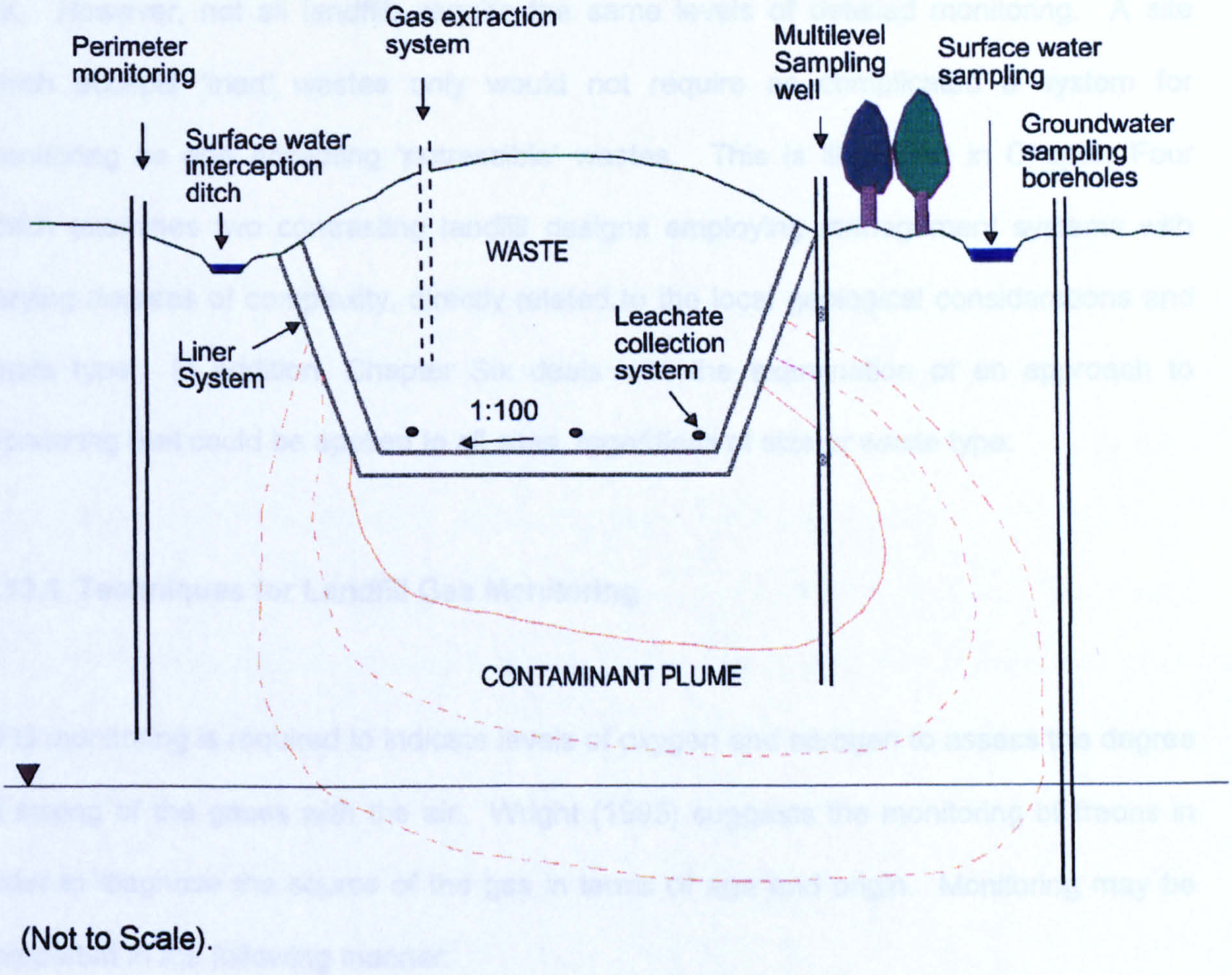


Figure 3.12 Schematic Diagram Illustrating Basic Forms of Landfill Monitoring. (Adapted from Bennet, (1997) and Christensen, (1992)).

Individual landfills have continuous monitoring schemes for both ground and surface water, as well as for gas in the soil and atmosphere around the site. The objectives of the monitoring strategies are stringent, in order to enable rapid response in the event of contamination. Indeed, Gervasoni & Piepoli (1989) state that monitoring strategy must be an *'integral part of the landfill design preceding its construction and should include the* *control of environmental quality and the control and study of the structures and the waste in order to create predictive scenarios'.*

This approach to recording the environmental quality has now been widely adopted in the UK. However, not all landfills require the same levels of detailed monitoring. A site which accepts 'inert' wastes only would not require as complicated a system for monitoring as one accepting 'putrescible' wastes. This is illustrated in Chapter Four which examines two contrasting landfill designs employing management systems with varying degrees of complexity, directly related to the local geological considerations and waste type. In addition, Chapter Six deals with the examination of an approach to monitoring that could be applied to all sites, regardless of size or waste type.

3.13.1 Techniques for Landfill Gas Monitoring

LFG monitoring is required to indicate levels of oxygen and nitrogen to assess the degree of mixing of the gases with the air. Wright (1995) suggests the monitoring of freons in order to diagnose the source of the gas in terms of age and origin. Monitoring may be completed in the following manner:

- Ground surveys to indicate emissions at surface level using a probe which detects results in parts per million (ppm). These techniques are particularly useful for detecting the integrity of the completed capping layer and efficiency of gas control systems;
- Spiking or searcher bar surveys and borehole monitoring to determine gas regimes in subsurface levels;
- Monitoring of buildings and confined spaces in the vicinity.

It is important, when considering the systems, to choose realistic strategies which can achieve the targets set for the site. However, the quantity and quality of the data must be assessed in terms of ease of collection and of comparison to standards, for example. It is pointless to collect unnecessary data which is not used in the general monitoring scheme. The importance of controlled computerised databases is critical to the extraction of relevant data, particularly in the identification of anomalous results.

3.13.2 Leakage Detection through Liners

Many of the most commonly used methods for leakage detection are outlined in Bagchi (1990) including: direct forms of monitoring, such as lysimeters, and indirect forms, for example, electrical and heat probes and salinity sensors. The electrical probes have been used since 1993 on sites employing geomembranes (Mosley & Crozier, 1996). Such liners have an insulating effect therefore, if no leak is detected the voltage produced by the hand held probe has a low current flow and uniform distribution. Leaks are detected when anomalies are found in the electrical potential gradient. Mosley & Crozier (1996) indicate that this is a highly effective method which reduces monitoring costs over the long term. Chapter Six highlights these forms of monitoring techniques in further detail.

3.14 DISCUSSION

This chapter has illustrated the principal components involved in the design of a landfill site in the UK and the complexities of current research. The issues for landfill design and construction thus encompass a diverse set of criteria. It is necessary to highlight this at this stage in the investigation in order to provide a foundation for the design and construction issues to be addressed in the following chapters. In addition, the chapter provides evidence of the intensity of current research in landfilling design and practice.

This review has illustrated the use of new materials in the field of landfilling and emphasised the fact that little is understood about their long term durability. The question whether the deployment of new liners in landfills, such as geomembranes, might raise the potential to cause future risks to the environment has not yet been fully answered through research.

Today's main problems in landfilling stem from older unlined attenuate and disperse sites. The prime decision for landfilling is which design should be employed to achieve an environmentally sustainable site. Sustainability, i.e. the creation of a non-polluting site in the future, is therefore a critical objective that must now be considered throughout the decision processes in landfill design, construction, operation and restoration.

There are, at present, various theories for landfill design which ultimately relate to the nature of the wastes, geological location and hydrogeological conditions of the site. Since research is conducted in different countries, there are varying approaches to design, related to the criteria imposed by contrasting national regulations. However, the research and opposing strategies need to be set in real environments in order to determine the precise nature of the problems. Research may be able to prove that a particular material is complementary to the parameters of a particular landfill design, but it is only through installation, operation as lining system component and monitoring of long term effectiveness, that underlying difficulties with the materials become apparent. For example, HDPE provides an ideal very low permeability barrier but it is difficult to install, i.e. it requires a high degree of expertise in order to complete proper seaming, joining and final quality assurance.

Leachate has the potential to be a highly polluting solution should it come into contact with the environment. Compounds produced within the waste body can be highly complex, with a potential to cause pollution in even extremely small quantities, for example phenols, trichloroethylene and metal complexes. Measures, natural or anthropogenic, must ensure that the impact of the leachates on the environment is minimised. It is also clear that the landfill design must incorporate the parameters of leachate composition and generation, in order to facilitate the construction of an environmentally sound and sustainable site. The engineering of such features within the design of the site is also of fundamental importance for LFGs, if complete containment is to be achieved. The reality of the issue of complete containment is addressed in further stages of the thesis, through site experience in construction and liner installation (Chapters Four and Five) and, most importantly, aspects of landfill monitoring (Chapter Six).

Landfill design parameters are, at present, so diverse that some aspects, by necessity, have not been dealt with in depth. This does not imply that they are less important, only that they are less relevant to the content of this particular study.

A wider scientific understanding of the role of leachates and LFGs in landfilling should improve future standards whilst also providing enhanced protection for the environment and public health. Change in current landfill technology is driven by the need to completely contain these products of deposited waste. It has perhaps, however, only encouraged their controlled release into the environment.

3.15 SUMMARY

- It is evident that landfills will leak over time whether they are constructed to do so (attenuate and disperse), or not (containment sites).

- Minimum prescriptive requirements for compacted clay liners comprise 1 m liner thickness and a permeability (K) of $\leq 1 \times 10^{-9}$ m s^{-1}. Composite liners must ensure attainment of the permeability requirement at least.

- Geologically engineered mineral barriers are a less effective landfill liner, in terms of hydraulic conductivity, in comparison with modern plastics and fabrics. However, they are not without advantages, such as, attenuation mechanisms and lower cost.

- Leachates and LFGs are potentially hazardous pollutants leading to contamination of vegetation, soils and ground waters. If managed and treated, their potential for pollution can be reduced, and sometimes create benefits, e.g. the production of electricity.

- Geosynthetics have enabled the exploitation of otherwise unused areas due to relative ease of deployment and more favourable material characteristics.

- A landfill comprises different systems which are independent, but intrinsically they must work together, e.g., leak detection and a lining system.

4.0 CASE STUDIES IN LANDFILL DESIGN AND CONSTRUCTION

4.1 INTRODUCTION

Landfill is inevitably set to remain a fundamental component of the waste management strategies in the UK and internationally. The development of landfilling practice today occurs alongside the evolution of Codes of Practice guidelines and legislation to facilitate a controlled approach. Prior to COPA (DoE, 1974), the organised design and construction of a landfill site was a rare requirement of the waste management and construction industries. Now, however, this is no longer the case since there is a well-developed international field comprising experienced engineers and researchers. Much of the data which have been recorded on landfills have been gained through practical experience of situations in on-site construction and, in post closure conditions. This illustrates the importance of site conditions for the evaluation of the short and long term performance of landfilling components, strategies, and procedures.

The main emphasis for this chapter concerns the construction of two landfills and illustrates the dependence of their design upon certain parameters. Fookes (1997) highlighted the possibility of the diversity of results from materials on-site compared with the results achieved under laboratory conditions, the latter being the most influential in determining site construction specifications. This chapter develops these concepts through a discussion of real situations and illustrates the value of procedures for assuring the quality of the work completed throughout all stages of landfilling. The case studies are an important aspect of this investigation since they provide an understanding of site procedures and inter-relationships between the parties involved in landfill construction.

4.1.1 Investigation Outline

An outline of the design and construction procedures is presented for two contrasting case study landfill sites in the UK: Site Alpha in Harmondsworth and Site Beta in Nottinghamshire.

Observations on the practical site engineering, which were completed over a period of three months on-site, are highlighted through this chapter. This investigation facilitated the collection and evaluation of information relating to the complexities of on-site practice and the variability that may occur between landfill sites as a result of the differing designs and extant ground conditions (SISG, 1993a). It was established through on-site experience that effective landfill design and site construction practice are directly related to the specific ground conditions of the individual landfill.

This chapter addresses the main construction issues which influence modern landfills. Legislation and Codes of Practice, as outlined in Chapter Two, guide these and the regulatory procedures enforced by the EA. In relation to site construction, these Codes of Practice and guidelines may be open to further interpretation by the engineer and contractor. As a result, contrasting site conditions will probably be the influencing factor in the application of these requirements and specifications. Figure 4.1 shows the decision processes and parties involved throughout the development of a landfill site, through the following stages:

1. Definition of potential objectives and concepts for the site;
2. Construction;
3. Operation;
4. Performance Monitoring;
5. Restoration and completion;
6. Continual environmental monitoring.

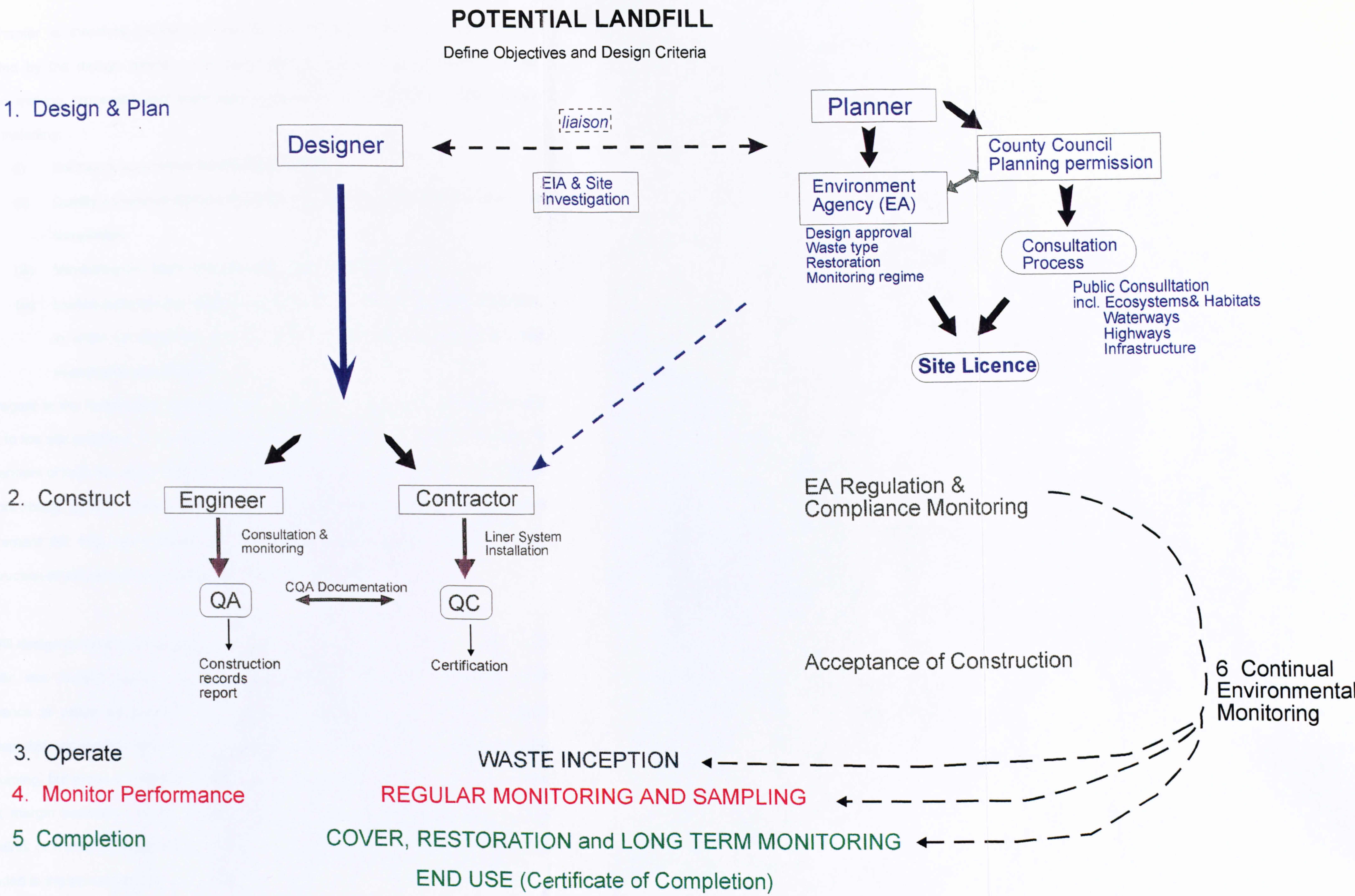


Figure 4.1 Simplified Route from the Inception to Completion of a Landfill

This chapter is therefore concerned with the construction stage which is primarily controlled by the design criteria. The case studies provide an understanding of the decision making processes and techniques involved in the construction of a modern landfill including:

(i) Earthwork supervision for the liner placement;

(ii) Quality Assurance (QA) for the liners throughout construction and after to completion;

(iii) Monitoring to ensure compliance by the contractors with the QA plan;

(iv) Liaison between the designer and contractor, (also other involved parties), in order to verify the level of QA in accordance with the design and construction specifications.

With regard to the fourth point, the author's role on-site was to monitor proceedings and report to the site engineer. For legal reasons, the QA engineer, a 'competent engineer', is independent of both the owner and the contractor on the site, in order to prove compliance with previously agreed working and operational plans. However, there is no statutory requirement for this, as opposed to, for example, the works associated with the construction of a reservoir dam (Seymour & Peacock, 1994).

Landfill design is inextricably linked to the ground conditions at each site. This results in specific site designs being considered with respect to anticipated conditions, whilst allowance is made for possible minor refinements throughout the procedure. Rigid, unadaptable approaches will inevitably lead to problems on-site, which are not only time consuming, but prove sequentially to become an increasing financial drain on the original profit margin estimate. SISG (1993b) state that it is the economic and the ground restraints of a project, which dictate the form of the structure, therefore, these should be included in the primary stages of the design.

In order to design and construct a landfill that meets an acceptable level of risk, good working and contractual relationships between the designer, construction engineer, QA engineer and regulation authorities, i.e. those represented in Figure 4.1, are of paramount importance. Discussion and negotiation between these parties usually reach solutions to complications that arise after construction has commenced. The results achieved depend upon combined knowledge of the best practical options for the individual site, i.e., mediation between all parties involved in the decision-making processes and putting cost effectiveness into practice.

4.1.2 Realisation of Landfill Design

This on-site investigation achieved an insight into the practical realities of working on the construction of a landfill site. The primary objective of this area of the study was to investigate the design approaches and construction programmes adopted on two landfills. Previous work by Fookes, 1997, Day & Daniel, 1985 and Daniel, 1984 has indicated clearly that it is necessary to attempt a comparison between the concepts generated by theoretical studies with those that are directly feasible on-site. The waste management industry requires the newly researched and developed applications to be workable and readily operational. Conversely, the theory presented is not always practically achievable in the first instance.

An illustration of the difficulties involved in Design Realisation may be demonstrated by a comparison of results of *in situ* field permeability tests after compactive action with results of in-house laboratory tests, such as the triaxial permeability test. For example, permeability tests on samples with modified (Heavy) Proctor effort (4.5 kg rammer), revealed that the laboratory results were lower than field tests by at least 2×10^{-3} times, at all moisture contents (Elsbury *et al.*, 1990). Previously, Daniel (1984) had determined that hydraulic conductivities of clay barriers were 10 to 1000 times higher than laboratory measurements performed on undisturbed and recompacted samples. This indicates that laboratory test results cannot be used in a comparison with *in situ* testing without error, which poses a question concerning the reliability of both. However, when considering the explanation, the evaluation of influences of laboratory conditions and sample preparation techniques is of importance. Research (Day & Daniel, 1985), proved that on-site testing alone should be used to calculate the hydraulic conductivity of clay liners. Further research is therefore essential to enable a direct comparison between results achieved in the laboratory and those encountered on landfill liners in real situations. Some 'theoretical' and 'real' differences have been highlighted in more detail in this chapter.

4.2 QUALITY ASSURANCE (QA) AND QUALITY CONTROL (QC)

At all landfill construction sites. a regime of rigorous testing procedures must be completed in order to provide assurance that the landfill has been constructed in accordance with the design specification (NWWRO, 1995 and Workman & Keeble, 1993) and is also within regulatory parameters. This demonstrates the importance of integrating Quality Assurance within landfill construction procedures in order to reduce the risk potential for environmental pollution.

QA may be defined as '*the features and characteristics, both planned and systematic, of a product or service that bear on its ability to satisfy stated or implied conformance to quality through contractual and regulatory requirements'*. (Adapted from CIRIA, 1996, DoE, 1996b and Belfiore & Magri, 1995). Therefore, the basic objective of QA in landfill construction is '*to verify, document and certify that, at the end of construction, the landfill meets or exceeds the design criteria and the legal requirements*' (Belfiore & Magri, 1995). QA monitoring must be incorporated into the design, operation and maintenance processes (NWWRO, 1996). Indeed, Waste Management Paper 26B (DoE, 1995b) states that '*quality cannot be inspected in, it has to be designed and constructed in'*. Ultimately, in current situations, the owner may employ QA as a means to protect himself against future unforeseen design faults and environmental problems. It provides independent third party assurance of the quality inspection stages and may result in stricter procedures than those stipulated by the regulators.

Conversely, Quality Control (QC) is *'the operational techniques and activities that are used to provide a means for measuring the requirements for quality according to plans and specifications'* (BSI 4778, 1987 and Belfiore & Magri, 1995). This is generally completed by the contractor in order to ensure compliance with the previously outlined design specifications.

Throughout the design and construction of a landfill, the Construction Quality Assurance (CQA) plan should address the following (Cossu & Muntoni, 1994):

- Design quality control and assurance;
- Construction quality control and assurance;
- Operating quality control and assurance.

Specific to soil liners, Daniel (1993) subdivides the Construction Quality Control (CQC) into:

(i) Tests to verify that the materials of construction are adequate;

(ii) Tests and observation to verify that the compaction process is adequate.

These strategies are completed in accordance with guidance notes on quality and British Standards. For example, the geomembrane liner system, must meet its performance criteria in terms of *'permeability, chemical and mechanical compatibility and durability'* (Haxo & Haxo, 1994), whilst also verifying compliance with stipulations upon completion. Since the geomembrane is prefabricated, a degree of materials compliance testing will have already been completed after manufacture, certification for which must accompany the material.

The QA engineer must also be concerned with effects on health, the environment and general safety against uncertainties, all within the financial framework of the project, and, as Koerner & Koerner (1989) state, the cost benefit ratio must also be addressed. DoE (1995b) indicates that the Construction Quality Assurance (CQA) of liner systems may constitute between 2.5 - 5 % of total construction costs. Cost effectiveness cannot be understated in the financial plan, which encompasses operational to post construction phases. The project plan must therefore allow for a reasonable profit to be made by each investing party.

4.3 GROUNDWATER CONTROL FOR LANDFILL CONSTRUCTION

This section highlights the considerations involved during landfill construction specifically in voids below the level of perched groundwater tables (Hopper & Leach, 1997). Construction of sites below the water table has become a necessity with the decrease in suitable sites throughout the UK, coupled with the increase in waste productivity (Table 1.1) of which 70 % now goes directly to landfill (DoE, 1995b). However, this may not be acceptable practice in other countries. For example, German regulations and practice would not currently permit the operation of such a design without a minimum 1 m barrier above the groundwater (TA Sieglungabsfall, 1993 & Stromberg, 1995).

Ground conditions will, under normal circumstances, be in a state of equilibrium with natural groundwater flow. However, variations can be related to a change in flow. Barnes (1995) states that ground engineering works will alter the stable state, disturbing the pattern of groundwater flow which will lead to inevitable instability problems, especially during excavations. This is a predominant problem affecting the construction of landfill sites. Groundwater controls must therefore be effectively incorporated within the design and working plans.

Interception of water entering a landfill is essential in order to minimise leachate production and reduce the potential for groundwater contamination. Installation of an interceptor system is required to divert groundwater temporarily since ingress is inevitable. Waste Management Paper 26B (DoE, 1995b) states that the design of the landfill liner should take into consideration the continual seepage of groundwater, its effect on leachate quantity and uplift pressures. Diversion of the ingress also serves to relieve the hydraulic loading on leachate control and management systems (NWWRO, 1995) which have to cope with natural influxes dependent upon weather regimes. The requirement for this should be established during the site investigation when regional and perched water tables are recognised (Whittle & Swanson, 1986). Finally, a hydrogeological model for the landfill can be put forward for integration into the design procedure. Investigation of the latter should include location, quality, movement, and seasonal variation of groundwaters all of which influence site conditions (Workman & Keeble, 1993).

4.4 SITE ALPHA LANDFILL CASE STUDY

4.4.1 Introduction

This section considers the aspects of design, methods of construction and the QA procedures involved in the construction of a single engineered mineral landfill liner of low hydraulic conductivity. Mollard *et al.* (1996) emphasise the controversy over clay liners, stating that *'there has been concern over the effectiveness and durability of such liners when exposed to some of the more aggressive leachates and liquids associated with waste disposal'*. In contrast, Workman & Keeble (1993) indicate that clays with a low hydraulic conductivity, less than $K = 1 \times 10^{-9}$ ms^{-1}, are *'commonly considered to provide long-term protection of the environment'*.

At Site Alpha, the single mineral liner was employed due to the local geological and hydrogeological suitability of the site and the relatively inert nature of the wastes to be deposited (Table 4.1). The latter could result in the production of a less aggressive leachate in comparison with sites accepting putrescible wastes. Therefore, the leachates produced at Site Alpha will be less aggressive than the ones referred to previously by Mollard *et al.* (1996).

Waste Type	**Max. Tonnes day^{-1}**
Category A: Inert Waste	130
Category B: General non-putrescible wastes	370

Table 4.1. Site Alpha Waste Acceptance Figures (LWRA, 1994).

The 'Waste Strategy for England and Wales' (DoE, 1996a) states that landfills accepting inert wastes only, as well as those sites that are *'well managed'* are unlikely to pose a pollution risk in the future. Landfills categorised as having a minimal pollution potential have achieved the principles of sustainable development. They are therefore compatible with the NWWRO's (1995) definition of sustainable waste management as *'disposing of wastes in a manner that, because it minimises the pollution control burdens we leave behind for our future generations, is compatible with the concept of sustainable development'.* It remains to be seen, however, whether a site can maintain sustainability through leachate recirculation or dry entombment.

This investigation concentrates upon the construction of the first cell of two at Site Alpha, a site owned and operated by a sand and gravel extraction company. The local geology has had a profound influence upon the area since there are many pits in the locality which have now been completely filled. This is important to consider, with respect to Site Alpha, which is only operated within a small area and is infilled with only inert wastes, in comparison with adjacent and nearby sites which are far larger and accepted putrescible wastes.

Since the completion of the site work, a second, 'mirror-image' cell at Site Alpha and an aeration lagoon, for the collection of both ground and surface diverted waters, have been constructed, as illustrated by Figure 4.2. The second cell is based upon a continuation of the design principles from the first cell, thus the groundwater control system in operation in the first is directly linked to that of the second cell. By November 1997 waste tipping had filled both cells and progressive restorative processes had commenced.

4.4.1.1 Site Location

Site Alpha (Figure 4.2) is located to the West of London, close to Heathrow Airport. Upon completion it is to be integrated into part of a development scheme for a 'Combined Business Centre' headquarters. This development, will eventually encompass an area comprising new landfills and landraises, as well as pre-existing landfills. The whole complex is due to be finished during 1998, when it is expected that the offices will have been completed for occupation (Nuttall News, 1995).

Essential remedial work had previously been completed on the pre-existing uncontained sites in the vicinity to enable the environmentally sound, future development of the entire area. It is important to consider that the pre-existing landfills were uncontrolled, thus their contents remain unrecorded and the sites probably did not benefit from a construction design procedure. It is known that some of the landfills received putrescible wastes, which have since produced aggressive leachates. As a result, the environmental impact of such a complex site was investigated in an Environmental Impact Assessment (EIA) using the current knowledge of the polluting potential of completed landfills. Site Alpha provides a direct comparison with these sites, in that it is a lined site, accepting inert materials illustrating the importance of the change in design philosophy as described by Chapter Three.

As the pre-existing landfills have potentially been producing leachates before the

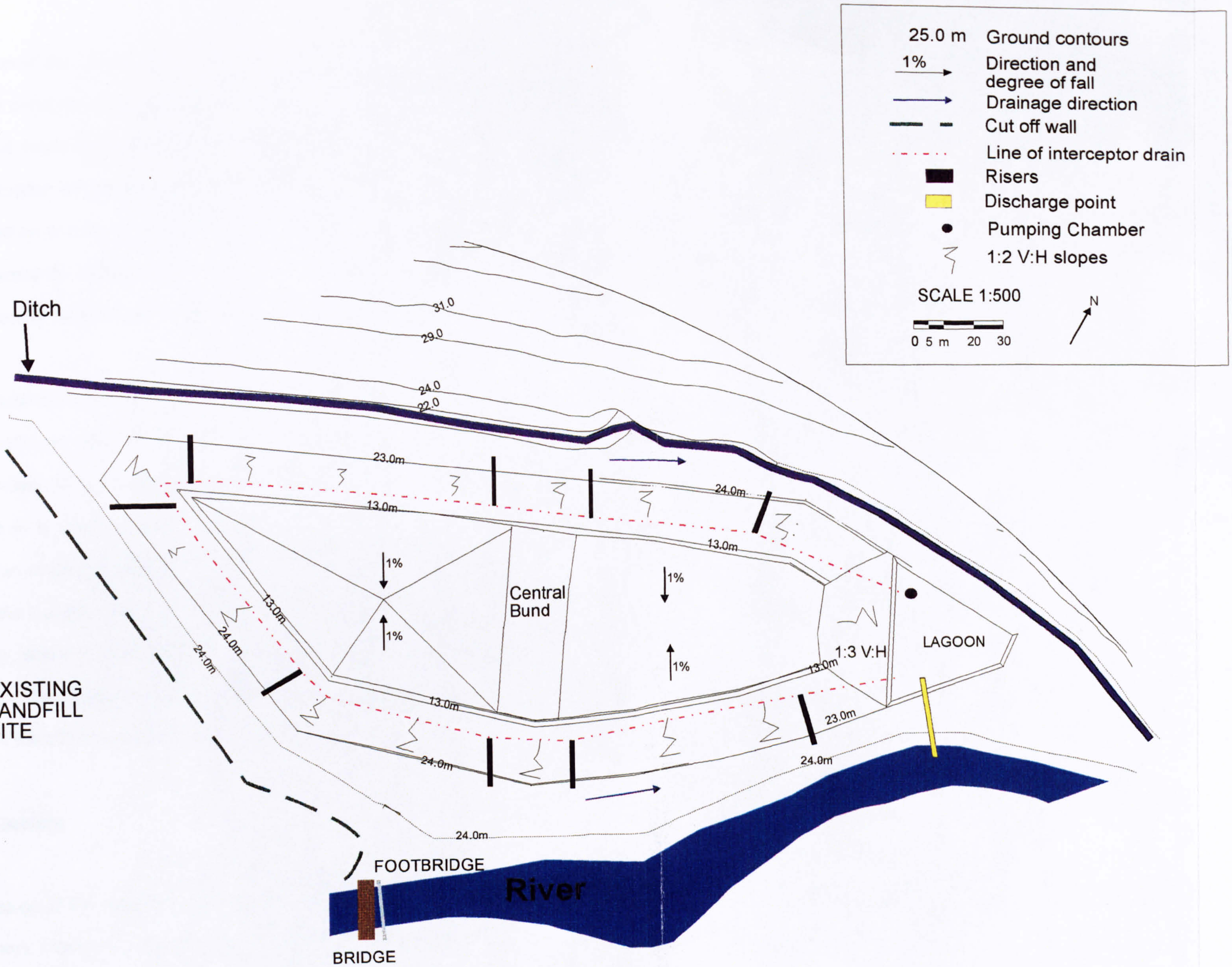


Figure 4.2 Plan of Site Alpha. (Adapted from Site Construction Plans (CQA, 1995))

construction of the new sites, monitoring was conducted, over a three month period to reveal any previous contamination of groundwaters from the pre-existing landfills. These background measurements were considered in relation to the results for the new sites. Such a situation will become widespread if, as it seems probable, future landfills will be constructed on or near to existing sites. Indeed, it is more likely that planning permission will be granted for an extension to an existing landfill site, as opposed to the construction of a new landfill on an undisturbed area of land (Hopper, 1994).

4.4.1.2 Site Description

The first cell to be constructed was 100 m by 50 m and rectangular in shape at a depth of approximately 13 m illustrated by Figure 4.2. The void was particularly suitable for landfilling as it was previously a shallow sand and gravel pit, excavated for superficial River Thames alluvial deposits. Following the site investigation and suitability testing of the *in situ* London Clay, the site was given planning permission and a licence for landfilling, with the employment of a single engineered clay liner as the containment structure. The presence of clay minerals would enable attenuation processes to reduce toxicity of the contaminants whilst also delaying their migration.

4.4.2 Geology

The geology of the area comprises Reading Beds overlain by Tertiary London Clay and Quaternary Floodplain Gravels, the lowest of the Thames Valley gravel terraces (BGS, sheet 269, 1920). These alluvial sands and gravels are in turn overlain by thin layers of Holocene Alluvium and Made Ground. Figure 4.3 illustrates the site geology and Table 4.2 provides the stratigraphic sequence.

The Floodplain deposits are sands and gravels comprising predominantly sandy coarse, flint GRAVEL, which was approximately 5 m in depth across the site. The gravels appear

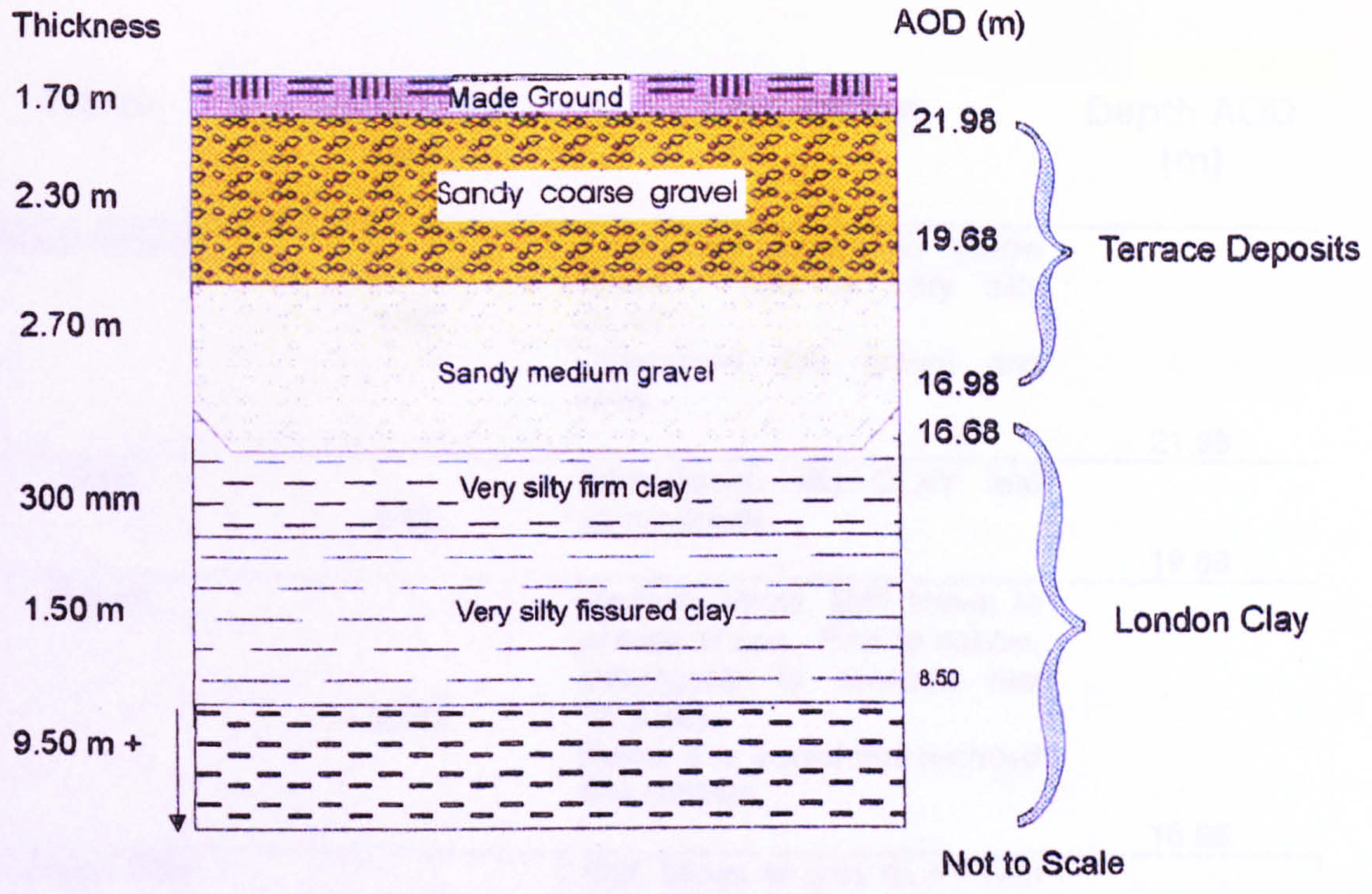


Figure 4.3 Site Alpha Geology

to be poorly sorted across the entire site and are bound by a matrix of weak ferrunginous, fine sands. The deposits exhibit noticeable stratification related to the size of the particles and their ferrous content (Plate 8.6). These floodplain deposits have been exposed on the slopes of the void for several months since the cessation of extraction.

The underlying London Clay is predominately a blue-grey, thinly laminated, heavily overconsolidated, stiff CLAY with inclusions of pale grey siltstone. Chapter Five will describe in further detail the geotechnical properties of this clay with respect to its potential deployment as a landfill liner. At the site, the clay was weathered to a depth below the base as determined by the ground investigations prior to construction (Foundation & Exploration Services, 1994). As seen from Table 4.2 the clay is fissured which was substantiated by Skempton's work (1964) in other locations.

Borehole investigations indicated the depth of the London clay to be in excess of 13.25 m below the base of the existing excavation. It was considered unwise to sink a new

Strata	Thickness (m)	Description	Depth AOD (m)
Made Ground	1.00	Firm, dark brown to yellow brown. Silty to very silty CLAY. Occasional flint gravel and brick.	21.98
Clay	0.70	Firm brown silty CLAY and some gravel.	19.68
Gravel	2.70	Medium dense, light brown to orange brown. Fine to coarse, subangular to rounded flint GRAVEL. Below 3 m occasional rounded flint cobbles.	16.98
London Clay	1.50	Stiff, brown to grey CLAY with close fissures.	14.48
	negligible	Brown, grey moderately weathered weak mudstone. Weak.	-
	> 30	Very stiff and very closely fissured CLAY. Thinly laminated very silty with occasional shell fragments.	To base of borehole
	?	Basement Reading Beds	

Table 4.2 Borehole Log Description for Site Alpha. (Adapted from FES, 1994)

borehole at any point across this site or in the rest of the development, in order to determine the base of the London Clay, since this could provide a pathway for subsequent leachate migration into the Reading Beds below. The boreholes in existence indicated the depth of the London Clay to be in excess of 30 m. The site investigation also revealed the slightly heterogeneous nature of the clay deposit with the existence of a thin band of siltstone (approximately 0.20 m in thickness) throughout the site at a depth of 8.5 m below the contemporary ground surface. In this example, the layer of siltstone would have little effect, since it is covered to a significant thickness (a minimum of 1 m) by the compacted clay barrier. The presence of such an horizon demonstrates that *in situ* materials are rarely perfectly homogeneous and should always be considered in the design of any landfill.

The clay exhibits other variable characteristics. For example, naturally occurring fissure spacing throughout the layers, (which was also revealed by the site investigation), which is a characteristic of all heavily overconsolidated clays. After clay extraction, extensive fissures are in evidence in newly exposed locations. These fissures can cause uncertainty in the integrity of the *in situ* material, because they encourage the flow of aqueous or gaseous landfill products along their profile and thus away from the site. Conversely, permeants from other sources could, in the same way, penetrate the liner, making a substantial contribution to the head of leachate. For the purposes of landfilling design of containment sites, it is unacceptable practice to allow fissures to remain. A containment structure must prevent, as far as possible, the release of contaminants from the cell.

4.4.3 Hydrology and Hydrogeology

The hydrology of Site Alpha is controlled by two bounding sources of surface water: a Ditch and, more importantly, a minor River (Figure 4.2). The river is the main water source flowing from North to South along the Eastern boundary of the site and through the main area of development. It was necessary to prevent point pollution of the river both throughout the construction works and the future of the site. In other areas of the development, however, the River was diverted to allow expansion of the site and preclude pollution from landfilling activities.

Hydrogeological considerations are very influential in determining the suitability of a site for landfill. The hydrogeology is dependent upon geological parameters with particular consideration given to the permeability and porosity of the underlying materials and the direction and degree of the hydraulic gradient. Ultimately, this is one of the main criteria for consideration during the site investigation.

At Site Alpha, groundwater is present in the Floodplain Gravel at a depth of approximately 2 m below contemporary ground level and forms a minor, but influential, perched water table above the aquiclude comprising the London Clay. The virtually free draining alluvial sands and gravels lying above the clay thus provide a medium for the passage of permeants via ingress or egress. Discharges out of the site are more problematical in terms of contamination potential. It is also important to consider the quantities of possible ingress waters because the influence of these pressures must be accounted for in the minimal risk liner design. Consistent groundwater levels were recorded in piezometers along the East of the site which revealed that the static water level was lower than the river level. Therefore, it was concluded that the river recharges the groundwater and ultimately the void. Along the Western side, groundwater levels are lower, which indicate that the general direction of groundwater flow on the site is to the North West.

One of the uncertainties during the construction of the liner was the strength of the hydraulic pressures bearing on the back of the liner, derived from the sands and gravels. Therefore, when placing the liner, it was necessary to consider the increased hydraulic pressure created as the groundwater is naturally drawn towards the void. As a result, the design necessitated the use of temporary groundwater control measures throughout the earthworks and placement of the liner. The existence of a groundwater control system also enabled the use of thinner side liners without compromising the integrity of the site. This proved to be important in terms of economics, as a thinner barrier meant that enough material was available on-site for the construction of the liners, the separation bund between the two cells, the future capping and for the restoration. Once the liner was completed and the wastes buttressed against the sides, groundwater control would no longer be necessary as the system would then be self-regulating.

4.4.4 Site Work Prior to Placement of Liner

4.4.4.1 Preparation

The entire site was geodetically surveyed prior to the commencement of work. The survey was completed from several pre-recorded triangulation points strategically placed on-site. A profile of the site was then produced on Computer Aided Design (CAD) software and progress updated throughout construction. The surveyors were then called upon to relocate the different site levels in accordance with the progression of the construction.

Levels placed on the batters or slopes of the landfill liner were sighted at appropriate locations and set to prearranged angles which enable the contractor to achieve the specified degree of slope by aligning the profile with the temporary slope of the compacted clay. This system is used by earthwork contractors throughout the UK and works adequately. Finally, upon completion of the site, profiles could then be rechecked by more accurate surveying techniques.

4.4.4.2 Drainage and Earthworks

The area comprising the first cell was already waterlogged through natural ingress prior to the earthworks which necessitated dewatering by continual pumping until long term measures could be put into effect. The unusable saturated material, forming the base of the extraction pit and comprising some London Clay and alluvial deposits, was removed from the void and deposited in the future, second Cell, alongside a temporary aeration lagoon.

Drainage was achieved by channelling the waters under gravity to several temporary sump points dug into the *in situ* materials. From there, two six inch pumps were used to pump the water into the temporary aeration lagoon discharge. The pumping rate was measured at approximately 4.5 $l\ s^{-1}$ from each pump.

The aeration lagoon was a temporary sump at the start of the works for the collection of the site drainage waters. Upon completion of the first cell, the sump area was lined with a High Density Polyethylene (HDPE) membrane (2.5 mm in thickness) and an aeration system for the water was installed (Plate 8.7). Discharge was subject to controls in terms of quality and quantity, i.e. the suspended solids and ammonia levels, such as those stipulated by the Water Authority and the NRA.

Groundwater ingress was collected in the temporary trench and diverted to two sumps at the Northern end of the cell where the pumps were situated. This worked successfully during the main earthworks. However, on one occasion when the pump broke down this led to flooding of the base and saturated material had to be excavated and deposited temporarily in Cell Two.

A bench was cut into the clay on three sides of the cell, at an elevation of 17 m AOD, except the North where a 2 m vertical compacted clay bund was constructed for cell division. The aim of the bund was to separate the leachate between the two cells, thus maintaining different containment systems for the leachate. In the unlikely event of a catastrophic failure of the liner, any problem area could then be traced back to a particular cell. The bund also allowed for the independent development of each cell, as the second cell was to be constructed whilst the first cell was being filled.

The 2 m height for the bund was determined by the site licence which stipulates a maximum 1 m head of leachate in the completed cells. Should the leachate rise above this level, it could then be extracted from the main sump at the centre of each cell base. The bund also had a minimum stipulation for a 4 m width at the crest to enable the plant to place and compact the material.

The slopes of the pre-existing void were lying at approximately the natural angle of repose for the *in situ* materials prior to construction of the liner. The slopes of the Thames Gravels were regraded to 1:1.5 (V:H) (generally less than the angle of repose for these deposits) and London Clay to a 1:2 (V:H) gradient providing sufficient standing stability throughout the works.

4.4.4.3 Plant

The plant employed for this work included an excavator, several 25 ton capacity dumper trucks for the transportation of the clay material and a D6 bulldozer with the facility to tow a vibrating compactor. In this case a sheepfoot compactor (static weight per metre width of roll >4000 kg) was used due to the nature of the material employed, for the construction of the mineral liner. In many situations the choice of plant will be affected by factors such as availability of plant and / or qualified operator, and, importantly, cost. In the case of the second case study site an alternative approach was employed due to the contrasting nature of the materials and the particular subgrade finish required in the design. Needham (1991) states that the type and weight of the compactor is crucial to the achievement of the compaction specification, since the dimensions, number and size of the feet could invite substandard permeability.

The natural London Clay was relatively dry, although within the moisture content specification, and had formed macrostructure clodding (Elsbury *et al.*, 1990), which had to be broken down in order to achieve maximum compaction and to reduce interclod voids (Needham, 1991). The hard, dry clods could inhibit compaction and lead to fissures in the structure of the liner, if they were allowed to remain unbroken. This particular soil is also brittle which could increase the probability of compaction-induced fractures (Rowe *et al.*, 1995) which are created during compaction by the roller feet. The clay is compacted in loose layers or 'lifts' at a specified thickness, no greater than 250 mm in thickness, and passed over by the compactor. Guidelines may specify that the top of each lift should be scarified in order to provide an adequate interlift bonding. If the surface is dessicated, for example at the start of the day's work when the liner section has been left semi-completed overnight, the surface should be wetted or scraped off. This provides a prime example of the difference between theory and on-site practice, since the actions required in theory are time consuming and costly. With regard to the wetting of the clay, this presumes a water supply on-site or the presence of a bowser and sufficent time to allow homogeneous distribution. Research investigations (Chapter Five) explain the presence of preferential flowpaths between lifts, but these could be reduced by adequate 'keying in' of the clay between the lifts with further passes of the compactor.

4.4.5 Groundwater Collection System

Due to the hydrogeological nature of the area, (i.e. the perched water table in the superficial deposits), groundwater ingress had to be controlled temporarily during the construction works and a permanent system was then installed for use throughout the lifetime of the site and post closure. Monitoring of the groundwater ingress into Site Alpha indicated that contaminant migration was occurring, even before the onset of waste tipping.

The origin of the water seepage was of particular interest. On the Western side of the site is a pre-existing fill, which was subject to remedial works before further landraising took place. The works comprised the construction of an HDPE and bentonite slurry containment wall to prevent seepage from the site. It seemed possible that the contaminated water emanated from this site, especially considering the hydraulic flow gradient across the area.

As the groundwater percolated through the lower 1 m of the sands and gravels, water was continuously seeping into the site. This proved to be a problem for several reasons:

- It caused contamination of surface and groundwaters;

- Site construction could not be completed in wet conditions as the plant could not operate on the saturated material;
- Once the moisture content of the London Clay had risen it could not easily be compacted to achieve the specified compaction requirements and first would require drying. This was deemed to be an impractical on-site procedure.

Temporary groundwater control measures were maintained throughout the earthworks until it was possible to install the permanent water collection system. Installation was completed in line with the construction of the side liners. The top of the bench height did not coincide with the base of the terrace deposits. As a result, approximately 0.5 m of clay existed between the two. Figure 4.4 provides a diagrammatic explanation of the design for the permanent groundwater control system.

The installation of the groundwater interceptor system involved excavating a 2 m width bench in the clay at a height of approximately 17 m Above Ordnance Datum (AOD), approximately 0.5 m below the Floodplain Gravel / London Clay contact (Figure 4.4a). The 2 m width was stipulated to allow it to serve as an access route for plant during liner deployment, since traffic was to be continual throughout side and basal liner construction. The weight of the daily traffic received by the clay bench would also contribute to the compaction of the clay. However, this was not an engineering design stipulation.

The collection system comprised a trench bedded with washed gravel into which a 30 cm diameter HDPE perforated slotted pipe was placed. The pipe system was covered with the same washed gravel to enable a good hydraulic connection. At regular intervals the pipe system was attached to riser pipes (Figure 4.2 and 4.4) using a junction comprising slotted, perforated HDPE piping 50 cm in diameter. These were attached to the groundwater system via small HDPE sumps for the collection of water (Figures 4.4b and 4.4c). The risers provided means of access to the system in case a build up of water due

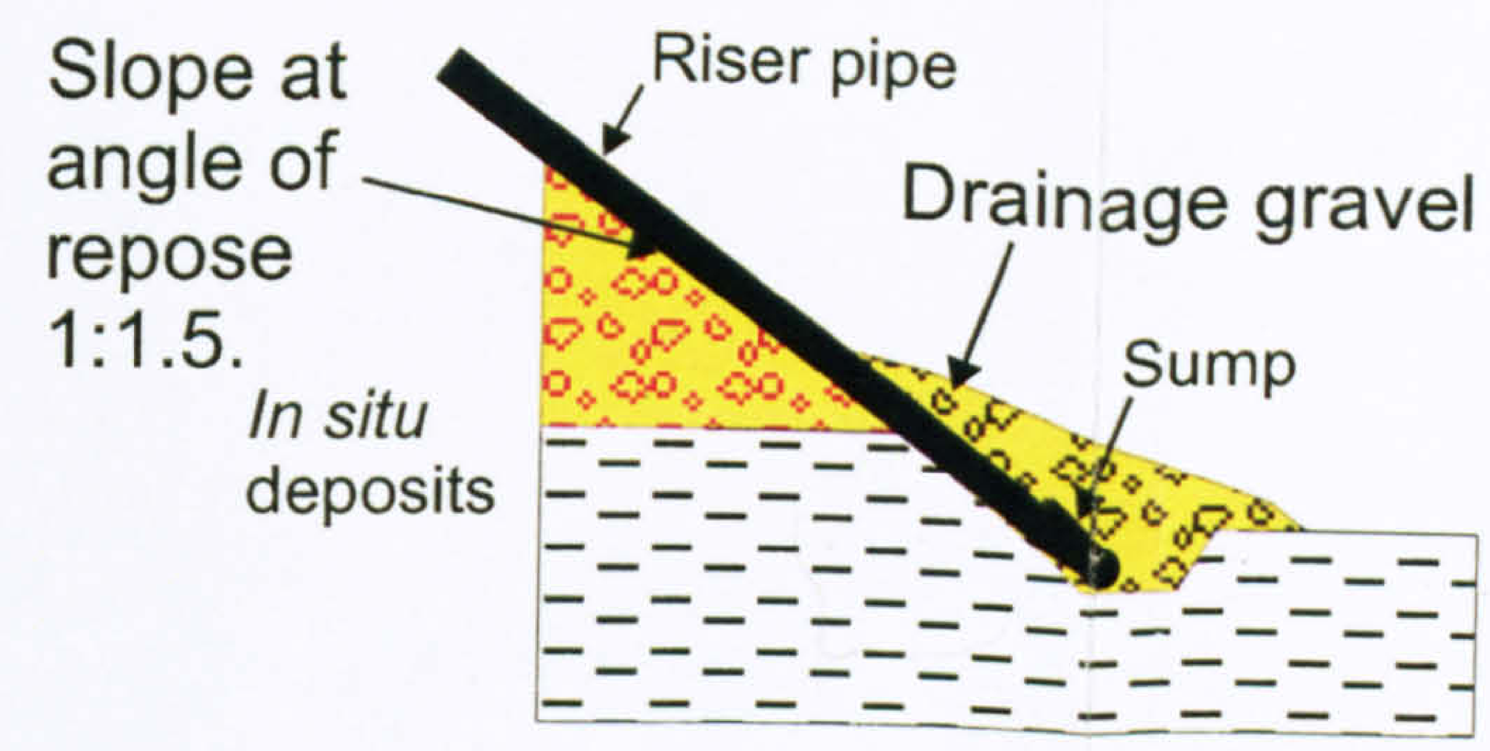


Figure 4.4b Riser pipe location.

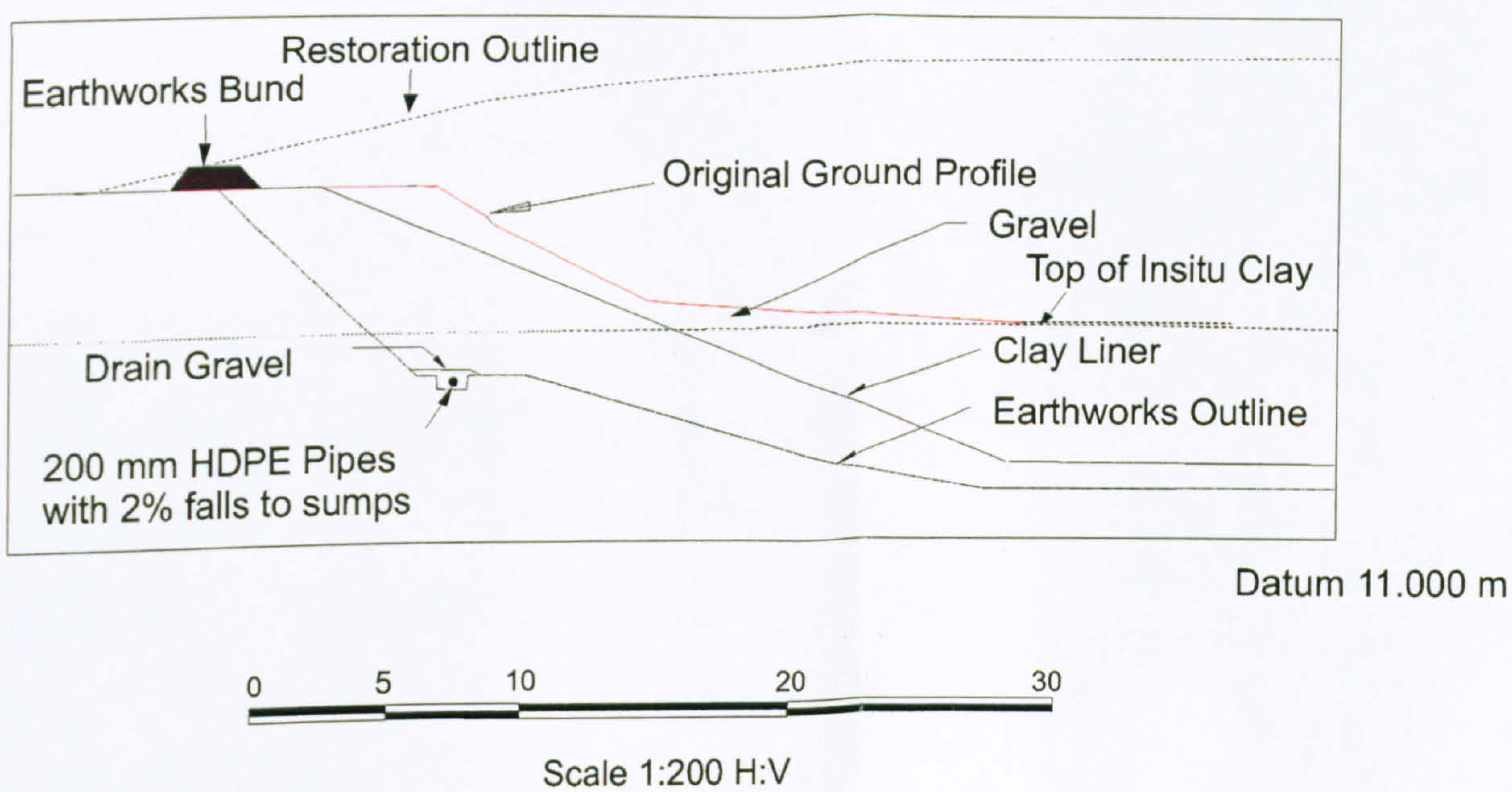


Figure 4.4a Section through liner

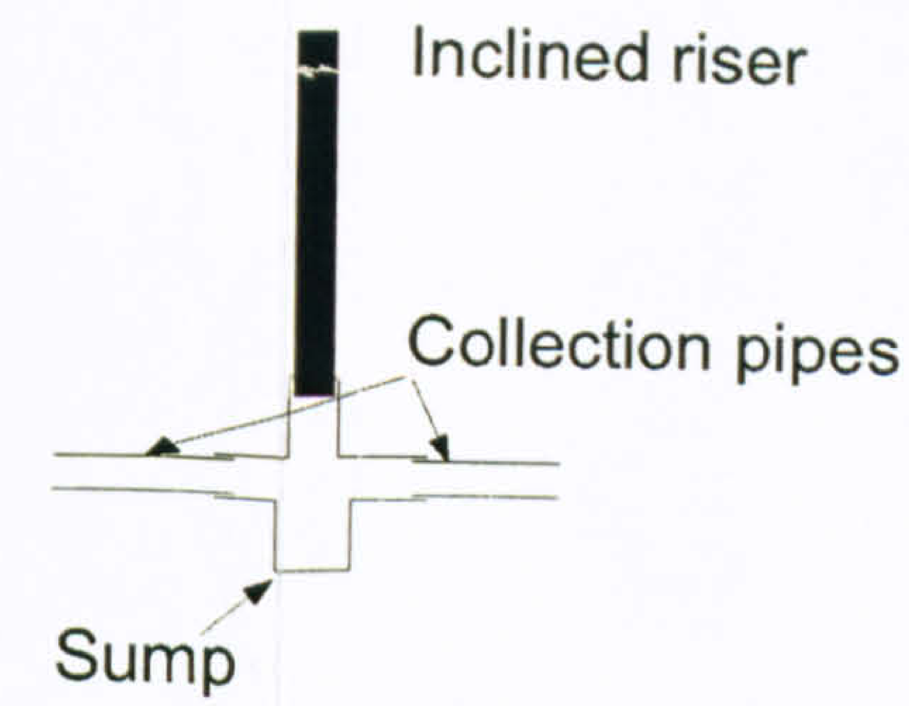


Figure 4.4c Schematic riser to sump connection

Figure 4.4 Details of the Liner and the Riser Connections at Site Alpha to a blockage or an excessive flow. The diameter of the pipe enabled a small submersible pump to be maintained inside, in case of any of the aforementioned problems incurred. The trench was graded towards the temporary sump which would also suffice for the permanent system, as this was directed to the aeration lagoon. The piping was covered with gravel which was also piled up the side of the slopes to abut the terrace deposits. The granular layer is required to have good drainage characteristics and a hydraulic conductivity of at least 1×10^{-3} cm s^{-1} (1×10^{-5} m s^{-1}) (Gordon, 1987). This provides a channel for the removal of the water without saturating the rear of the clay liner. Saturation of clay could possibly lead to instability problems and eventual slumping of the finished liner.

4.4.6 Clay Liner Specifications

The landfill liner comprised both a basal and side barrier system of London Clay to encompass each of the two cells. The side liner extended up the edge of the cell to surface level, except at the adjunct of the two cells, where it forms a 2 m high separation bund. Thickness of the soil was agreed between the regulators and the designer at 1 m minimum, which is the standard minimum (Cossu & Muntoni, 1994). The main parameter for the placement of the clay is the consideration of the hydraulic conductivity which should be a maximum coefficient of permeability of $K = 1 \times 10^{-9}$ ms^{-1}. This value was derived from Waste Management Paper 26 (DoE, 1986) and in accordance with the standards employed by the US (Seymour & Peacock, 1994).

Based upon the above liner thickness, hydraulic conductivity and leachate head parameters, it is possible to assess an approximate rate of seepage from the site. This is done in order to calculate the possible effect on the environment in relation to leachate egress.

Prior to the start of construction at Site Alpha, testing was completed to determine the optimum moisture content and maximum dry density of the material using the Proctor Test (rammer 4.5 kg) (Table 4.3 and Appendix 9.1). The clay liner specification for the maximum permeability coefficient, as stated, was 98 % of the maximum dry density, that is, 1.53 Mg m^{-3}.

Optimum Moisture Content	Maximum Dry Density
25 %	1.53 Mg m^{-3}

Table 4.3 Clay Specifications

Field density QA measurements were completed to ensure that the engineered clay consistently attained values within the parameters in Table 4.3. Values recorded included those in Table 4.4 and Appendix 9.2 which were taken in the first stages of the liner construction works. Action was taken to remediate those locations which did not fall within the specified limits. This is to be expected on-site owing to inconsistent weather and material conditions.

Moisture Content Oven dry %	Dry Density Mg m^{-3}	Relative Density %	Comments
27	1.48	97.2	Recompacted
27	1.46	96	Recompacted
24	1.5	98	OK

Table 4.4 Some Typical In-situ Density Test Results From Site Alpha.

4.4.7 Deployment of the Clay Liner

London Clay was placed on the bench in 250 mm lifts which were monitored in accordance with the construction specification and QA guidelines. The clay was deposited on the ramp and along the bench through the constant cycle of transportation vehicles and dumper trucks. The D6 bulldozer was then able to push out the clay in thin layers, dragging the vibrating tamping foot compactor behind it, over the material. The machine was also able to compact the sides of each individual lift, down the slope (Plate 8.8).

The base of the site was excavated a further 1 m beyond finished base level, reworked and recompacted to the same specification as the rest of the mineral liner. The placed clay was graded at a shallow fall (V:H 1:100) towards the centre of the cell, from the toe of the slopes, where the leachate sump was to be situated. This is a sufficient fall to facilitate the removal of the leachate from a central recovery pumping chamber, should it reach its maximum head limit.

Once the liner had been completed and permission given by the EA, waste tipping began. Initially, waste had to be deposited around the outside of the cell, in order to provide support to the base of the liner. Creep of the clay down slope had become visible since completion of the liner and so it was important to provide support to the base. The liner was also subject to the effects of the high daytime summer temperatures experienced and lack of precipitation, from June to September 1995, approximately 25 - 28 ^{o}C. This was evident from the desiccation cracks which appeared at the top level of the liner and around the riser pipes (Daniel, 1984).

4.4.8 Leachate Collection System

Site Alpha is a containment site, implying that the leachate must be collected upon production and removed, if necessary. The leachate control measures were installed to discourage the egress of leachates from the site. The system employed enables the collection of leachate at a central point from where it can then be extracted, if necessary.

In larger sites, preparation would usually be made to treat the leachate on-site, but at Site Alpha this system of management would not have been an economically viable option due to:

- (i) The small scale predicted leachate production from inert wastes;
- (ii) The overall (small) area of the site.

Upon completion of the site it will slowly become flooded with the leachates, and precipitation and groundwaters seeping in through the clay barriers. In this event, groundwater control would no longer be necessary and a flushing effect is created.

4.4.8.1 Installation

Gravel finger drains, with perforated HDPE pipe at 15 cm diameter, were placed in a radiating position out from the central leachate sump (Figure 4.5a). The sump comprises a concrete base, 0.5 m from the top level of the clay liner, on top of which rests a 50 cm diameter perforated HDPE pipe (Figure 4.5b). This was surrounded and held in place by well graded washed gravel. Throughout this procedure the pipes were checked for blockages from gravel and clay. There is an obligation to place the pipes at specified areas of the base in line with its fall, in accordance with the design criteria. However, where necessary, supplementary pipes were placed with junctions to the main system. Continuous monitoring of the junctions was necessary in order to ensure that the pipes fitted and would not drift apart at the start of tipping.

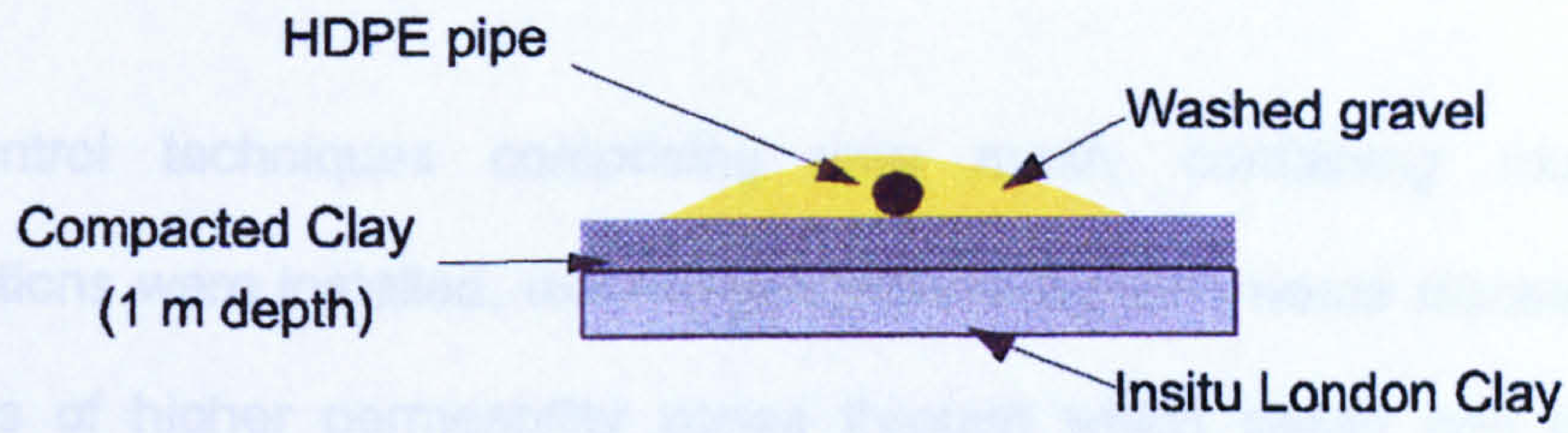


Figure 4.5a Typical Detail of the Gravel Finger Drain

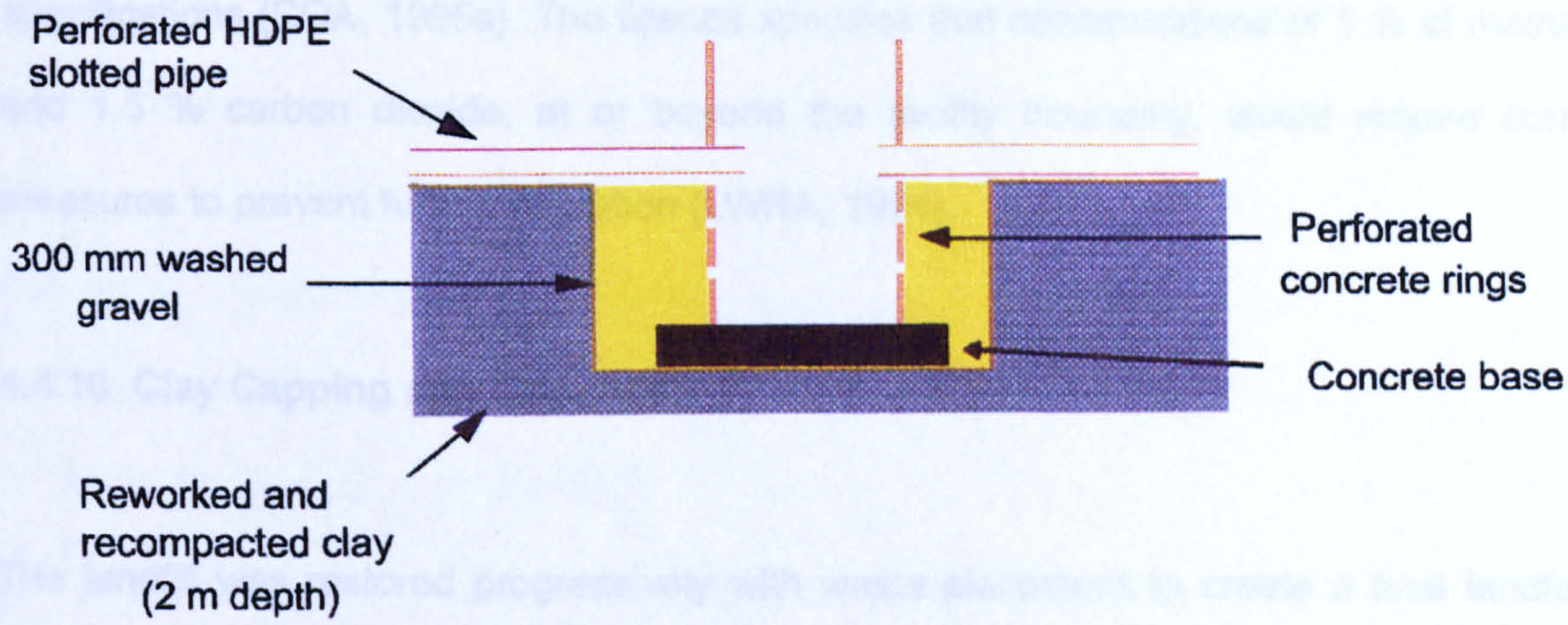


Figure 4.5b Schematic Diagram of the Leachate Sump

Figure 4.5 Details of the Leachate Management System for Site Alpha

The sump pipe was extended upwards in conjunction with the level of waste. It provides access for leachate removal throughout the waste deposit operation and post restoration.

This design is possibly one of the most standard approaches to leachate management, as outlined previously in Chapter Three. This site did not demand any leachate removal construction programmes, beyond the normal requirements of an inert site.

At the start of waste placement, the first amount of stipulated fill was inert waste, free from sharp objects. Such material could prove detrimental to the leachate collection system and could cause damage to the finished liner, thereby affecting its integrity.

4.4.9 Landfill Gas Control

Gas control techniques comprising wire mesh, containing roughly-broken brick constructions were installed, extending concurrently with waste placement. This creates passages of higher permeability zones through which gases can be channelled and dispersed to the atmosphere. Each of the cells has several diffusion mechanisms. Gas monitoring was completed in accordance with the site licence and the gas control design specifications (CQA, 1995a). The licence specifies that concentrations of 1 % of methane and 1.5 % carbon dioxide, at or beyond the facility boundary, would require control measures to prevent further migration (LWRA, 1994).

4.4.10 Clay Capping and Closure

The landfill was restored progressively with waste placement to create a final landform above original ground elevation. The water retention lagoon is decommissioned at this stage, enabling groundwater levels to return to those prior to construction, until the site eventually becomes water logged. It was proposed that the lagoon will be back-filled with inert material to attain the previous elevation. Telescopic HDPE pipes were placed in the leachate sumps which allow for settlement in the future. The leachate pumping chambers extend to the height of the waste to enable access for leachate removal.

The clay capping comprises material stockpiled during excavation of the cells and the layer comprises clay compacted to a minimum of 1000 mm, placed in 250 mm lifts. The compaction specification complies with that for the clay liner outlined in the original earthworks specification. The cap is keyed into a trench, 0.5 m in depth, located at the top of the engineered cell walls, along the perimeter of the landfill and the cap follows the graded contour of the waste at a gradient of 1:4 (V:H) it is finally covered with thin lifts of compacted top soil. This comprises 750 to 1000 mm of soil forming materials, combined with some original soils (CQA, 1997).

4.4.11 Quality Control and Assurance

Since most incidences of damage to landfill liners occur mainly in the construction and operational phases (Workman & Keeble, 1993), strict QA and QC procedures must be implemented and adhered to. The QC and QA for this site were completed by the engineer through continual visual monitoring, materials testing and compliance of the works with the design plan.

The CQA programme for Site Alpha (Hopper & Leach, 1997) comprised:

- Material suitability: clay content, liquid limit, plasticity index, moisture content (BS 1377 Tests: 2, 3, 7) (BSI, 1990);
- Checking of setting out and earthworks outline for the waste cells;
- Monitoring dewatering and quality of discharge;
- Monitoring installation of groundwater interception drain and pumping chambers;
- Monitoring placement of soil liner in terms of moisture content, dry density and lift thickness per 250 m^2 (Table 6/4 (Method 1) of DoT Specification of Highway works, Part 2 (DoT, 1991) and BS 1377 (Tests 1 and 15) (BSI, 1990);
- Monitoring formation of earthworks outline for groundwater retention lagoon. This is achieved upon completion using surveying techniques;
- Construction of lagoon outfall upon completion;
- Construction of the groundwater pump chamber and lagoon outlet;
- Monitoring of the installation of HDPE liner in the lagoon and supervision of non-destructive testing;
- Sampling of the geomembrane liner for third party testing;
- Documenting the works and the preparation of the Construction Records Report.

Third party testing of the clay soil after installation was completed by a visiting testing laboratory, which was consulted on an 'as required' basis. A nuclear density meter was employed at the site to test for bulk density and moisture content at a frequency of 1 per 250 m^2. If tighter controls were necessary over these measurements, the testing frequency could be increased. At Site Alpha however, this was unnecessary and only a few locations required recompaction and further testing.

At the start of the density testing procedure it became apparent that the moisture results on-site did not correlate with those in the laboratory. This was a recognised problem in Ward *et al's*. (1965) work, where a comparison of site and laboratory testing on the London Clay was completed to determine a relationship between undrained shear strength and depth. At Site Alpha, soil samples at each test site were taken and the material retested under laboratory conditions. The necessity for retesting indicates that although QC is being undertaken, it cannot guarantee that the finished material will be within the requirements of the QA design plan. QA can only help to reduce the possibilities of failing standards, but cannot alone act as a guarantee for the future integrity of the site.

4.4.12 Discussion

The Site Alpha case study example has provided an illustration of the design and construction of an engineered mineral barrier system. This might be regarded as a '*typical*' landfill site in that the waste was to be deposited in a redundant sand and gravel quarry which was then to be lined with the London Clay found in location. Chapter Five illustrates that London Clay was highly suitable for use as landfill liner and no construction problems were related solely to the properties of this material.

This site necessitated the control of groundwaters within the top horizons of sand and gravel behind the engineered clay liner. The importance of this control system was reiterated during a break through of groundwater which was caused by increasing pressures behind the *in situ* clay deposits. The river had been blocked downstream and had backed up to increase the hydraulic pressures towards the cell. The liner had not been placed at that point so the cell wall was particularly vulnerable. The event resulted in the excavation of saturated material from the base and the installation of a replacement 5 m section of the interceptor drain. Work on the liner was then diverted from other areas of the cell in order to strengthen the cell wall at that point. This example strongly demonstrates the requirement for adaptable landfill design and construction practice and, also, the effects of delaying construction, i.e. costs and changes in the schedule. The landfill design and construction plan was otherwise implemented successfully at this site but the example proves that, even on small sites, unexpected ground condition related problems may occur.

The groundwaters are diverted around the site, this is not to say that, at some time in the future, leachate produced by the inert waste deposited might dilute with the groundwaters. However, the likelihood at Site Alpha is minimal, since this type of waste produces a small amount of leachate and the site has a stipulation for a 1 m leachate head. In addition, the groundwater is only to be found in the top 5 or 6 m of sands and gravels adjacent to the clay liner.

The procedures for and the importance of the assurance of quality have been demonstrated in this section. The techniques involved, although straight-forward, are necessary to prove compliance with the site specifications in terms of compaction and, therefore, coefficients of permeability. The main discussion at the end of this chapter provides an examination of the different QA procedures in relation to the type of liner employed.

4.5 SITE BETA CASE STUDY LANDFILL

4.5.1 Introduction

The second case study landfill involves rather more complex design criteria than those relating to Site Alpha. In this respect, the two landfills create an interesting contrast in terms of the choice of liner and, ultimately, the QA procedures involved. This contrast is largely influenced by selection of the site and the waste type licensed for acceptance.

As the design and construction of Site Beta is still under contract, the actual name and location cannot be specified. Indeed, the extreme sensitivity of the project was compounded by the relationship between the design specifications and the geology and hydrogeology of the area. The site, which is here referred to as Site Beta, is located in the Trent Valley in the East Midlands. There are two previous phases at this site, one restored and one operational, that include land raise and a combination land fill and raise.

The principal objective of the designer was to minimise the risk of environmental pollution from the third phase at the site through: a suitable liner system; competent monitoring and QA schedule; and action plans. Not only does a lining system have to be appropriate to the waste type, but it should also provide a level of environmental protection and make use of locally available resources, in order to contain costs of construction and operation.

4.5.2 Site Details

The cell, to be used for waste placement, was approximately 100 m by 150 m and rectangular in shape, as predetermined by prior extraction of overlying sands and gravels. Preceding the commencement of the earthworks, the cell base was located in the top of the Mercia Mudstone, since the overlying superficial deposits had been excavated to a depth of 5 m. Excavations left the side slopes at an angle of 1:3 (V:H) which remained the criterion for the cell wall design. Uncontrolled flooding of the void occurred after the excavation of the water-bearing alluvial deposits had taken place. The standing water was then allowed to stagnate until the start of the works.

Site Beta is licensed to accept domestic refuse, i.e. putrescible wastes, alongside more inert construction wastes. It is also a busy civic amenity site. It is this combination of different types of waste which enables production of a more hazardous leachate.

A single composite liner was chosen as the best option for Site Beta. It comprised an *in situ* compacted marl subgrade overlain by a Geosynthetic Clay Liner (GCL), HDPE and a geotextile layer (Figure 4.6). The requirement for the GCL was governed by the fact that the properties of the *in situ* Mercia Mudstone did not facilitate the construction of a mineral layer component of the barrier.

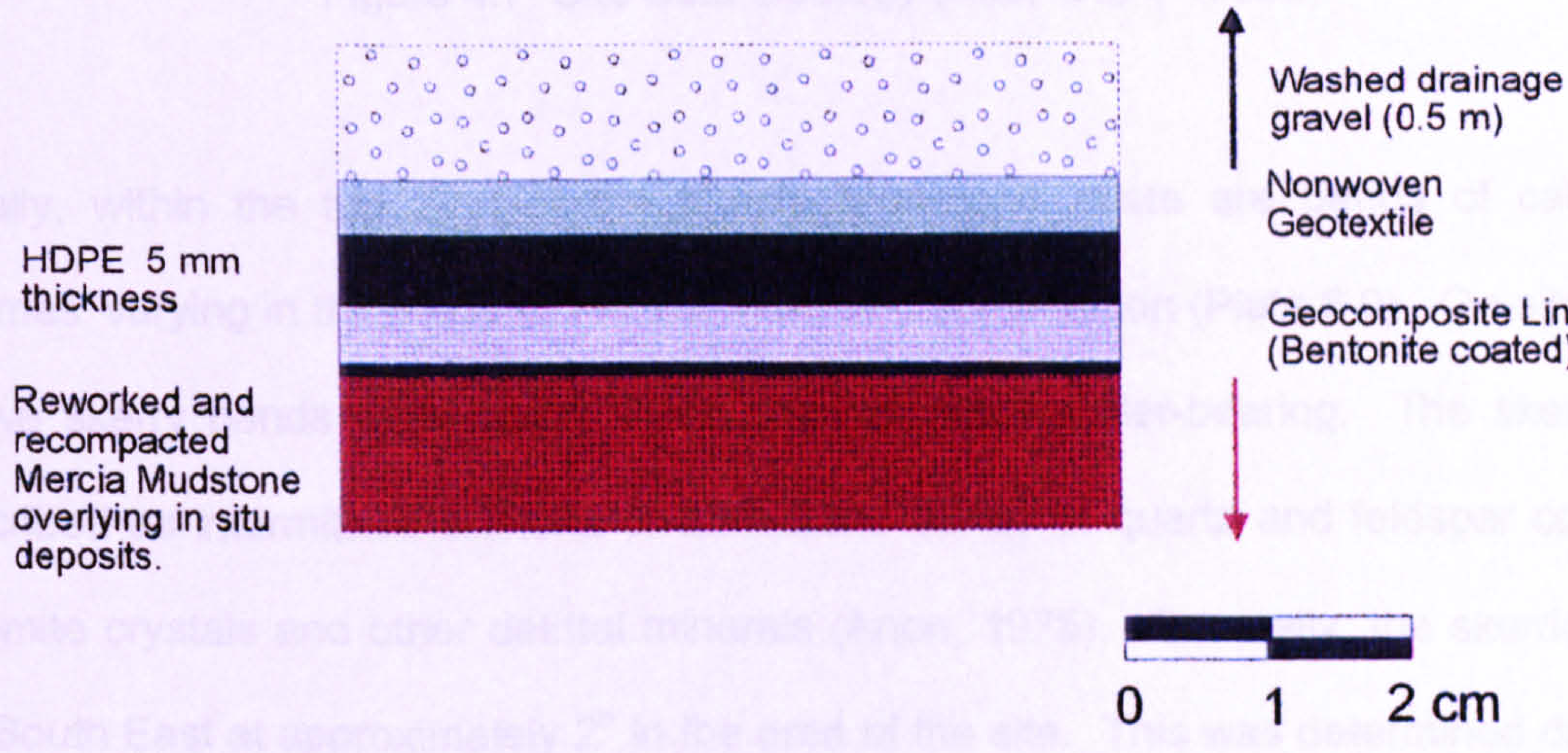


Figure 4.6 Composite liner Typical Detail

4.5.3 Geology

Site Beta is located on the ancient flood plain of the River Trent where Recent alluvium and sand and gravel terrace deposits overlie Triassic Mercia Mudstone (previously the

Keuper Marl) as indicated in Figure 4.7. The mudstone is generally fine grained although it does include approximately 10 % rounded flint gravel and cobbles with an average diameter of > 30 mm. Chapter Five provides a detailed description of the materials on-site in terms of their geotechnical and mineralogical characteristics.

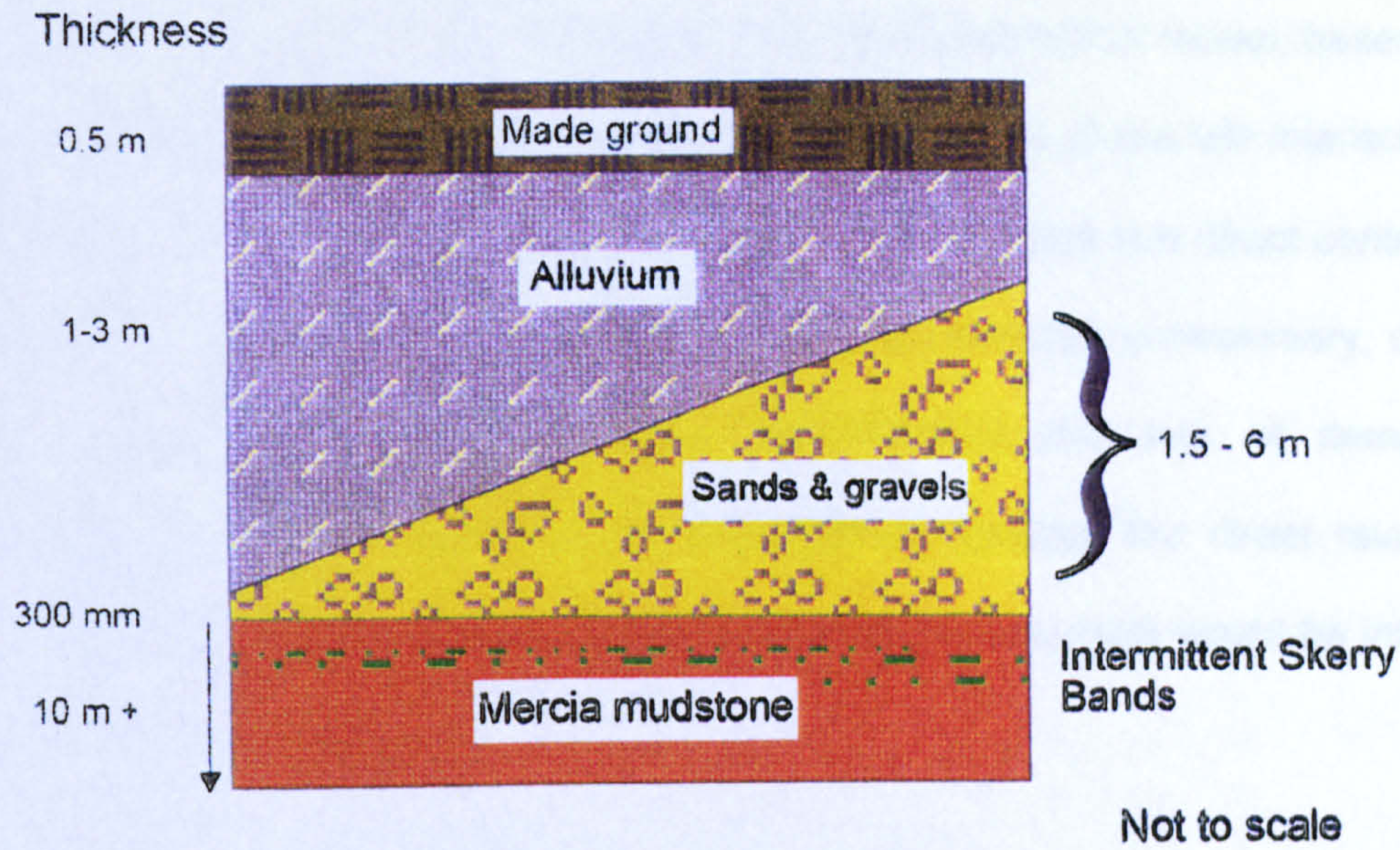


Figure 4.7 Site Beta Geology (After CQA, 1995a)

Locally, within the top 2 m of the Mercia Mudstone strata are bands of calcareous 'skerries' varying in thickness (50 to 250 mm) and composition (Plate 8.9). On-site, a total of five skerry bands were found, three of which were water-bearing. The skerries are described as intermittent siltstone or sandstone bands of quartz and feldspar containing dolomite crystals and other detrital minerals (Anon, 1975). Generally, the skerries dip to the South East at approximately 2° in the area of the site. This was determined during the ground investigations. The predominant thickness of skerry band is found in the North West corner at an approximate elevation of 10.42 m AOD and the South East corner at 9.37 m AOD. (Prior to site development, the base of the site lay at an approximate average elevation of 15.5 m AOD). On investigation, these skerry bands appeared to be finely laminated, cross bedded siltstones.

4.5.4 Groundwater Considerations

Prior to the construction of the cell, background readings of groundwater levels were taken and the direction and rate of flow were also recorded. These measurements enabled flow rate calculations to be input into a computerised 3D hydrogeological model, based on the principles of Darcy's Law, and, also, established how the new phase will interact with or adversely affect the current hydrogeological situation. Here, there is a direct contrast with practice at Site Alpha where such detailed models were deemed unnecessary, owing to the comparatively straight forward design characteristics and lack of demand for interactive models. At Site Beta, it was important to consider the direct relationship between the existing phases in order to determine how the new cells would be integrated within such a model.

There were two highly influential hydrogeological factors for consideration at Site Beta:

1. Groundwater was present in a perched water table in the superficial deposits, which flowed in an Easterly direction. This was the main source of water ingress to the site and could be controlled by continuous pumping throughout the earthworks and liner installation until waste placement.
2. The skerries have a relatively high capacity for bearing water and if they were disturbed during the earthworks, water seepage would occur through the base of the site, even after engineering of the Mercia Mudstone to the required specification. Experience at this site, from site investigations and trial pits, proved that the skerries were a permanent source of groundwater, being recharged at a considerable rate. This proved to have considerable impact in terms of construction of the subgrade, owing to the lack of manoeuvrability and margin for error, whilst working in the top 2 m of Mercia Mudstone.

It was necessary to contain the waters from the skerries within a separate system under the liner to prevent underlying instability problems. There were problems of basal heaving and rolling that were exacerbated by the installation of the groundwater control system which took place millimetres above the most extensive skerry band. The heaving and rolling in front and behind the plant indicated that excess pore water pressures were developing within the basal materials. In single engineered liners, this would indicate that it would be impossible to attain the specified densities and shear strengths (Matheson & Oliphant, 1991). In this example, since this material was only intended for subgrade, this would not be detrimental to the integrity of the earthworks.

Along the site perimeter, except for the Eastern side, a slurry cut-off wall (Figure 4.8a) had previously been installed. It was designed to prevent the ingress of groundwater into either phase 2 or the proposed new landfill cells. It became apparent during the ground investigations of Site Beta that this cut-off wall was inefficient. It resulted in the continuous seepage of groundwater into the site, prior to completion of the subgrade, through the sands and gravels exposed on the side walls.

The possible causes of the resultant failure of the cut-off wall included insufficient keying depth into the marl and fracturing within the slurry wall. These factors encouraged hydraulic continuity of the intermittent skerry bands. Tedd *et al.* (1995) also suggest that bentonite slurry may be highly susceptible to chemical attack from leachate. The extent of this is a function of the original composition of the slurry. In Phase 2 of the site, the external groundwater level is 1 m higher than the leachate levels within the site, therefore the groundwater flow from the slurry wall is into, and not out of, the site.

As these earthworks were completed prior to the current ownership of the site, documentation about the exact work completed, namely the specifications indicating the depth of the wall, were not available. Previous site records were not available, even through the regulatory agencies. The faulty cut-off wall could give rise to future risk,

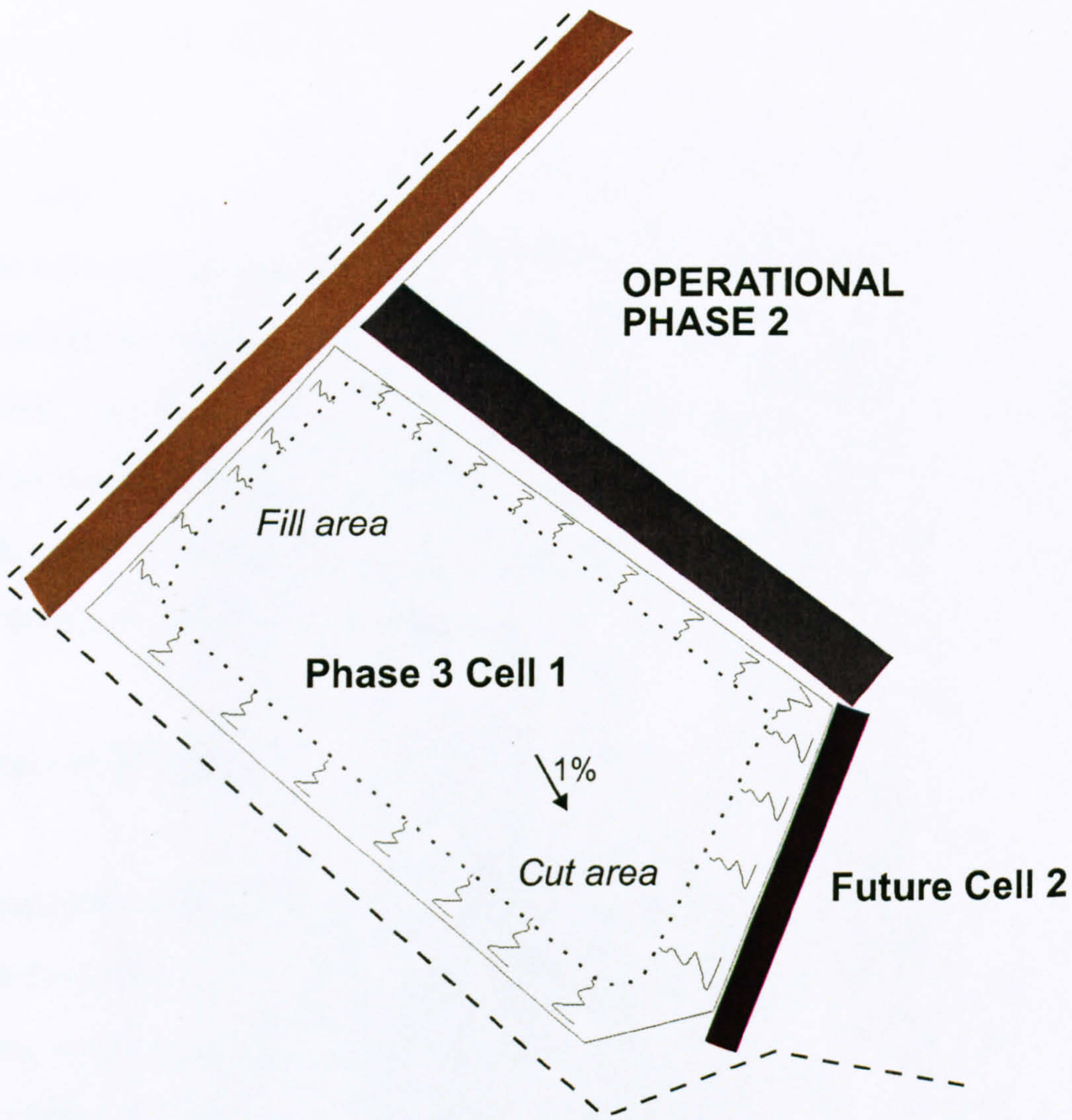


Figure 4.8a Earthworks

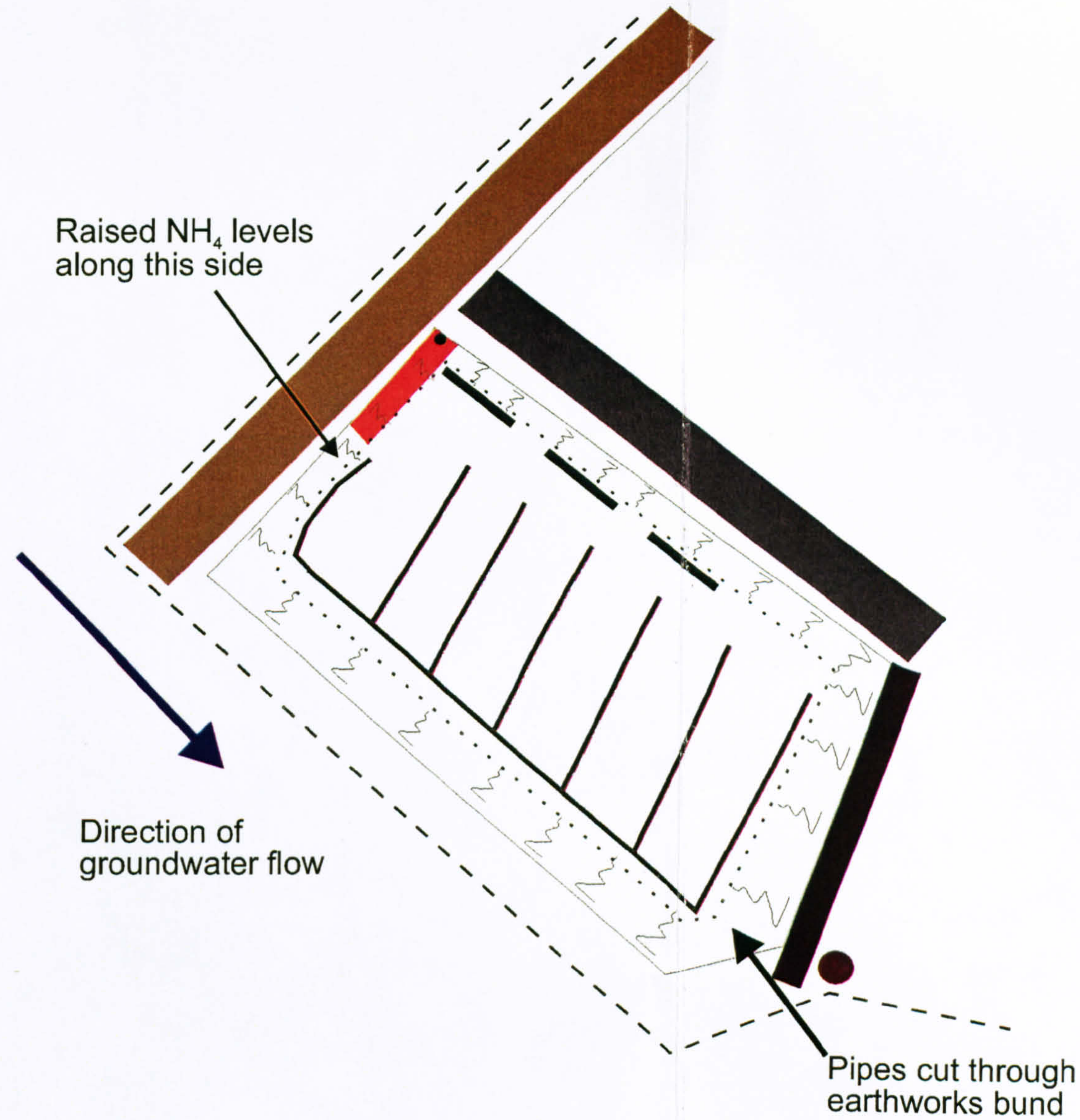


Figure 4.8b Groundwater Control

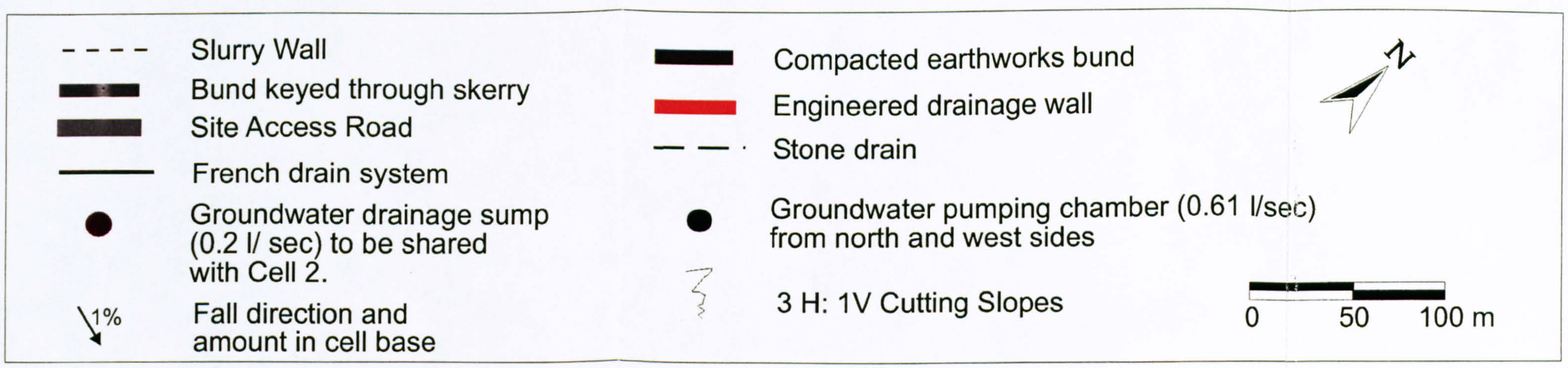


Figure 4.8 Earthworks and Groundwater Controls at Site Beta.

should the leachate from existing phases one and two and contaminated surface waters disperse in the groundwater at the site.

Ultimately, cross contamination would be inevitable to some degree. Separate groundwater drainage systems were therefore designed to contain the potentially polluting perched groundwater, thus separating it from the currently uncontaminated groundwater below the site. During the site works, all waters were tested monthly by the relevant authorities (at that time the NRA and Waste Regulation Authority (WRA)) prior to being pumped into a drainage culvert on-site. This culvert diverted the contaminated waters in an open channel to a major River, where they would be diluted.

4.5.5 Subgrade Preparation

The base required cut and fill earthworks to achieve the required basal gradient of 1 %. Cutting was completed in the South East corner to a maximum depth of 1 m. At the start of the cutting, the material was suitable for fill since it was particularly dry. However, nearer completion of the cut, ingress through the sands and gravels had saturated the material which had to be removed for use as daily cover later. Ingress had occurred due to:

(a) Disturbance of the skerry bands during cutting;

(b) Water in the sands and gravels along the side of the void was now flowing more freely since the removal of vegetation and superficial material.

The fill area of the site, the Western side (Figure 4.8a), had its own similar problems. This area had been the worst affected by the original flooding of the site prior to the earthworks. Not only was it necessary to build up the basal height of the site, but further material had to be removed from the original level, as it was unsuitable for use as the subgrade. Dry Mercia Mudstone from another of the Owner's sites, which met the site specification for Site Beta, was used to achieve the completed level.

The compacted Mercia Mudstone was to be the subgrade for the liner, but, unlike Site Alpha, it was not intended that this should be an important integral part of the liner system. However, it was recognised that the presence of such suitable subgrade would assist in reducing the risks of contamination should a failure of the main lining system occur. No liner, clay or composite, is one hundred percent efficient over time, therefore, a clay subgrade would reduce the migration potential of polluting leachates and gases from the cell by encouraging a degree of attenuation.

4.5.6 Groundwater Drainage Systems

As Site Beta was water logged at the start of the works, dewatering techniques were employed to enable construction of the subgrade and liner. A system of pumps was temporarily installed in two opposite corners of the cell to counteract ingress and enable continual efficient removal of water (Figure 4.8b). Efficiency of leachate removal is enhanced by large and properly designed draining systems which will enable influence of the leachate flow regime (Cossu *et al.*, 1997).

A system of french underdrains was used in order to contain the groundwater below the basal liner. They were installed within the top 1 m of reworked or *in situ* Mercia Mudstone subgrade. The actual placement of the system was highly dependent upon the location of the skerry bands, since their disturbance would lead to groundwater ingress and associated problems of basal uplift.

The design of the drain was standard, comprising a trench, 0.5 m by 0.5 m in depth and width, excavated by minidigger. It was constructed in herringbone fashion, extending from the South Eastern corner of the site, (Plate 8.10) where the groundwater sump was to be positioned. The trench was lined with 10 mm thick needle punched geotextile (Terram Polyfelt 600) to act as a filtration system for fines, as illustrated in Figure 4.9 and Plate

8.11. The slotted, perforated 0.3 m diameter HDPE pipe was placed on the clean Terram and covered in 30 mm graded, washed, gravel similar to the finger drains in the leachate drainage system at Site Alpha. Once the pipe was covered, the Terram was wrapped around and weighed down, until it could be covered with the Mercia Mudstone subgrade. The stone was to act as a filtration system to assist in the prevention of clogging of the pipe. However, the actual effectiveness of such systems is highly debatable. Research completed to date has indicated that clogging will occur to partially, or, even totally, block the drainage pipes (Rowe *et al.*, 1997, Bordier *et al.*, 1997, Brune *et al.*, 1994, Koerner & Koerner, 1989 and Bass, 1985). Although clogging is a subject of research, it appears that it has not been recognised in operational stages, where designers must reduce any risks of leakage from a contained landfill site. Obviously, further studies are needed to influence the type and management of leachate control techniques used in landfill design.

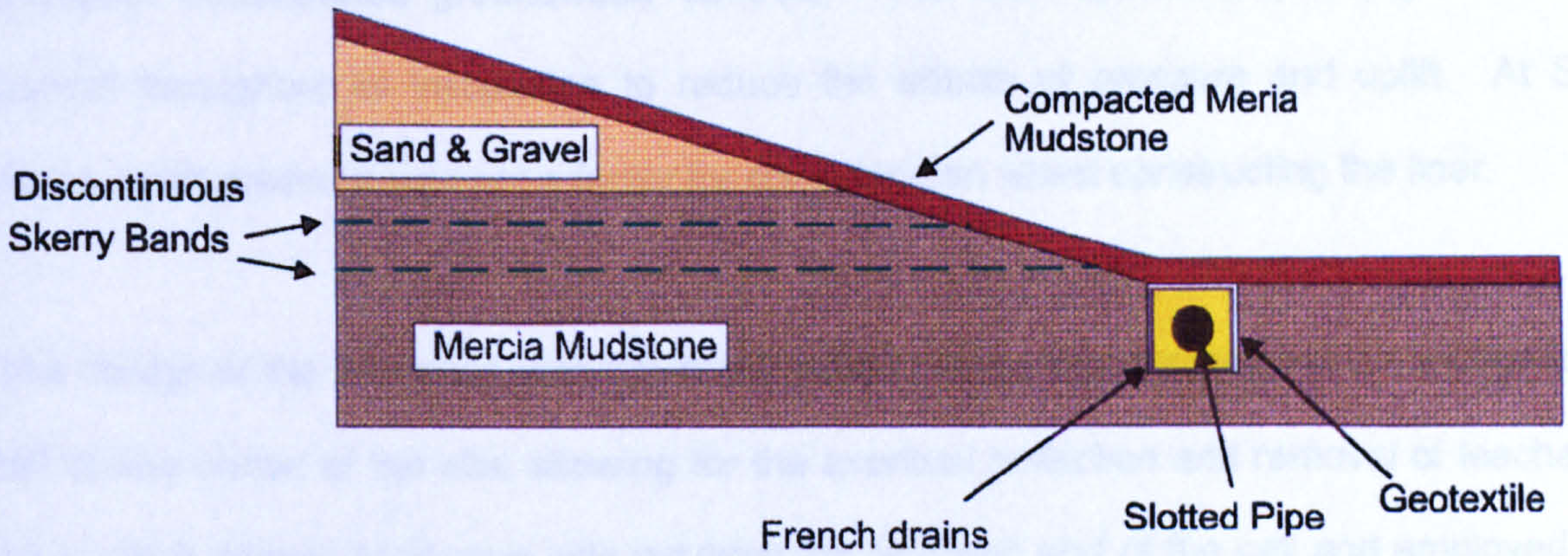


Figure 4.9 Schematic Diagram of the Groundwater Drainage System at Site Beta (Not to scale)

The thicker band of skerry was at a depth of only 50 to 100 mm in places below the trench and subgrade which did not allow for much margin of error. A more detailed diagrammatic representation of the drainage system can be found in Figure 4.9. The entire drainage system was required to be graded to 1:100 (V:H) towards the sump to facilitate gravitational drainage.

The designer adopted standard controls that were hampered by the Mercia Mudstone being at a state of 100 % saturation (Plate 8.10). The South East corner of the site was waterlogged and as a result it was decided to attempt dewatering through underdrains. In fact, the drainage varied slightly from the original preconstruction plan, since the ground conditions demanded a more extensive system. An alteration in design such as this is dependent upon parameters such as:

- The availability of materials on-site;
- Delivery time from stockists;
- The construction time scale plan.

The local geology, hydrogeology and the putrescible nature of the domestic wastes to be accepted necessitated groundwater controls. The liner system required groundwater control throughout its installation to reduce the effects of pressure and uplift. At Site Alpha, uplift pressure was not a factor for consideration whilst constructing the liner.

The design of the subgrade was obviously influenced by the requirement for a degree of fall to one corner of the site, allowing for the eventual collection and removal of leachate. As a result, Mercia Mudstone was cut from the Northern end of the cell and employed as fill in the Southern to attain the required levels.

The completed side slopes of the subgrade revealed the Floodplain Gravel / Mercia Mudstone contact which allowed seepage from this groundwater pathway into the site. Seepage occurred on a small scale in comparison with that from the perched water table in the Skerries, but had to be contained to create workable conditions for the installation of the GCL liner. Mercia Mudstone was smeared along the length of the contact using the bowl of the excavator to achieve a minimum covering of 50 mm. As the subgrade was not an integral part of the lining system, testing was not required on the side slopes.

The water was pumped at a rate of 0.2 l s^{-1} from the underdrain, in comparison with 0.61 l s^{-1} from the pump in the engineered wall at the North Eastern side of the site. Once the water was removed, the saturated clay (and some decaying organic matter) was excavated and stored for use as cover material during future operational phases.

4.5.7 Subgrade Completion

The primary stipulation for the subgrade was to achieve a smooth and even finish in order that the plastic liners could be installed without damage. The completion of this task was the earthwork contractor's final responsibility on-site. Subgrade completion was monitored by the QA engineer and all sharp and loose objects were removed from the basal and side subgrade. The final grade of the base was to a gradient of 1:100 (V:H), the same as at Site Alpha. The achievement of such small gradients is difficult owing to the weight of the plant and lack of manoeuvrability in constricted areas. Once subgrade completion is finished, guidelines, such as NWWRO (1996) and Waste Management Paper 26B (DoE, 1995b), state that under no circumstances should plant be allowed to track on the site. In the event of plant being allowed to track across the site, it would result in inevitable rutting and destruction of the smooth finished layer. On some sites, however, drainage layers must be laid using a bulldozer and a delivery vehicle.

Due to the problems with the Mercia Mudstone, (i.e. its partial saturation), earthworks to achieve the shallow gradient proved difficult. The water in the clay was brought to the surface, creating a sheen, by continual trafficking during compaction. The groundwater in the skerry bands and that held within the clay soil structure had migrated upwards through capillary action and loading during continual trafficking. This led to an increase in the moisture content of the clay subgrade in isolated pockets or 'blisters'. These were unacceptable as subgrade since the GCL and HDPE require a smooth, relatively solid subgrade.

On both basal and slope surfaces, the excavator employed a smooth iron bar to remove loose debris, such as, stones and vegetation. The slope subgrade was completed using a small, 3 ton smooth sit-on roller for the sides and base. Its use was restricted to the base and bottom half of the slopes since it was deemed to be unstable at higher gradient and was not equipped with a safety roll bar. An agricultural tractor, with low pressure tyres and a wide roller (4 m in length), was brought onto site to complete the finish of the basal subgrade since the weight of the original plant had rutted the base.

4.5.8 Additional Permanent Drainage Systems

As a result of the continuous seepage in the North West corner of the site, side slope instability developed as slippage due to an increase in pore water pressures within the Mercia Mudstone. This created the problem of an unstable slope subgrade for the liner placement which, if ignored, would be unacceptable practice (Mollard *et al.*, 1996 and Adams, 1997). In order to control the ingress of water behind the liner it was deemed necessary to remove the affected material and replace it with an engineered wall.

The engineered wall was developed using geotextile wrapped around washed gravel in a 'step form' to build up the new slope to the angle and height of the adjacent slopes. A 25 m length of side wall was removed and replaced as shown in Figure 4.10. Dry, imported Mercia Mudstone, with almost identical geotechnical properties, was then placed against the newly engineered wall and 'moulded into shape', using a small smooth wheeled sit-on roller.

Seepage control was maintained through the installation of a groundwater collection sump which prevented a build up behind the liner. The pipe is perforated for the first 1 m and allows a one inch pump to remove the build up of water at its base. Such groundwater control is necessary throughout the placement of the liner and into the future. The

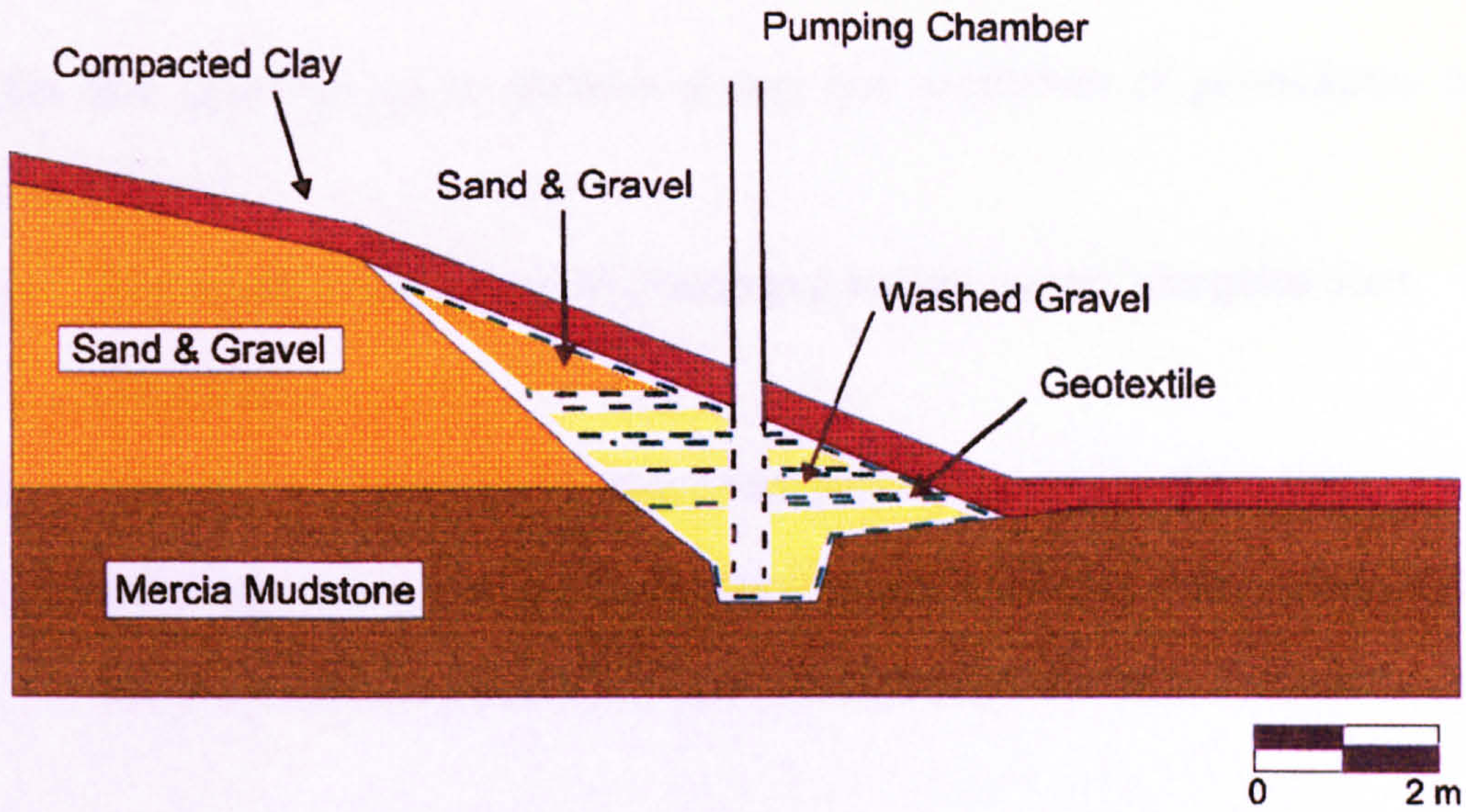


Figure 4.10 Typical Detail of the Reconstructed Toe of the Slope.

importance of this system was demonstrated when the pump stopped, which caused immediate flooding. This delayed the construction programme for approximately three days as some of the filled subgrade had to be removed and replaced with dry material.

This is an example of an adaptation to the original design plan, which may have been envisaged during conceptual stages of the cell design, since there was a high potential for groundwater ingress. The rate of seepage and relative instability of the slope through the earthworks called for remedial measures prior to placement of the geosynthetic barrier system. This illustrates the important effect that ground conditions have on the installation of these types of lining systems.

Once the subgrade of the engineered wall had been completed to the satisfaction of the QA engineer and liner contractors, installation of the lining system could then commence.

4.5.9 Composite Liner Specifications

A composite liner was chosen to achieve a very low coefficient of permeability for a number of reasons:

(1) The landfill was licensed to accept putrescible wastes alongside inert materials;

(2) The nature of the groundwater conditions in the vicinity of the site;

(3) Although, less likely, should failure occur in the liner, other system components would provide a further interception barrier.

4.5.10 Liner Installation Procedures

The installation of the GCL, HDPE and Geotextile was completed by trained personnel and verified by the QA Engineer. The manufacturers' representatives first drew a layout plan for the geomembrane liner with standard requirements for:

(i) The least amount of seaming possible;

(ii) The minimum amount of materials wastage.

It is important to consider the expense of these lining systems in comparison with a single mineral liner where the material may be located *in situ*, as at Site Alpha. Landfills with complex lining systems are able to accept those wastes which are more costly to deposit.

4.5.10.1 Anchor trenches

In order to hold the liner in place, it was necessary to excavate trenches along the perimeter of the top of the slope. They were located 0.5 m back from the top of the slope and were 0.5 m in depth. The cell design had allowed for the width of a small excavator to track around the length of the site, constructing an anchor trench just preceding deployment of the liner. The liner was laid along the depth of the near-side and base of the trench (Figure 3.5 and Plate 8.2). Once each section of the liner had been placed, the trench was backfilled with the excavated material provided, it was free of sharp objects, stones etc., which could cause damage to the barrier system. The liner was keyed into the ground to prevent slippage down-slope and to maintain coefficients of friction between the subgrade and liner.

4.5.10.2 Geosynthetic Clay Liner (GCL) deployment

The GCL was laid flat upon the approved subgrade which was free of projections and had a smooth surface. The Gundseal panels were deployed from the top of the slope. An excavator held the roll aloft using a length of chain through the roll, demonstrating the need for adaptability on-site should suitable plant or kit be unavailable.

The slopes were covered sequentially and the GCL was cut at the toe each time. The basal layer was rolled flat and cut prior to installation of each section of HDPE. Each panel of GCL was overlapped by 25 cm on each connecting side which enabled the material to self-seal. Self-sealing has been proved in laboratory experiments, at the bentonite / polyethylene point of contact, upon addition of moisture (Daniel, 1993). The seal provides an added barrier to reduce leakage should penetration of the top components of the lining system occur.

The GCL may face difficulties in transportation due to bentonite erosion from the edges of the rolls, or, if the cover is compromised, the bentonite may have already swelled due to wetting. The latter destroys the main properties of the GCL and does not enable adequate sealing. Hence the need to cover the GCL as soon as possible, once its installation is complete.

4.5.10.3 HDPE Installation

The HDPE was used together to prevent leakage through to the underlying GCL. Chapter Three has already outlined the different methods of liner welding: namely heat fusion, through varying methods and extrusion.

At Site Beta, both fusion and extrusion welding methods were employed. During heat fusion welding, the overlap of HDPE must be kept clean, smooth and free from debris and dirt to enable a high weld quality. The temperature of the welder must be maintained throughout the bonding procedure and is therefore measured at the start. In this case, the welder maintained a temperature of 415^{0}C. Section 3.8.4 highlights the tests completed on the welder prior to operation and the individual test welds completed in order to verify this. Each panel is fusion welded to the adjoining side and base panels. Any sections which require internal or circular welds such as boots and skirts (Figure 3.7 and Plate 8.4) necessitate the use of an extrusion welder.

4.5.10.4 Geotextile and drainage layer deployment

A layer of geotextile was placed over the HDPE to protect the lining system from sharp objects and to enable leachate filtration before it came into contact with the liner. The effectiveness of similar protective systems has recently been questioned, since they could be clogged by the waste and also by soluble species within the leachate, particularly, shortchain carboxylic acids combined with ammonia, sulphate, calcium, carbonates, silica, and metals such as magnesium, sodium, potassium and iron, (Campbell *et al.,* 1983 and Rowe *et al.,* 1997). Some of these, in the long term, will precipitate to form a calcite-rich cement around the stone inhibiting drainage. This will also occur within the drainage layers of the landfill, in this case, the washed gravel. Approximately 0.25 m of gravel was placed on top of the geotextile and pushed out by bulldozer to achieve a drainage system above the composite liner. It was within this gravel layer that an interconnecting leachate drainage system was laid.

4.5.11 Quality Assurance Procedures

4.5.11.1 Subgrade QA testing

At Site Beta, QA monitoring of the following activities was an integral part of the construction programme:

1. Groundwater installation system;
2. Subgrade;
3. Contractors obligations;
4. Composite liner testing.

Moisture content and density testing of the Mercia Mudstone liner was completed using a nuclear density meter, this being an accepted approach to *in situ* testing. Measurements were taken on the surface layers of the compacted marl. Tests were completed on the cut section of the site, but the material here was still *in situ* and, as proven by the ground investigation results, was of superior compaction.

Although the Mercia Mudstone was only intended as a subgrade for the lining system, tests were completed on the clay in line with those at Site Alpha. Employing a nuclear density meter, the moisture content and the dry density of the compacted material were measured. Approximately 20 tests were completed on the base in order to prove that the material was homogeneous and that a degree of compaction had been achieved.

4.5.11.2 Geomembrane QA testing

As each site is an individual project, the CQA procedures vary accordingly. In this case, site QA practices comprised the following procedures:

(1) Visual inspection during deployment, which included inspection of the materials upon delivery and throughout installation. Random spot monitoring of liner thicknesses and climate readings were completed

accordingly;

(2) Trial seam preparation;

(3) Trial seam testing;

(4) Production third party seam destructive testing at a rate of 1 sample per 160 m of seam with a total of 16 samples;

Two peel and two shear tests on tabs cut from two ends of each weld with a total of 300 tests in total;

(6) Production seam non-destructive testing in the form of air pressure tests on each fusion welded seam and spark testing on extruded seaming;

(7) Visual inspection of the finished installation.

(Adapted from Hopper & Leach, 1997 and Adams, 1997).

Table 4.5 illustrates how all uses of the plastic geomembrane liners on-site were logged. Documentation of individual rolls of liner (GCL and HDPE) was also a stipulation for the CQA procedure. Liner placement and associated documentation was recorded in the event of future problems, i.e. faulty batches of materials and break outs, for example.

Date of Arrival	**Roll No.**	**Weather; Temp.**	**Panel No.**	**Panel Size and Shape**
29/10/95	9022115	dry and sunny. 14°C	12	rectangular 9 m by 3.2 m
29/10/95	9022116	as above. 15°C	13	pie
30/10/95	9022118	Damp start becoming dry. 12°C	14	boot

Table 4.5 Typical QA Documentation Procedure for HDPE Sheets

The two seaming techniques employed on-site had to be tested individually using different procedures. The techniques used are currently accepted as standard approaches to geotextile seaming QA, for instance, those outlined by the American Society of Testing Materials No. D4437 (ASTM). Firstly, the weather throughout the welding process has to be dry and there should be no adverse weather conditions. Secondly, it is of vital importance that the welder reaches the stipulated temperature (usually 200 °C) before welding can begin. Failure to achieve this may result in impairment and an increased possibility that completed HDPE welds may separate during expansion and contraction under variable atmospheric conditions and changes in loading.

Hall & Marshall (1992) discuss the importance of QA in the installation of geomembranes and conclude that welding is the most critical area. The HDPE was subjected to test welding using off cuts, prior to the start of liner deployment each day, in order to assess the suitable temperature of the fusion welding machine. Once the seam had cooled sufficiently, approximately five peel tests were completed per day on a range of samples. The weather was monitored on a daily basis, specifically the temperature and humidity which can affect the efficiency of the welding by reducing or varying the temperature of the welder along the length of the weld itself. This leads to substandard welds which would weaken and fracture at points along the length. Not only would they permit leakage to occur, but may also be susceptible to persistent chemical attack over extended periods of time.

The geomembrane should also be clear of dirt and debris from the travel and loading procedures and wiped dry of moisture prior to the start of welding. Any moisture or dirt in the weld will increase the likelihood of an unsatisfactory finish to the seam which will weaken its performance over time. In view of this, tests on finished welds are also completed which would hopefully identify problematic areas of seaming. It is important to consider at this point that QA is only a means of minimising the risks of leakage from the site and cannot be considered as a guarantee that the HDPE composite liner system will be completely free from holes.

4.5.12 Leachate Control System (LCS)

An HDPE leachate sump was placed at the bottom end of the fall and welded, using an extrusion seal, to the liner. A herringbone network of leachate drainage pipes was laid in the gravel and attached to the sump, in order that all the leachate is drained to the sump from where it could be extracted and treated.

4.5.13 Monitoring Procedures

The monitoring procedures for this site, (Table 4.6) are more detailed than those for Site Alpha. Similarly, however, background monitoring was required, data for which was available from the previous two phases of the landfill. The important requirement was the integration of this third phase into a long term monitoring plan which could be completed for the entire site. In addition, if there should be a pollution related incident the aim would be to achieve an indication of the locality in terms of phase, cell and even exact location and possible nature of the fault.

4.5.14 Discussion on Site Beta Design and Construction

Site Beta is more complex than Site Alpha in terms of design and construction techniques. The QA of a geomembrane requires more detailed recorded data and when combined with a clay liner in a composite form, techniques and procedures will vary considerably.

This case study has illustrated how the nature of the wastes affects the landfill design in

Product	Frequency	Determinants
Surface Water	**Monthly** (dependant on water body and flow rate)	pH, Temp, EC, DO, COD.
Groundwater	**Monthly**	Water level, pH, EC, Temp, DO, NH_4, N, Cl
	Quarterly (may be reduced To 6 monthly if evidence of stable conditions	as monthly plus: SO_4, Alk, TON, TOC, Na, K Ca, Fe, Mn, Cd, Cr, Cu, Ni, Pb, Zn.
	Weekly	Discharge volume, pH, Temp, EC
	Monthly	as weekly plus: NH4, N, Cl, BOD, and COD.
	Quarterly	as monthly plus: SO_4, Alk, TON, TOC, Na, K, Ca, Mg. Cu, Ni, Pb, Zn.
	Six monthly	
Leachate	**Monthly**	Leachate level, pH, Temp, EC.
	Quarterly	as monthly plus: Cl, NH_4N, SO_4, Alk, COD, BOD, TON, TOC, Na, K, Ca, Mg.
	Annually	as quarterly plus: Fe, Mn, Cd, Cr, Cu, Ni, Pb, Zn.
Landfill Gas	As WMP 27 (1991)	CH_4, CO_2, O_2, Temp.
Other Parameters	**Annually**	Void utilisation, settlement.
Leachate Pumping Chamber	as above	as above
Sample Location	**Frequency**	**Determinants**
Groundwater Pumping Chamber, (SW Corner)	49 Hrs.	NH_4N (on-site)
	Weekly	DO, NH_4N, Suspended Solids, BOD, COD, Cl, Conductivity, water level,
	Monthly	pH, EC, Temp, DO, NH_4N, Cl.
	Quarterly	as monthly plus: SO_4, Alk, TON, TOC, Na, K, Ca, Fe, Mn, Cd, Cr, Cu, Ni, Pb, Zn.
Groundwater ingress monitoring point (NE corner pumping chamber)	Weekly	pH, EC, NH_4N, Cl, COD, DO, BOD.

Alk: Alkalinity
COD: Chemical Oxygen Demand
TON: Total Organic Nitrogen
TOC: Total Organic Carbon
EC: Electrical Conductivity
DO: Dissolved Oxygen
BOD: Biological Oxygen Demand

Table 4.6 The Proposed Monitoring Plan for Site Beta, Phase 3, Cell 1.(Adapted from CQA, 1996).

order to ensure further protection for the environment in the long term. However, this has created new areas for concern through modem approaches to landfilling. For example, the use of geosynthetics as landfill liner components is now questioned, since little is understood about the effects of these materials and, also, their long term properties. Research has nevertheless, been completed in these areas, but, as this chapter has illustrated, results obtained under laboratory conditions may not reflect the true circumstances on-site and the influencing variables cannot always be replicated. For instance, a synthesised leachate will not be identical to that which is produced in a 'real' landfill at a specific time. The properties of the *in situ* waste will usually be different as accurate waste proportions are generally unknown and infiltration data can only be predicted. The constituency of leachate has also been proven to vary through time, affected by the age of the wastes in terms of their stage of decomposition. As such, different constituencies will have variable effects on the geosynthetics, some being much more vigorous than others.

Lined landfills are becoming more common in the UK, since it seems more likely that an existing site will be granted planning permission and a license. This may be true even with regard to potential sites with existing voids, as consideration of the following will also be required:

- Impact on local highways in terms of traffic frequency;
- Mud on roads;
- Public opinion.

However, Site Alpha was a new site, but its location, within the close vicinity of older sites and gravel pits, warranted its use for landfilling.

4.6 DISCUSSION

This research has illustrated, using real examples, that landfill sites must attain a previously agreed degree of design and construction in order to pose the least possible environmental risk. This chapter has outlined the details for the design, construction and QA monitoring of two contrasting landfill sites in the UK. It can be seen that both sites have similar hydrogeological considerations, but due to variations in other parameters, they employ contrasting operational containment systems. These parameters include; waste type, site location, licensing requirements, availability of on-site materials and ultimately, the site specific design and construction influenced by ground conditions.

The research has demonstrated the importance of QA to ensure that construction work is completed in accordance with the design and construction plans, therefore providing a degree of assurance. However, the ultimate assurance is dependent upon the final achievement of the required level of QA. Planned and competent performance of QA will reduce the risk of leakage through the liner (Giroud & Bonaparte, 1989). Landfill construction is generally monitored by the contractors' QC engineer, through the tests outlined, while the QA engineer will ensure the performance, relative to the entire project. This enhances the significance of a QA procedure formulated using approved guidelines derived from Codes of Practice. Moreover, the importance of an experienced third party for the completion of these tests cannot be understated.

The concept of Design Realisation can be portrayed through examples of the procedures involved in the QA programme at Site Alpha. A comparison between the on-site procedures at Site Alpha can be made with those of Jessberger's (1994) criteria in order to illustrate that the procedures stipulated in theory are not always realistic and sometimes unnecessary. Jessberger (1994) stipulates that QA should, importantly, aim to achieve measurements of the following:

- Characteristics of materials to be used; grain size, Atterberg testing (as described in Chapter Five section 5.7) etc. every 1000 m^2.

At Site Alpha, three tests were undertaken on the whole site as the material appeared homogeneous.

- Moisture content and homogeneity upon placement, number of passes with the compactor every 1000 m^2;

The Site Alpha working plan stipulated a minimum of five passes with the vibrating sheepsfoot roller, although in some cases further passes were deemed appropriate. It is also impractical to test for the moisture content after the placement of each lift with the present testing methods available today.

- Lift thickness and adherence to specifications per 1000 m^2;

In some cases specific lift thickness testing is disregarded and a general trust placed by the engineer in the experience of the construction worker involved in lift placement and compaction, as was the case at Sites Alpha and Beta.

- Determination of the permeability of the sealing layer of each lift every 2000 m^2.

Conversely, NWWRO (1996) stipulates a general testing frequency of 1 per 250 m^3 although hydraulic conductivity, particle size distribution and density could be completed at a rate of 1 per 500 m^3.

- Degree of compaction in determination of density, moisture content and plasticity per 1000 m^2;

At Site Alpha, a frequency of 1 test per 250 m^2 was employed which related only to density testing.

Testing at the frequencies suggested by Jessberger (1994) is generally regarded as impractical, since it is both time consuming and costly. It may add several days onto the time scale of a project, this also being dependent upon the receipt of laboratory results. Maintaining a technician on-site in order to measure these criteria and produce a fast turn around of data is usually unacceptable in view of the financial cost, particularly on small projects. Such testing would also delay construction, particularly if results were required before the next stage of liner placement could commence. If invalid results were obtained in clay liner compaction, for example, retesting would also mean the removal or recompaction of the newly placed lifts.

Such an '*ideal*' system of QA testing would result in a liner of greater integrity, but, at relatively small sites, the economics would be questionable. At Site Beta, the installation of a geomembrane liner may partially reduce the importance of the clay component since there are further barriers comprising the composite liner. As such, there may be a reduction in density and moisture content testing which is not in line with the best practice of landfill engineering.

These differences illustrated between actual and proposed criteria for QA (Jessberger, 1994 & NWWRO, 1996) are evident throughout the comparison of research with on-site practice. The guidelines vary due to:

1. The different design specifications and site characteristics;
2. The type and deployment of materials involved;
3. The influence of the designers and regulators over proceedings and their interpretation of guidelines and Codes of Practice.

These factors demonstrate that, although there are precedent regulations and Codes of Practice, there appears to be little recognised uniformity between them. There are few statutory controls in this area and only the QA engineers test data collection and final assurance report to prove that the efficient QA has been completed.

Furthermore, a site accepting inert wastes only (Site Alpha) would not warrant the complex depth of QA testing as indicated by Jessberger (1994), if the lining material, specifically clay, is homogeneous and deployed correctly. However, if engineered leakage is designed into the site, this will affect the frequency and complexity of the QA testing.

Indeed, combined with design, construction, restoration and after-care, QA must remain within economic limits in order to render the landfill site financially viable. Ultimately, landfills must be constructed and operated to produce a return on their investment whilst also combining the associated environmental risk reducing criteria, i.e. the BPEO.

Another aspect of the Design Realisation concept can be illustrated in the construction phases of a landfill site. An example of this can be portrayed through the design and installation of leachate collection systems. In the design stages of a landfill site, leachate systems are planned to cope with a predicted, estimated volume of liquid. More often, important aspects for consideration, such as installation difficulties and faults and future risks of clogging, may be neglected. The main causes for the failure of leachate control schemes are outlined in Chapter Three. It may become apparent during the construction of the leachate control system that the initial allotted gradient of fall for the scheme only enables minimal flow and, also, possibly encourages settlement of solids within the system. Therefore, if the construction work were completed by experienced, competent engineers and construction workers, combined with an efficient QA procedure, such occurrences would be minimised. For example, theory suggests that leachate control systems, such as those at Site Beta would work effectively. However, research has proven that blockages occur. As a result, pipes should be checked upon completion and monitored throughout the life of the site. With regard to the latter, this is not a common occurrence at present.

The small scale failure of the cutting for the side liner bench at Site Alpha was an unexpected event which occurred as the result of a blockage in the river up-stream. This scenario could not have been built into the design of the site. For the purposes of this investigation, it illustrates that an element of adaptability should be achieved by the overall design plan. The event highlights the possibility that varying ground conditions may give rise to changes in design and construction techniques which must additionally be covered by rigorous QA techniques.

On the basis of the research carried out on two landfill construction projects, this investigation has illustrated that an element of adaptation needs to be built into the landfill design plan. This is, therefore, highly dependent upon the ground conditions at the site. Indeed, unexpected conditions are usually the result of inadequate ground survey and site investigations. On the microscale, substantial discrepancies are not generally encountered at ground level. Clearly, at Sites Alpha and Beta, the site investigations were adequate. For example, on the microscale at Site Beta, the approximate thicknesses and variances between the flow rates in the skerries were known prior to construction of the liner. On the macroscale, the location of water bearing skerries was known and, also, the high possibility of water ingress, once exposed. However, despite this, minor adaptation to the original plan was still necessary during construction.

One of the main points for consideration was the subgrade drainage system at Site Beta, as it provides an ideal example of how theory cannot be effectively completed on-site. The achievement of the gradient (1:100 (V:H) fall towards the sump) was particularly difficult due to the restricted availability of suitable plant and site conditions which comprised saturated subgrade and water bearing Skerries. It was necessary to avoid penetrating the Skerry deposits which, therefore, did not allow much grounds for manoeuvring along the 150 m length of the cell (Figure 4.4). In effect, the design of the French drains, which although suitable in the plan, could not be completely efficiently realised which may result in future siltation within the system. In addition, a more comprehensive network of drains had to be installed in order to attempt to drain the saturated Mercia Mudstone.

This chapter has illustrated many of the material differences between two sites which must be placed in context within the field of landfilling in the UK. These case studies comprise an investigation of one of the cells at two sites and therefore each cell will be integrated upon completion of the site. They also indicate areas where further research is required in order to improve the efficient installation and operation of encapsulation systems. Most importantly, the chapter has addressed landfill design and construction in real terms in order to provide an applied study of aspects of Design Realisation.

4.7 SUMMARY

- Detailed case studies of site work involved in the construction of two landfill sites have for the first time provided vital information on actual construction procedures central to the theme of landfill Design Realisation. The case studies have highlighted the site specific nature of design issues and construction related problems.

- The investigation of practical Design Realisation is proving to be of growing interest in the current environmental climate. Landfill sites must fulfil their approved design criteria and need to be constructed under conditions which achieve Best Available Practice or BPEO.

- Researchers and the waste management industry are both keen to establish extensive applied links in order to minimise differences between theoretical knowledge and that which is directly applicable under site conditions.

- The two case studies have illustrated some aspects of the contrasting nature of landfilling in the UK related to Design Realisation. The key reasons include site locality, licence requirements, geology, hydrogeology, hydrology, waste type and amount, climate and further anthropogenic factors which, generally, can be integrated within a site design plan.

- Sites Alpha and Beta highlight the nature and importance of QA procedures throughout the design and construction of a landfill site. QA enables an assurance that the design and construction specifications have, to a degree, been adhered to. This research has demonstrated that the QA strategy will vary according to construction practices and, even, interpretation of guidelines and Codes of Practice.

5.0 GEOTECHNICAL ENGINEERING PROPERTIES OF CLAYS

5.1 INTRODUCTION

Chapter Three has outlined the use of clays in single and composite liners of solid waste landfill depositories and Chapter Four has investigated the practicalities involved in their use. However, neither have fully explored the reasoning behind the specific choice of clays. This chapter examines the application of clay soils in terms of their geotechnical requirements for the achievement of low permeability engineered landfill liners and defines the relationship between moisture content and dry density which may be used to calculate compaction specifications.

Site experience (Chapter Four) revealed the necessity for a review of compaction testing procedures since existing methods have proved to be complicated and time consuming. In order to ensure that the design specifications were adhered to in terms of compaction and material type, compaction Quality Control (QC) procedures were carried out on the clay liner. The research examines a testing method, the Moisture Condition Value test (MCV) which has to date not been commonly used on-site in England and Wales (Green & Hawkins, 1987). The MCV test is examined in comparison with recognised, standard laboratory tests, namely the Proctor methods (BS 1377) (BSI, 1990), for its effectiveness in terms of ease of use on-site, acceptability and reliability of results, time consumption and labour efficiency.

5.2 CLAY LANDFILL BARRIERS

Clays are currently the predominant form of landfill liner, employed either as single liners or in double and composite systems. Clay barriers are already established in approved, quality controlled single liner systems against which the new technology of geofabrics and geomembranes must compete (Anon, 1997b & Rankilor, 1981).

The aim of an engineered compacted clay liner is to provide a barrier of low permeability to discourage the escape of *'silent'* leachates and gases from the landfill sites (Jessberger & Stone, 1991). Increasingly, research (Thornton *et al.*, 1997 & 1993, Mather, 1989, Daniel & Shackleford, 1989, and Griffin *et al.*, 1976), is orientated towards examining the effects of landfills on clays, especially those in the long term, and how this influences the choice of liner.

It is inevitable that there will be some quantity of leakage from a site and as a result there is a necessity for research into the assessment and improvement of liner performance covering all barrier systems (Thornton *et al.*, 1997). Examination of the geotechnical properties and behaviour of clays, under the conditions experienced by landfill liners in the field and also under controlled laboratory conditions (Hird *et al.,* 1997), is necessary in order to address the following (Adapted from Thornton *et al.*, 1997):

- Define possible contaminant release in terms of quality and quantity;
- Define a possible time-scale for this release;
- Quantify the environmental risks caused by liner failure;
- Investigate the form and level necessary for future landfill remediation strategies.

Soil, (i.e., engineering 'soil') is a particularly variable material, so the engineer may experience disparities in its type and condition even over small areas. This was explained by Croney (1977) in relation to subgrade compaction for road pavement, and the same concepts can also be applied to the construction of a landfill liner. Croney (1977) accepts that an average assessment of soils for road pavement design will necessitate future remedial work to the structure. However, this cannot be permitted in landfill liner construction due to the potential detrimental environmental effects that failure would create. It is, therefore, critically important to be precise in the measurement and suitability testing of the clays used as liners. To investigate the nature of the materials and their variability, prior to the commencement of works, the engineer must complete tests, some of which are outlined in this chapter.

As with any construction, an element of risk is accepted by the engineer since, as the case studies in Chapter Four illustrate, there may be unexpected variations in ground conditions or inhomogeneities within the materials. In order to reduce these risks, a programme of testing must be completed to enable identification of possible problem areas by the geotechnical engineer and to ensure that the stability of the works is maintained (Barnes, 1995). Material suitability testing is completed as part of the site investigation and then again regularly throughout the construction of the landfill site in order to maintain the assurance of the quality of materials. Therefore, a reduction in the time taken by these tests is necessary in order to prevent the expensive cessation or slowing down of construction.

5.3 SOIL CHARACTERISITCS

One of the most influential characteristics of soils is their variability of engineering parameters from location to location, even within the same horizon. This may be particularly true of marls, such as those at Site Beta, which may show a *'high degree of variability in terms of cementation and weathering'* (Seymour, 1992). It may not be necessary for the geotechnical engineer to be aware of the exact composition of the soils used in construction of the landfill barrier, though the fundamental behavioural characteristics must be understood. This does not generally take into consideration the fact that the liner will be subject to chemical and mechanical stresses which may react with the composites of the soil. Neither does it consider the role of attenuation processes within the liner or unsaturated zone beneath. In order to consider these mechanisms, one must examine the suitability of the liner material and *in situ* deposits in terms of factors which influence attenuation processes (Table 3.4).

The three fundamental components of a soil system include soil particles (including detrital material); air (in the form of voids between the individual particles) and water. However, air content is of limited concern under these circumstances except in the fact that it affects the movement of moisture through the soil (TRRL, 1952). Individual soil particles are surrounded by a mineral skeleton and in turn are kept apart by pore spaces which contain both air and water. Thus, it is by the reduction of the air and water that the particles are brought closer together and the overall volume of the soil is reduced (compaction). This is obviously dependent on the constraining forces applied to the soil which is important to observe when comparing laboratory test results to those in the field. Indeed, a more reliable measurement of compaction characteristics and permeability may be achieved from field tests. Ultimately, soil behaviour depends upon the protean factors of pressure, time and environment. Time being the dependent variable for other factors which may contribute to a change in the behaviour of the soil.

5.4 SAMPLE DESCRIPTIONS

Chapter Four has described the construction works of the liners and testing procedures which were duly implemented on-site. Clay samples from the case study landfill sites in Chapter Four were tested for their mineralogical and engineering characteristics in relation to their use in engineered landfill liners. The inclusion of an investigation on the engineering properties of the materials was deemed to be an appropriate, complementary measure alongside a detailed description of liner installation, in order to provide a representative description of the processes involved throughout the design and construction of a landfill liner. This chapter illustrates the methodology and tests involved in the determination of material suitability. The tests and methods involved could be used on other landfills, most being common practice, demonstrating that in general one can apply the equivalent guidelines to all liner construction.

5.4.2 London Clay

The dominant clay facies of the London Clay sequence was deployed as a single engineered mineral landfill liner at the Site Alpha landfill. London Clay comprises a suite of facies including sands, silts and clays. It comprises predominantly marine strata deposited throughout transgression and regression stages, as indicated in the sequence through silting up processes from marine to estuarine and lagoonal deposits (Burnett & Fookes, 1974). The London Clay deposit, described by Cripps & Taylor (1986) and Burnett & Fookes (1974) in detailed studies, is an over-consolidated Tertiary marine clay formed in the cratonic basin of South East England, and is located in both the London and Hampshire Basins. Details for the weathering grading scheme of London Clay are given in Chandler & Apted (1988), portrayed in Table 5.1, based on a study of the deposit in Essex.

Zone	Classification	Description
IV	Fully Weathered	Remoulded clay or a few lithorelicts occupying < 30 %, in a matrix of soft to firm remoulded clay; brown or light grey, mottled brown.
IIIb	Partially Weathered	Larger lithorelicts separated by remoulded matrix, occupying 30 to 70 %; fissure surfaces and matrix often gleyed; selenite crystals common
IIIa		Dominantly brown (oxidised), with clay fragments showing original clay structure (lithorelicts) with 30 to 70 mm average dimension occupying >70 %; remoulded matrix developing in fissures and joints; some selenite crystals.
Iib	Partially Weathered	Clay fragments bounded by heavily iron stained joints and fissures, the brown colouration penetrating up to 20 mm; centre of fragments colour of IIa clay; fissure spacing 70 - 120 mm.
Iia		Weathering on surfaces of discontinuities only, with rusty yellow staining on joint, fissure and bedding planes, bulk of clay grey-brown; fissure spacing > 100 mm.
I	Unweathered	Uniformly grey-brown or grey-blue; discontinuity spacings typically > 100 mm.

Table 5.1 Weathering Scheme for London Clay at South Ockenden, Essex.

(Chandler & Apted, 1988)

Skempton (1964) states the weathering zone is typically 9.1 to 12.2 m in depth. The weathering zone comprises the whole strata of 'Brown' London Clay which extends from approximately 6.1 to 9.1 m and also includes 1.5 to 4.6 m of the predominantly unweathered 'Blue' London Clay. On-site at Site Alpha the exposed London Clay appeared to be grey-brown, typically Zone I but, also, exhibited aspects of Zone II, and some selenite crystals were found. This could be attributed to the variation in factors affecting weathering in the locality, such as climate, groundwater fluctuations and exposure.

Skempton (1964) identified that fissured clays and joints in natural slope formation can lead to progressive slope failure, over a period of 19 to 49 years, until the residual strength is reached. The investigation was based upon clays exhibiting pore pressures which were in hydrostatic equilibrium with the groundwater. This stage is not reached by cutting formations until months, or even years, after excavation and is dependent upon clay permeability. Further to this, Skempton & LaRochelle (1965) attributed slips in over-consolidated London Clay primarily to the migration of pore water and the presence of fissures. This is an important factor for consideration if cutting and filling is required on a landfill site in order to construct slopes which are stable in the long term and able to maintain the integrity of the overlying compacted clay and geomembranes liners. It also illustrates the importance of groundwater control through earthworks and post construction where cuttings exist behind a liner,e.g., the side liners at Site Alpha.

The excavated material at Site Alpha was a light grey silty CLAY with a dull, smooth, fine texture. From field identification the clay was found to be firm to stiff since it could be moulded by strong finger pressure or indented with the thumb. The average natural moisture content of this clay on-site was approximately 20 %.

5.4.2 Mercia Mudstone (formerly Keuper Marl)

The Triassic Mercia Mudstone formation comprises evaporites, sandstones, calcareous mudstones and red-brown to green shales and silty mudstones (Chandler *et al.*, 1968). Sandstones and siltstones (Skerries) are interspersed within the mudstones. These are mainly found in the most common situation where the red-brown Mercia Mudstone (formerly known as the Keuper Marl) is the predominant deposit.

Previous research (Chandler *et al.*, 1968) indicated the absence of definite boundaries between these minor features. This situation was proven by the field investigations carried out at Site Beta for this study. It is this part of the main deposit, i.e. the shales and calcareous mudstones (Marl), which this investigation is concerned with.

The heavily over-consolidated Mercia Mudstone deposit is exposed in Central England today, forming outcrops either side of the Pennines. Chandler *et al.* (1968) estimated an overburden of between 1219 m and 1829 m of the mudstone in Central England. In the Nottinghamshire area, Chandler *et al.* (1968) state that the deposit may now be as little as 225 m in thickness, in comparison with 1200 to 1500 m to the west of the Pennines.

The skerries in the deposit possess higher permeabilities than the facies in which they are present which can cause problems as they allow increased groundwater flow. This is illustrated in Chapter Four where temporary and permanent groundwater controls were necessary throughout the earthworks and post site completion. Site conditions were exacerbated by stability problems, such as basal heave, and the ability to maintain the marl in a workable form in order to comply with the compaction specifications. Further details of these are outlined later.

An important feature of the Marl deposits is the degree of weathering of the material. This has been studied and categorised by Chandler (1969), Chandler & Davis (1973) and

Zone		Description	Notes	*Liquid Limit* w_l	*Plastic Limit* w_p	*Plasticity Index* *PI*
Fully Weathered	**IVb**	Matrix only	Contains no pebbles. Plastic slightly silty clay. May be fissured.	35-60	17-33	17-35
Partially Weathered	**IVa**	Matrix with occasional clay-stone pellets less than 3 mm diameter but more usually coarse sand size	Little or no trace of Zone 1 structure, though may be fissured. Lower permeability than underlying layers			
	III	Matrix with frequent lithorelicts up to 25 mm. As weathering progresses lithorelics become less angular	Water content of matrix greater than that of lithorelicts	25-40	17-25	10-18
	II	Angular blocks of unweathered marl with virtually no matrix	Spheroidal weathering. Matrix starting to encroach along joints: first indications of chemical weathering	25-35	17-25	10-15
Un-Weathered	**I**	Mudstone (often fissured)	Water content varies due to depositional variations			

Table 5.2 Weathering Classification for Mercia Mudstone

(After Chandler & Davis, 1973).

Cripps & Taylor (1981 & 1986). It was impossible to examine and classify the degree of weathering of this material on Site Beta since earthworks had already commenced and the ground was disturbed. However, examination of small exposures and particle size analysis has led to the conclusion that the material at this location was partially weathered as in Zone IVa, indicated in Table 5.2 (Chandler & Davis, 1973).

At Site Beta, the mudstone was a very soft reddish brown sandy CLAY. Although it was mainly fine grained, there were some small rounded gravels present within the material. It had a weak dry strength and was relatively friable due to the nature of the particles and relatively high granular content.

5.5 CLAY MINERALOGY

5.5.1 Sample Suitability for Landfill Liners

Burnett & Fookes (1974) state that *'generally the London Clay is homogeneous'* although Bishop *et al.* (1965) had previously attempted to attribute the geotechnical trends within the clay to mineral variations. Indeed, suitability of clays for use in a landfill barrier system is highly dependant upon their individual mineralogical components and structure (Batchelder *et al.*, 1997). Thus, for this study, an investigation of the mineralogy of the clays was required.

5.5.2 X-Ray Diffraction (XRD) Results

Samples of the clay and mudstone from each investigated landfill site were subjected to whole rock XRD quantification using an Enraf-Nonius diffractometer with a fixed geometry 120^0 position-sensitive detector (PSD) (Batchelder & Cressy, 1998). The samples were gently ground and dry-loaded into a 1 mm deep plastic holder prior to analysis. Data acquisition time was 10 minutes, using a primary-beam monochromated $CuK\alpha_1$ radiation.

Identification was achieved by comparison with the whole-pattern database held at the Natural History Museum and corrections for absorption were then applied to the raw data.

Mineral	Mercia Mudstone (Wt %)[+]	London Clay (Wt %)[+]
Quartz	16	20
Fe-oxide*	1	7
Dolomite	24	1
Haematite	3	0
Plagioclase*	2	0
Calcite	0	2
Chlorite	1	2
Muscovite	0	3
Kaolinite	4	12
Illite	29	14
Illite-smectite	16	35
TOTAL	**97**	**96**

Table 5.3 Mineral Proportions Determined by XRD.

[+]All proportions are given in weight %. Totals are less than 100 % due to the presence of X-ray amorphous material such as organic matter.

* Denotes a poorly-crystalline phase. *Data supplied by the Natural History Museum, (Batchelder, 1997).*

The PSD was the preferred approach since conventional scanners, (i.e., those with moving components), do not provide adequate reproducibility for quantification purposes as *'non-random orientation of crystallite, changing size of irradiated area with scan angle or variable slit systems preclude this'* (Batchelder, 1997).

5.5.3 Interpretation

Burnett & Fookes (1974) state that, in the London Clay, calcite and dolomite usually appear in approximately equal amounts which concurs with the results of this investigation (Table 5.3). The clay content of the London Clay is dominated by illite-smectite (montmorillonite) (35 %), a highly swelling clay mineral. Sellwood & Sladen (1981) state that the clay minerals in this unit comprise in excess of 60 % of total weight. In contrast, these results indicate 50 % clay minerals by total weight. The London Clay is dominated by illite, as in Sellwood & Sladens' (1981) study. Shaw (1981) states, of the Mercia Mudstone, that previous research has concluded that the clay minerals present were mainly detrital illite, and small amounts of chlorite, supplemented by assemblages such as, smectite and illite-smectite.

The percentage of illite present within a clay will positively affect its ability to adsorb species, such as heavy metals, since the CEC of illite is in the region of 25 meq per 100 g (measure of the number of positive ions (in meq) to neutralise 100 g of clay) (Rowe *et al.*, 1995). The nature of the structure of this clay mineral, i.e. its 2:1 layering with a strong K^+ band (partially sunk) and the fact that there is no inter-layering, does not allow for swelling or contraction. As a result of these properties it is recommended for use in a landfill liner. However, the effect of low pH concentrations could cause leaching of the K^+ layer which will affect the clay minerals' properties and may lead to the formation of degraded illite. Erosion of the K^+ layer may result in distortion since this inter layer is usually strong enough to resist.

The illite-smectite mineral is a clay swelling mineral which is highly suitable for landfill liners, the most commonly used being Bentonite, a sodium enriched clay. It is the interlayer which enables it to swell due to the high void ratios. This mineral may have hydraulic conductivites of as low as $K = 1 \times 10^{-11}$ to 10^{-15} m s^{-1} (Rowe *et al.*, 1995 and Rowe 1994). Their characteristics are important to understand, with regard to the addition of chemicals present in some leachates which can make clay minerals inherently unstable.

5.6 PARTICLE SIZE ANALYSIS

5.6.1 Method

Disturbed samples of the clays were prepared for particle size analysis using a Malvern Mastersizer instrument. Pre-preparation comprised sieving the clays in order to remove particles larger than 2 mm. In the case of the London Clay the material was so fine that this proved unnecessary. Small rounded flints, approximately 300 mm in diameter, were picked out by hand from the Mercia Mudstone sample. In proportion, these larger particles accounted for most of the weight of the total sample but in terms of percentage present, made up < 5 % of the total volume of the material. It was determined that there would be a relatively high sand content in the Mercia Mudstone in comparison to that of the London Clay.

Preparation was completed using 5 ml of the sieved sample which was added to a mixture of 0.1 % calgon and distilled water. The calgon acted as a dispersant for flocculants in the sample. It is important to note that organic material will alter the results from the analyser. It was believed that the proportions present in these samples, if any, would be safe. The prepared sample of each clay was placed on a magnetic stirrer for several minutes and then centrifuged for one minute in order to accelerate the process of the dispersant.

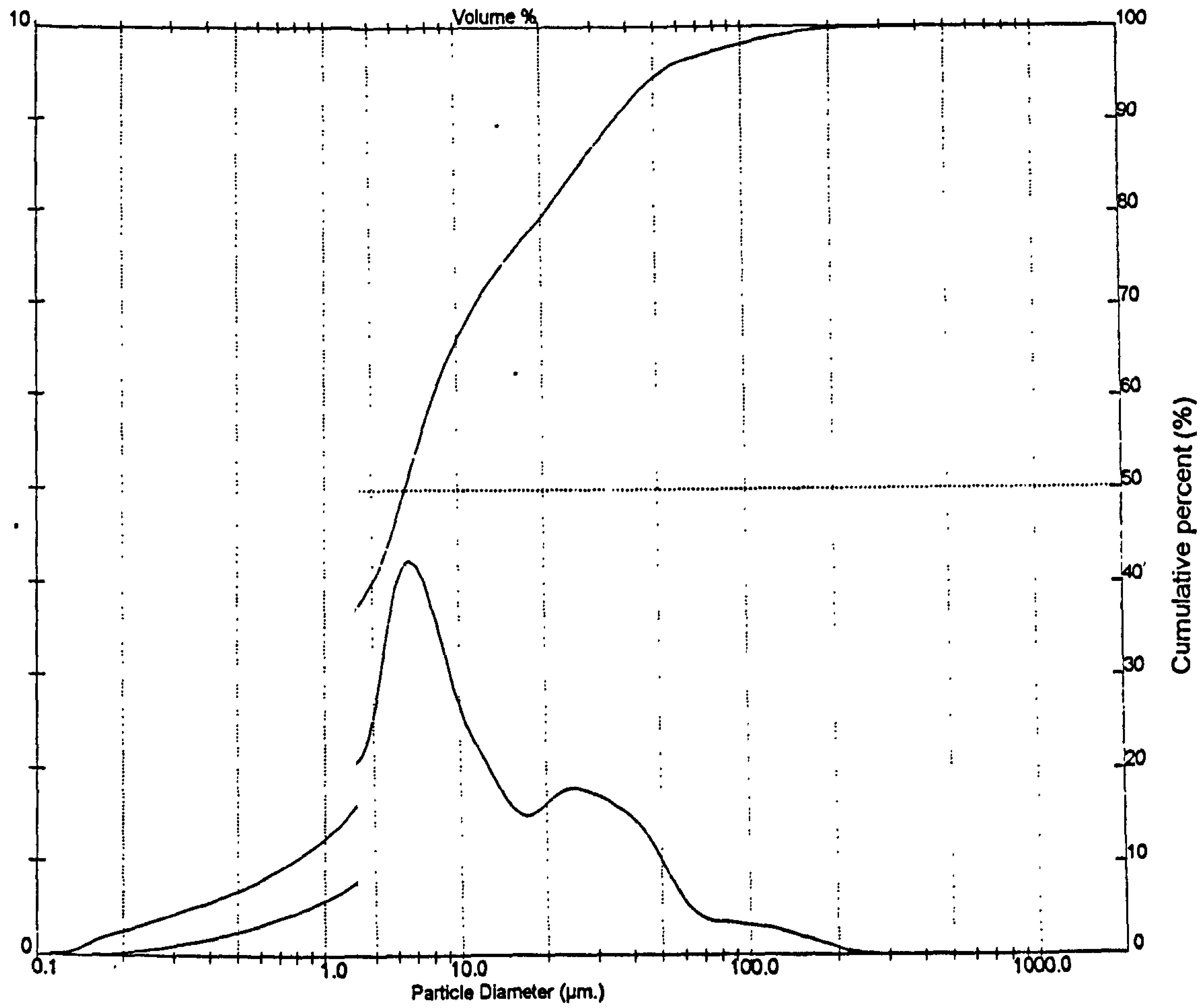
5.6.2 Results

The results, in Figure 5.1a, show that the London Clay has a normal particle size distribution. It has a relatively low obscuration (14 %) in comparison to the Mercia Mudstone (31.2 %) as the larger particles will block the deflection from the smaller ones. This is evident from Figure 5.1b which shows a minor bimodal distribution for the cumulative particle size. The first being 64 % at 7.9 μm and 12.5 % at > 1000 μm.

Fraction	Size	% present in London Clay	% present in Mercia Mudstone
Clay	Very Fine 0.1 - 2.0 μm	20	12
Silt	Fine 2.0 - 60 μm	76	68
Sand	Fine - Medium 60 - 1000 μm	4	16
	Coarse 1000 μm - 2 mm	0	4

Table 5.4 Breakdown of Fraction Sizes (%) for the London Clay and Mercia Mudstone.

From Table 5.4 it can be seen that the average particle size for the Mercia Mudstone is in the silt region which supports Sellwood and Sladens' (1981) statement that the grain size averages less than 64 μm. These results (Table 5.4) indicate that the London Clay is a clayey SILT with minor quantities of fine to medium sand. The Mercia Mudstone is a clayey sandy SILT comprising similar quantities of sand and clay. This demonstrates that although the initial classification on-site was completed to the best ability it did not reveal the extent of the silt content within either material.



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5.1b Mercia Mudstone

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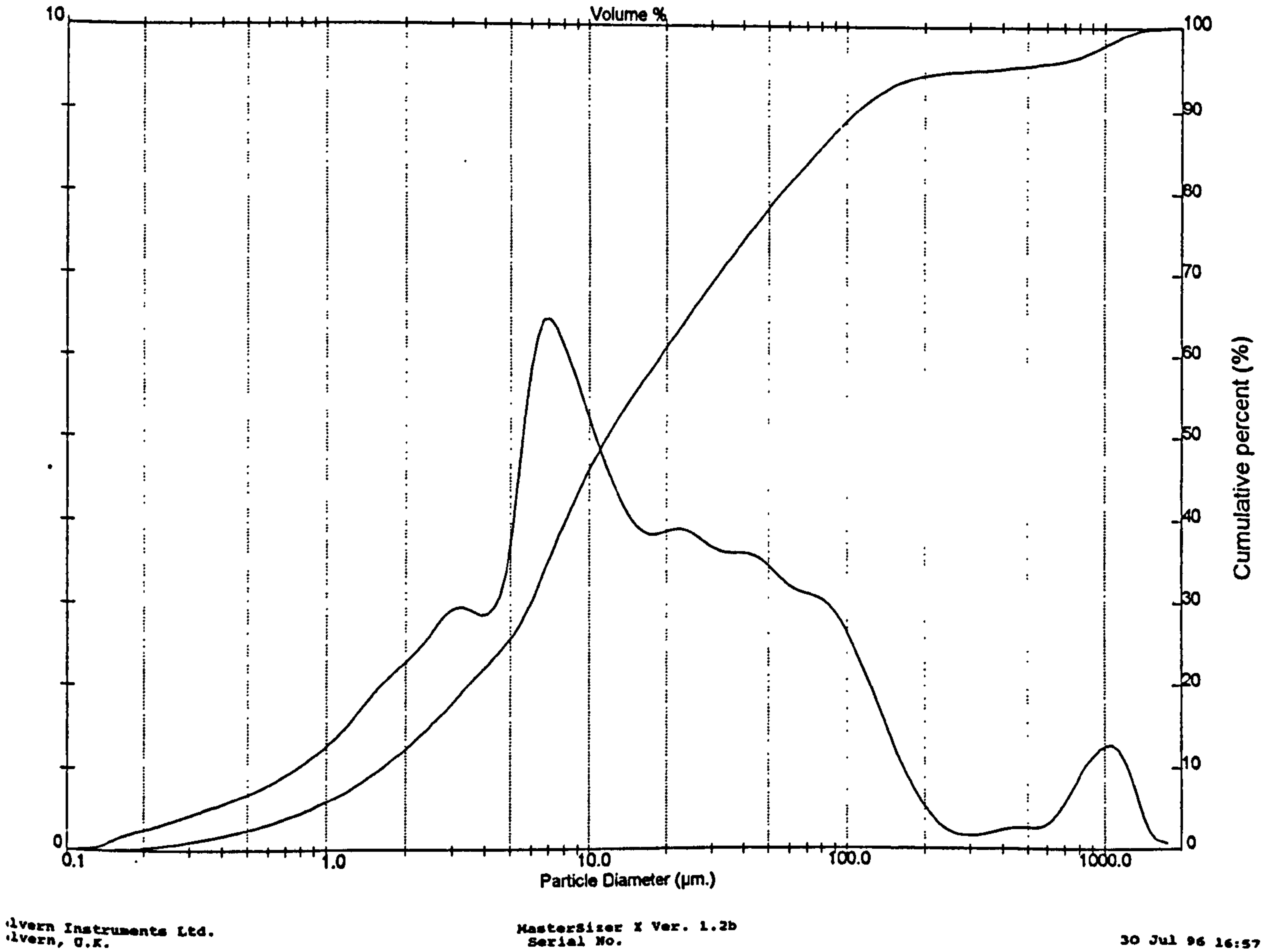


Figure 5.1a London Clay

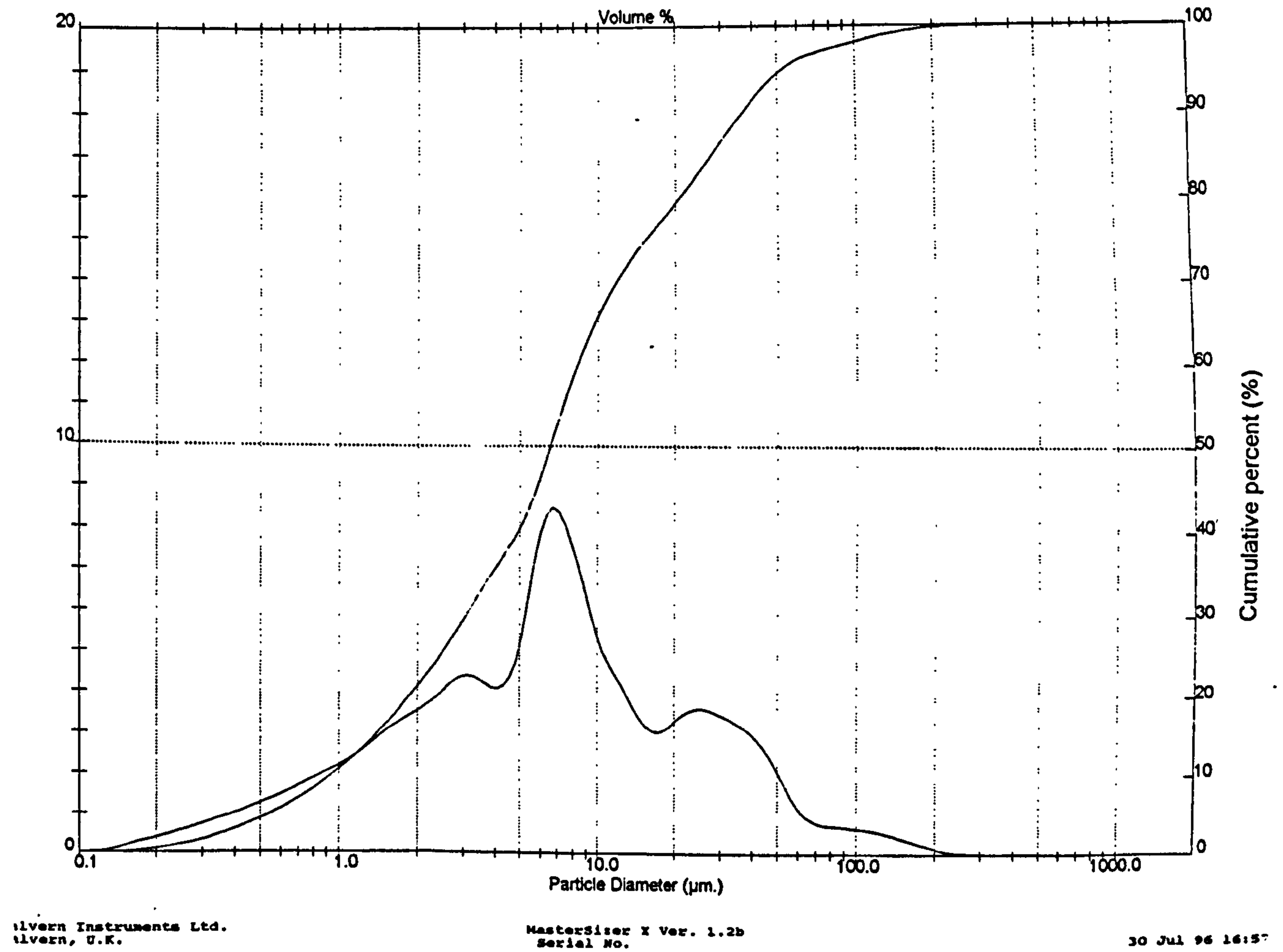


Figure 5.1b Mercia Mudstone

Figure 5.1 Particle Size Distribution Results

Modal grain size	Fissile	Non-fissile
> 2/3 silt	Silt-shale	Siltstone
1/3 - 2/3 silt	Mud-shale	Mudstone
> 2/3 clay	Clay-shale	Claystone

Table 5.5 Classification of Argillaceous Rocks (Shaw, 1981)

In addition, Table 5.5 provides a classification of argillaceous sedimentary rocks. If compared to Table 5.4, a contrast to an engineering geological classification can be achieved. Therefore in geological terms, from Table 5.5, the Mercia Mudstone may be classed as a Siltstone, bordering on mudstone, and the London Clay as a definite Siltstone.

NWWDO (1996) states the requirements for landfill liners in terms of material properties, namely:

Percentage fines > 20 - 30%

Percentage Gravel < 30%

Maximum particle size 25 - 30 mm.

The materials used in this investigation fall into these specific categories and are therefore classed as 'suitable' in terms of the above. This is provided that the minor gravel content is removed from the Mercia Mudstone if it is to be used either as a single or composite barrier.

indicated in Figure 5.2.

For the purposes of this investigation, in order to measure the Atterberg limits, the samples were prepared in accordance with BS 1377: Part 1 (BSI, 1990).

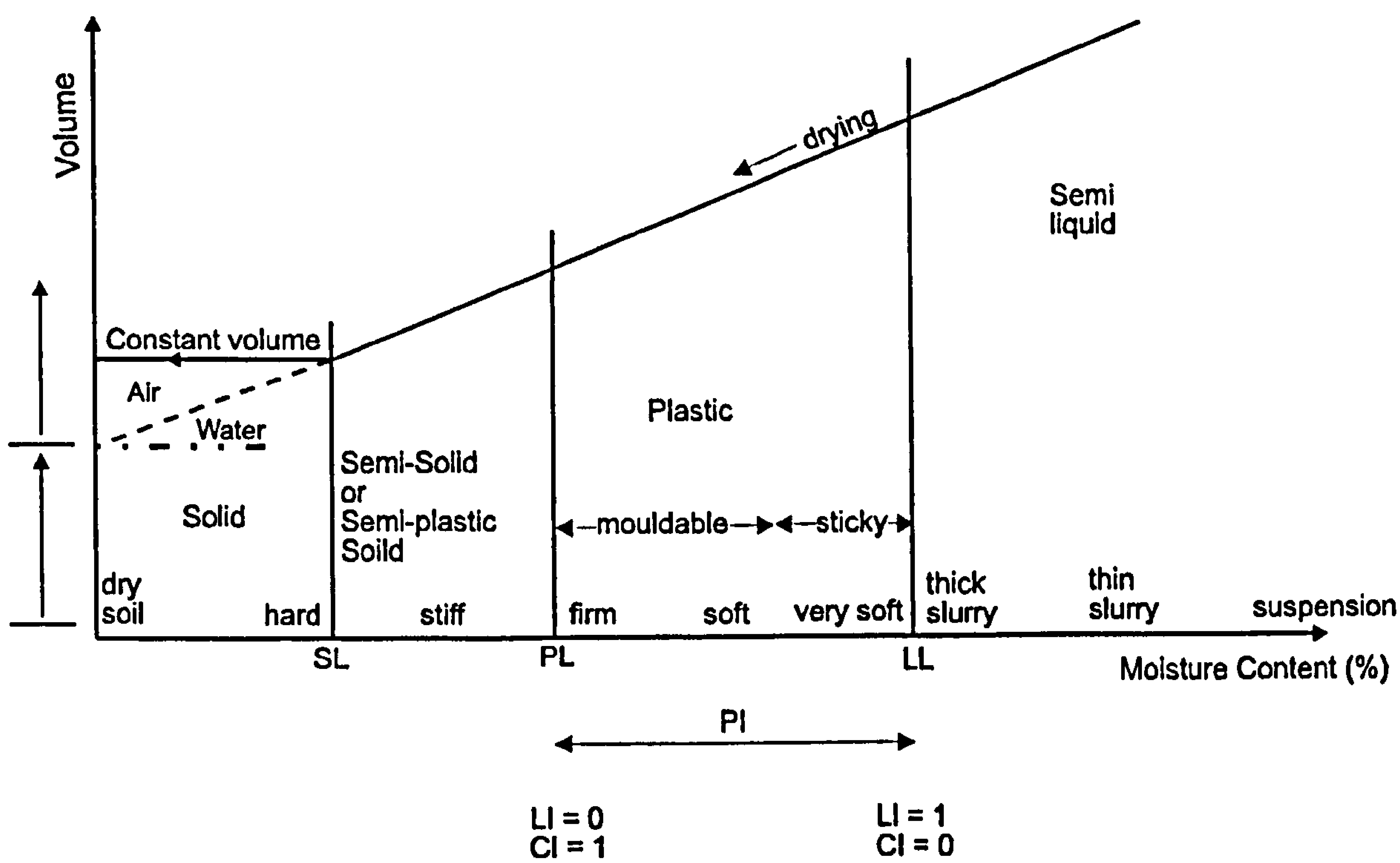


Figure 5.2 Schematic Diagram of the Consistency Limits of Soil.

Adapted from Barnes, 1995 & Whyte, 1982.

5.7.2 Liquid Limit (ω_l)

The liquid limit was calculated using the cone penetrometer (definitive method) in accordance with BS 1377 (BSI, 1990): Part 2. The Casagrande type percussion cup was considered but was deemed to be unreliable (Whyte, 1982). Moisture content and cone penetration were recorded and plotted against each other to ascertain the liquid limit. The average liquid limit for London Clay was 68 % and for Mercia Mudstone was 32 % (Figure 5.3 and Appendix 9.3). Burnett and Fookes (1974) indicate that the liquid limit of the London Clay to the west of London is lower than 70 % and extends to 95 % in the East and the area exhibits more lateral as opposed to vertical variation. In the location for this investigation there would not have necessarily been a great variation in liquid limit since the site covered only a small, shallow area.

Property	1	2
Liquid Limit	80%	68%
Plastic Limit	28%	28%
Plasticity index	44%	40%
Natural Moisture Content (%)	23 - 49	18 - 32 (12 - 28)*
Bulk Density (Mg m^{-3})	1.7 - 2	1.74 - 2

1 from Cripps & Taylor (1986) for weathered clay.

2 *in situ* from Colnbrook, west London. (* corrected measurement)

Table 5.6 Typical (average) Atterberg Values of London Clay.

The liquid limit of the Mercia Mudstone appears to be at the lower scale of the results of Chandler *et al.*'s (1968) work, the latter ranging with variable depths between values of 27 to 50. However, the liquid limit of the Mercia Mudstone from this investigation is identical to typical results as shown in Table 5.7.

5.7.3 Plastic Limit (ω_p)

The plastic limit is the empirical moisture content at which point the soil becomes too dry to be plastic (BSI 1377: 1990). It defines the arbitrary limit between the plastic and semisolid states of soil consistency. The Atterberg test for the plastic limit of the samples was completed under the guidelines of BS 1377 (BSI, 1990): Part 2 using the bead rolling test. Whyte (1982) suggests that a preferred method would be extrusion testing which produces more reliable results. However, this was not considered for inclusion in the revised BS 1377 (BSI, 1990) which to date provides the main scientific basis from which to compare the results of soils testing.

The plastic limit for London Clay is 28% (Appendix 9.3) which, when compared to the results of West (1991), is at the upper end of the results range. However, 28% is an average value for samples taken across the site. Table 5.6 gives an indication of the comparison between 'typical' published data from Cripps & Taylor (1986) and those results recorded from the site.

Liquid Limit	32%
Plastic Limit	18%
Clay Size Content	32%
Specific Gravity	2.74

Table 5.7 Tests Completed on 'Typical Keuper Marl'.

(Data from Chandler *et al.*, 1968).

The Mercia Mudstone plastic limit at Site Beta is 26% (Appendix 9.3). With reference to the results for the Mercia Mudstone, the difference in plastic limit from that in Table 5.7 can be explained through variation in local soil attributes.

5.7.4 Plasticity Index (PI)

The British Soil Classification System (Dumbleton, 1981) provides a plasticity chart to determine fine grained soils in terms of clays (C) or silts (M). Most soils lie below the 'B' line and silts and organic soils are found below the 'A' line. This is well documented in Barnes (1995).

$$PI = LL - PL\ (\omega_L - \omega_P) \quad \text{(Equation 5.1)}$$

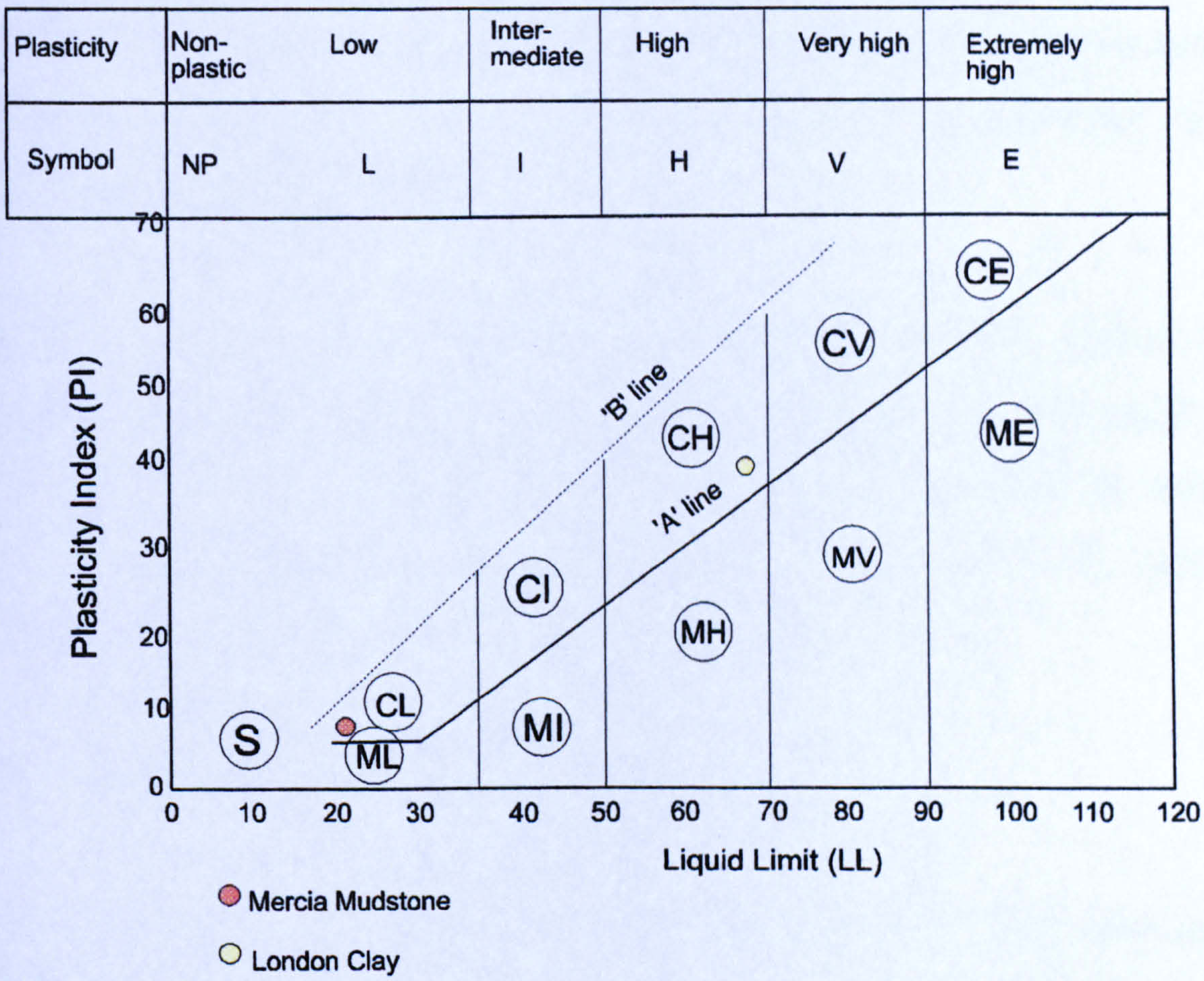


Figure 5.3 Plasticity Chart (BS 5930: 1981)

The London Clay PI value was 40 %, which from the plasticity chart (Figure 5.3) indicates that the clay is highly plastic (CH) and it falls within the values specified by West (1992) of 18 - 48 %. Burnett & Fookes (1974) state that the plasticity index variations resemble those of the liquid limit across the deposit but it is important to consider these variations on a site specific basis since local variations will affect engineering properties. The Mercia Mudstone results indicate that it is a low plasticity clay / silt with a PI of only 6 %, placing it almost on the 'A' line as CL / ML. This is confirmed by the particle size analysis which demonstrates the high silt content of the material.

On comparison of the results of this investigation with the work of Chandler & Davis (1973), the plasticity index results indicate that the Mercia Mudstone should perhaps be classified in weathering Zones II to III since Zone IV is typical of clays with much higher liquid limits and plasticity indexes.

Burnett & Fookes (1974) research on the London Clay (Orford Ness) indicated that Atterberg limits will increase with decreasing quartz grain size, all plotting above and parallel to the 'A' line on the Plasticity Chart. This could account for some of the variation between published results and those of this investigation which are directly related to variation between location due to formation, mineralogy and weathering.

5.8 ACCEPTABILITY OF MATERIAL FOR FILL

The main discussion on the acceptability of material for fill is found in the Conference on Clay Fills, (Anon, 1979) although, in addition, material is deemed acceptable if it meets the requirements of the Specification for Highway Works Clause 601 (DoT, 1991). The term suitability has been replaced by acceptability in order to cover a wider range of materials available for use in earthworks (Perry, 1995). The Specifications (DoT, 1991) outline acceptable materials in terms of compaction methods used to achieve a specific state of compaction or the final compaction required to be achieved. The following comprise the main parameters associated with acceptability (Barnes, 1995):

- *Nature of the works,* i.e., appropriate use of materials on-site;
- *Earthmoving efficiency* in terms of maintaining trafficability which is related to the strength of the soils (Vaughan *et al.*, 1979 and Parsons & Darley, 1982);
- *Compactability* associated with air voids content, permeability and strength.

These are addressed in this chapter and Chapter Four and are of fundamental concern throughout on-site construction procedures.

In addition, engineered fill comprising landfill barriers will be subjected to other criteria which are of less concern for the engineering of highways works. These are chemical attack, frost action and desiccation cracking, alongside liner deformation caused by differential waste settlement (Jessberger & Stone, 1991). Therefore, the specification requirements for the liner material must take this into account.

5.9 MOISTURE CONTENT

The determination of the *in situ* moisture content (ω) is a primary function of the suitability of the soil for use in a landfill barrier system. It is a highly influential factor affecting the properties and hence behaviour of soils (Anon, 1974 Harrop-Williams, 1985 and Day & Daniel, 1985). A small change in moisture content will lead to major consequences in terms of earthworks construction. Such changes in moisture content may be due to either natural or human induced causes.

The Optimum Moisture Content (OMC) is that which is necessary to achieve the compaction specification, i.e. as in a Proctor Compaction Test (BS 1377: Part 4) (BSI, 1990). The dry density[1] achieved by a certain compactive effort depends on the amount of water present (Anon, 1974). Therefore the dry density will increase to reach a maximum (γ_{dmax}) for the given compactive effort at which point the OMC is also achieved.

In terms of earthworks, the control of the moisture content is of importance in order to ensure the minimum of settlement, and maximum strength and, hence, stability upon completion. In relation to landfill liners, after completion of compaction the material must have a hydraulic conductivity of no greater than 1×10^{-9} ms^{-1} stipulated by regulations (DoE, 1995b). Attempts to compact material which has a moisture content wet of OMC will result in deformation, rutting, possibly heave and less than the maximum dry density. However, compaction of material dry of OMC results in only a small amount of deformation at the base of the lift (Whyte & Vakalis, 1988), although the maximum dry density will not be achieved. The greater the discrepancy between the achieved density and the maximum, the greater will be the post-placement settlement.

Moisture tests are taken to determine suitability during the site investigation and continual quantitative testing must then be completed throughout the ensuing works to provide insurance that the liner achieves its minimum specification. The proposal made by Harrop-Williams (1985) is to specify confidence limits to the measurement of hydraulic permeability which allows for the distribution of permeability results generally found on sites. Instead of the landfilling construction guidelines for a specific permeability coefficient of $K = 1 \times 10^{-9}$ ms^{-1}, the specifications should allow for a distribution around this value but within a minimum and maximum specified. This would enable material

[1] (γ_d = mass of soil particles / volume occupied)

suitability testing using the values of dry density (γ_d) and moisture content (ω) throughout the construction process and, would also allow for repairs to the liner on an as required basis.

5.10 PERMEABILITY / HYDRAULIC CONDUCTIVITY

The permeability of compacted clays will reach a minimum value wet of OMC which coincides with a maximum dry unit weight (dry density) as illustrated in Figure 5.4.

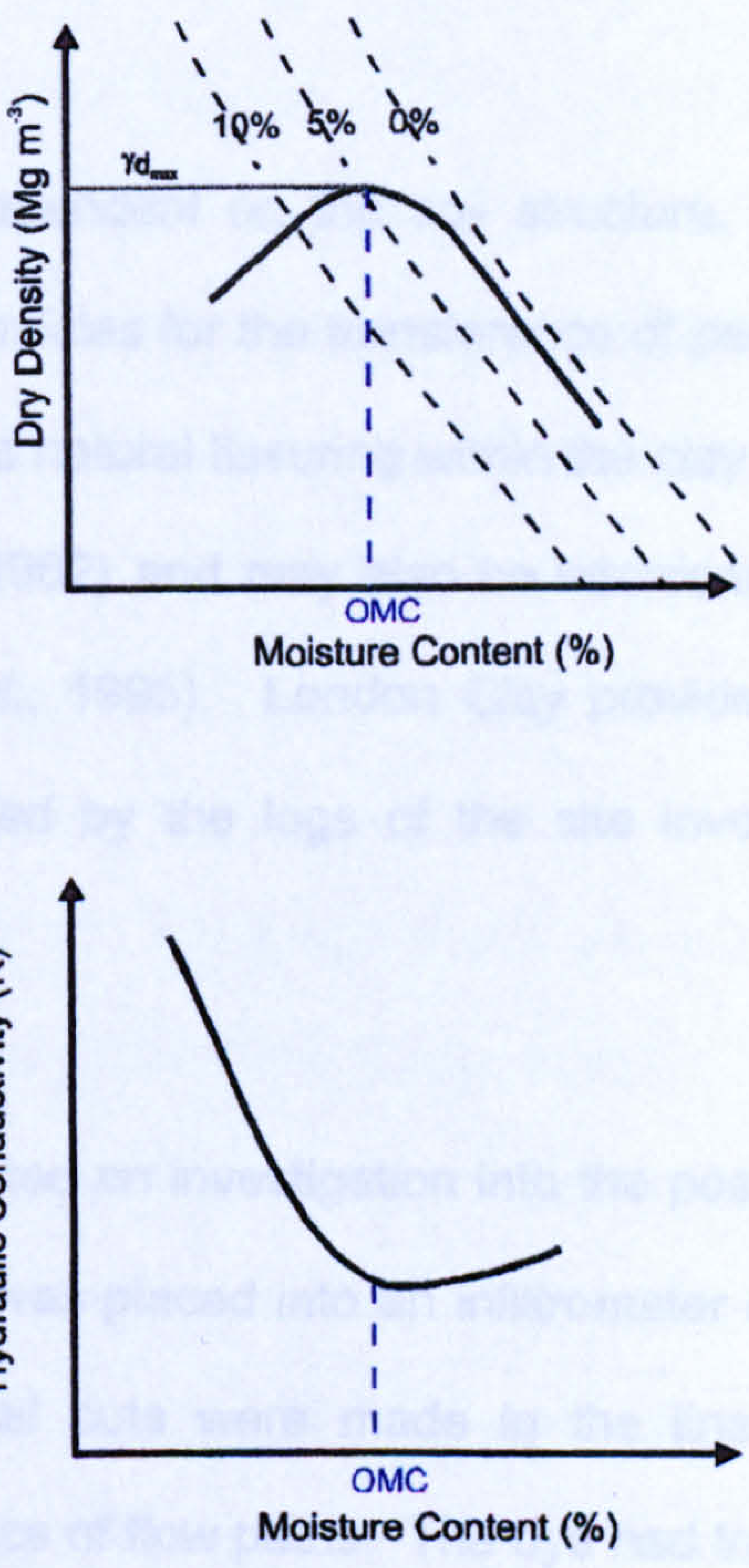


Figure 5.4 Typical Compaction, Moisture Content and Permeability Relationships. (After Mitchell *et al.*, 1965 and Seymour, 1992).

Therefore, for a specified moisture content and dry density the permeability can be minimised (Harrop-Williams, 1985). Rowe *et al.* (1995) state that under these initial conditions, the performance of a liner may improve over time. This is owing to increased consolidation, and diffusive chemical migration that results in the replacement of calcium and magnesium ions with sodium within the clay structure (Griffin *et al.*, 1976).

Hydraulic conductivities will vary over time and are dependent upon many variables as outlined below.

5.10.1 Internal Flow Structures

Hydraulic conductivity is dependent on the soil structure, primarily relying on the void space between individual particles for the transference of permeants. There are however, other possible voids, such as natural fissuring within the clay soils. Fissured pathways are generally tortuous (Olsen, 1962) and may also be interconnected to provide preferential seepage paths (Jones *et al.*, 1995). London Clay provides an example of a naturally fissured material as indicated by the logs of the site investigation boreholes (Chapter Four).

Elsbury *et al.* (1990) completed an investigation into the possibility of flow systems within the completed liner. A dye was placed into an infiltrometer and left to permeate the liner for six days. Three vertical cuts were made in the liner below the location of the infiltrometer to reveal evidence of flow paths. The dye had travelled along the lift interface and there was evidence of horizontal voids along its length. Pathways ranged from 1 to 10 mm wide and proved to be tortuous. Elsbury *et al.* (1990) noted that the lift interface was the location of deepest penetration in most areas, although interestingly, the dye penetrated 20 cm into the liner. This provides evidence that even in engineered fills, completed in accordance with the design parameters, seepage can occur.

An alternative potential pathway of permeants is through the fissures created during compaction. This anthropogenically induced route may be laterally extensive along the lifts whilst also interconnecting each lift vertically through fissures created during compaction procedures, desiccation etc. (Elsbury *et al.*, 1990).

5.10.2 Clod Theory

Clods are particle aggregates which will affect the size of the pore structures in the compacted clay, i.e. big clods will form large interpore spaces, increasing hydraulic conductivity thus enabling the movement of water through these areas (Olsen, 1962). The London Clay was susceptible to clod formation which at low moisture contents resulted in solid aggregates of material which proved very difficult to break down. Chapter Four has outlined the difficulties associated with such material.

The removal of clod features is, therefore, of vital importance to ensure that the liner achieves its specified hydraulic conductivity. In addition, if the clay is to be used as subgrade to a geomembrane, dry clods may damage the material, adversely affecting the integrity of the liner. Under circumstances dry of optimum moisture content, large pores between clods were noted at standard (2.5 kg rammer) Proctor effort. This produced permeabilities at least 25,000 times greater than those completed on homogenous material (Elsbury *et al.*, 1990).

5.10.3 Permeability Monitoring

Continual permeability monitoring is necessary throughout the construction thus demanding rapid monitoring techniques which enable continuation of construction. Control of permeability may be by:

(i) Reduction of hydraulic conductivity (coefficient of permeability);

(ii) Reduction of hydraulic gradient;

(iii) Control of the permeant.

It is impractical to measure permeability *in situ* or in a laboratory with *in situ* samples due to the long duration of these tests. In addition to this, it is also difficult to acquire undisturbed site samples. It is important to consider that permeability is a highly variable parameter spatially. Indeed, adjacent test areas could show huge factors of difference which could be attributed to local variations in moisture, soil mineralogy, compaction effort and type received (Seymour, 1992). All the aforementioned variables, either in combination or individually are likely to affect measurements of the hydraulic conductivity. Harrop-Williams (1985) indicates that large hydraulic gradients may be applied in laboratory testing techniques for rapid measurements, which are not indicative of the site conditions and may also cause particle migration (Hird *et al.,* 1997). Field testing procedures are advocated by Daniel (1984) and Harrop-Williams (1985) due to the following uncertainties associated with laboratory sample preparation and testing:

- Smear zones formed during trimming;
- Incorrect temperature;
- Air in the samples;
- Voids created from sample preparation;

- Selecting samples on-site without representative distribution of desiccation cracks, fissures and slickensides, indicated by γ_d and ω values;
- Incorrect modelling (in the laboratory) of the compacted effort which would be achieved in the field.

(Adapted from Daniel, 1984 and Harrop-Williams, 1985).

Measurement of the moisture content on-site is also prone to error, particularly in clays where strata may exhibit variations in mineralogy. For the case studies included in this investigation, the soils are believed to be relatively homogenous and are well within the permitted criteria for their compaction specification in terms of moisture content and dry density. This must be considered by field testing techniques which must generally be calibrated to the material on-site. Consistency in sampling and monitoring is also necessary in order to provide some degree of uniformity of the results, thus reducing the margin for error. Indeed, Lambe (1958) encourages determination of the moisture content at different depths in the sample area, excluding areas which have undergone excessive drying.

Current methods of hydraulic conductivity testing in the laboratory (triaxial permeability) would inevitably mean the cessation of construction until the results are available. This leads to immediate negative impacts in terms of:

(a) Financing of the project;

(b) The detrimental effect on the work completed to date.

As a result, Harrop-Williams (1985) states that to achieve '*real-time control of clay placement*' other measured parameters (moisture content and dry density), as part of the compaction process, are used to correlate and therefore imply permeability. This enables the faster turn around of results and it can be seen comparatively quickly whether or not the compaction specifications have been met in terms of the hydraulic conductivity. Therefore, if the ideal moisture content and dry unit weight are known, it is possible to reduce the permeability of the clay liner by compacting it within these identified parameters.

It is, therefore, immediately apparent that a rapid on-site technique is required for the measurement of permeability, or even, suitability of the material. Such a method should allow the continuation of construction works directly after testing on-site in order to reduce the effects of (a) and (b) highlighted above.

5.11 COMPACTION

5.11.1 Compaction Process

Compaction is the process by which the volume of voids in the soil are reduced through the compression and constraint of soil particles, typically by the application of mechanical pressures (Parsons, 1992 and Lambe & Whitman, 1969) at constant moisture content (Cox, 1996). The degree of compaction may be measured in terms of the dry density (γ_d) of the material, thus the higher the rate of compaction, the higher the dry density. However, the dry density of a material will vary according to the moisture content (Section 4.9).

5.11.2 Behaviour of Soils During Compaction

The bulk density (γ_b) will initially increase with the moisture content until the zero air voids line is reached, at which stage, once a maximum has been achieved, it will decrease with increasing moisture content (Figure 5.5). This can be explained in that at low moisture contents, the soil is stiff and difficult to compact, so low dry densities and high air contents are obtained.

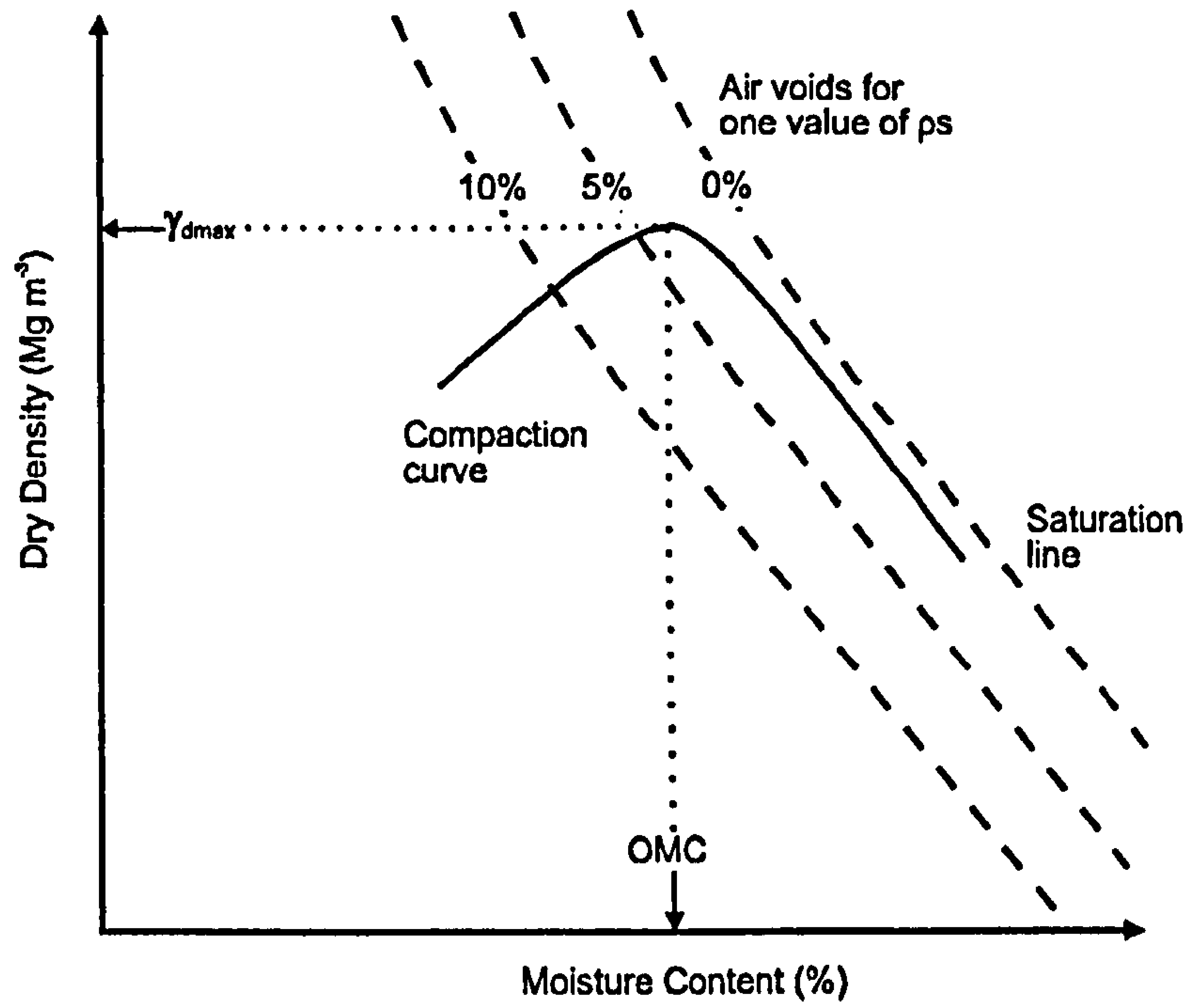
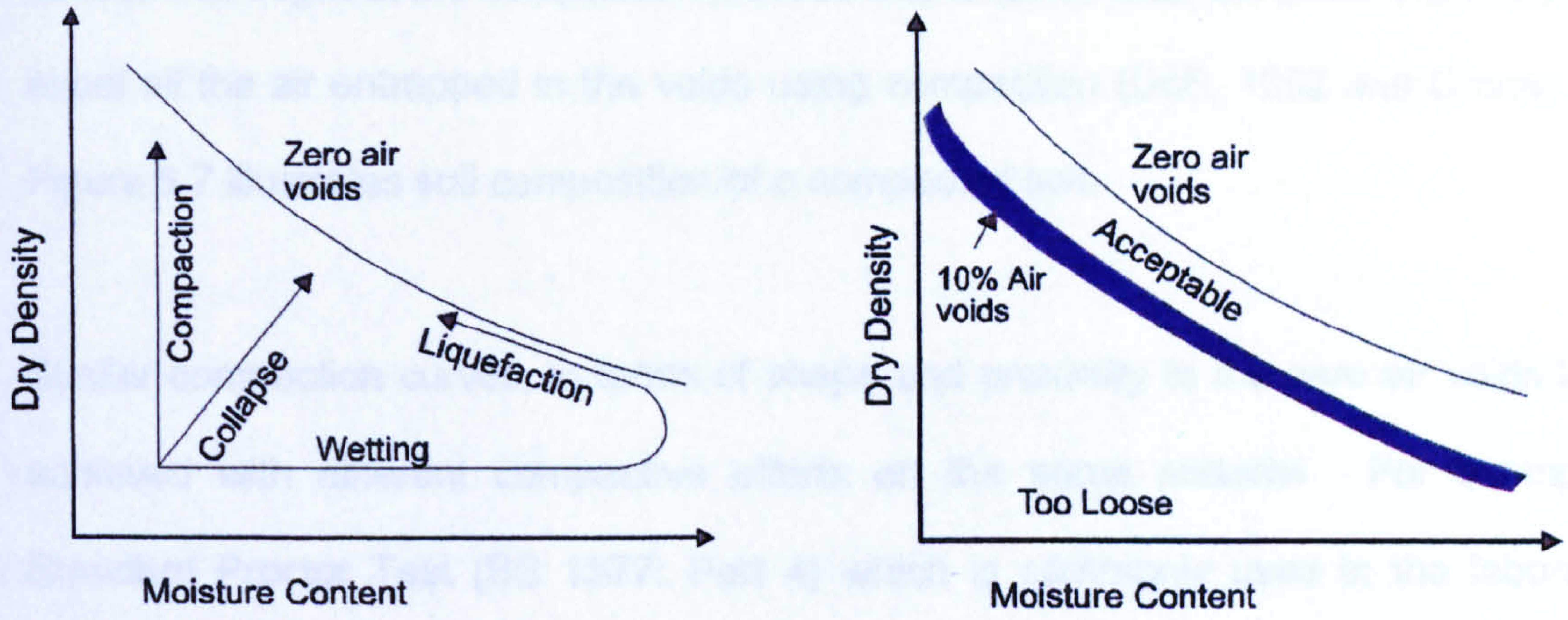


Figure 5.5 Typical Compaction Curves (Adapted from Barnes, 1995).

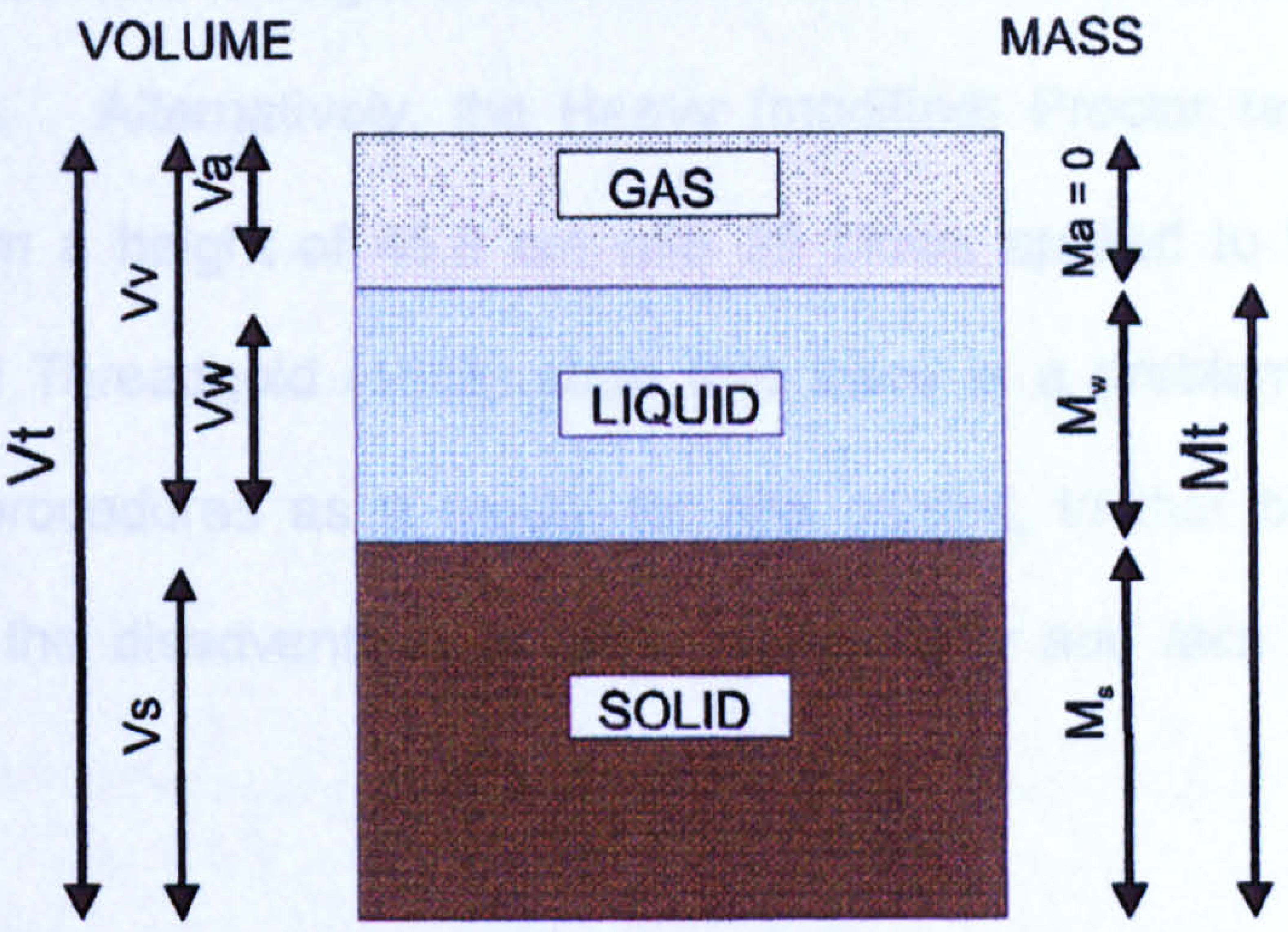
An increase in moisture content results in lubrication of the particles causing softening and creating an ease of workability whereby there is a decrease in air contents and higher dry densities (Figure 5.6). The total air voids continue to increase with the moisture content resulting in a decrease in dry density. The saturation line (zero air voids) remains a



Changes in Density After Placing

Air Voids Specification for Compaction

Figure 5.6 Soil Compaction (Cox, 1996)



Vt Total Volume
Vv Voids
Vs Volume solids
Va Volume air

Mt Total Mass
Mw Mass Water
Ms Mass Solids
Ma Mass Air

Figure 5.7 Soil Composition

After Parsons, 1992, Lambe & Whitman, 1969 & Barnes, 1995.

constant throughout the compaction process and is never attained since it is impossible to expel all the air entrapped in the voids using compaction (DoE, 1952 and Croney, 1977). Figure 5.7 illustrates soil composition of a compacted soil.

Similar compaction curves, in terms of shape and proximity to the zero air voids line, are achieved with different compactive efforts on the same material. For example, the Standard Proctor Test (BS 1377: Part 4) which is commonly used in the laboratory to determine compaction specifications for materials in the field. A 2.5 kg rammer was originally used for the test, although an additional test has been employed using a 4.5 kg rammer. This was specified due to an advance in the technology of site plant which enabled the use of larger, heavier machines on-site. The Standard Proctor test employs a 2.5 kg rammer dropped from a height of 30.5 cm. A total of 25 blows is used to compact each of three layers. Alternatively, the Heavy (modified) Proctor test uses a 4.5 kg rammer dropped from a height of 45.8 cm with 25 blows applied to five layers of the sample. Cobbe and Threadgold (1988) state that there is a problem with the current compaction testing procedures as a model for site control, in that both the Standard Proctor Tests, have the disadvantage of *'poor repeatability and lack of a well defined optimum in practice'*.

5.11.3 Field Compaction

The Specification for Highway Works (DoT, 1991) Clause 612 states that compaction should *'produce a minimum state of compaction equal to 10 % air voids at a moisture content at the dry limit for acceptability'*. This can be applied to the compaction of material used to form a landfill liner at the required permeability.

Earthworks require a state of compaction which is commonly specified as a percentage of the maximum dry density which is obtained from laboratory testing or in terms of a maximum percentage of air voids. The percentage air void lines (Figure 5.5) used are the 0 %, 5 % and 10 % air voids of the material. For civil engineering purposes, such as roadworks (Chandler *et al.*, 1968) and clay fills (Charles *et al.*, 1998), the percentage air voids method is most widely employed as a measurement of the compaction.

A series of lab and field compaction tests therefore must be completed prior to earthworks in order to determine the maximum dry density and optimum moisture contents in order to achieve the compaction specifications. Seymour (1992) indicates that there may be variability in compaction across the site when using equivalent densities to those of laboratory investigations. The moulds used in the lab enable the breakdown of the material into basic clay particles due to confinement whereas in the field the material is able to move laterally thus avoiding remoulding. These problems may be more significant in clays of an inhomogeneous nature.

Compaction is measured in terms of the dry density of the material which is calculated by:

$$\text{Dry density } (\gamma_d) = \gamma_b \times 100 / 100 + w\ (\%) \qquad \text{Equation 5.2}$$

Where γ_b is bulk density

And w (%) is moisture content.

Dry density increases with moisture content until the zero air voids line is approached. As this stage is reached, the soil will respond to the stress of compaction and excess pore water pressures will be achieved. In addition, a fundamental parameter in determining the maximum efficiency of compaction may be the choice of plant.

5.11.4 Field Compaction Plant

Compaction machinery or 'plant' are primarily chosen according to the nature of the material which is to be worked. However, choice is also dependent upon; size and shape of the area for compaction; lifespan of compacted material; current state of the material; compaction specification; end use; and financial cost.

The list below illustrates the main different mechanical compacting plant which are available for use on-site:

- Smooth drum rollers with or without vibration are used to produce smooth surfaces. However, these cause problems in clay compaction as they can produce plant-created shear surfaces, although, scarification could reduce the effects of this. Speeds between 2.5 to 5 km hr^{-1} without vibration are needed and 1.5 to 2.5 km hr^{-1} with vibration (Barnes, 1995);
- 'Sheepsfoot' (tamping foot) or club-foot compactor. This is a smooth drum covered in sturdy, radially extensive hooked projections or feet, 180-240 mm long. These penetrate the clay and compact it from the bottom of the lift upwards providing good interlift connection (O'Flaherty, 1974);
- Grid rollers are towed providing high localised pressure and are more effective in breaking down clods in cohesive soils;
- Vibrating plate compactors are slow and manually operated for use in small, confined spaces;
- Pneumatic-tyred rollers use a kneading action to apply pressure, which may be increased with ballast or by the adjustment of tyre pressures;
- Power rammers manually operated and actuated by explosions

(Barnes, 1995);

- Dropping weight or dynamic compactors, where a 200 - 500 kg weight is dropped from 1 - 3 m using a hoist.

Either of the first two can be separately towed compactors (Plate 8) or self-propelled and are the main plant used in landfill liner placement. The tamping foot roller is generally used in the compaction of the waste at landfill sites. For example, a Macpactor machine with block feet, shallower in depth than those of the club or sheeps foot compactors.

Figure 5.8 illustrates the difference in compaction achieved between static and vibrating rollers on silty clay soil. The difference in compaction is extremely noticeable, in fact the compaction capacity is doubled when a vibrating roller is employed and the lowest values for K are achieved with a kneading as opposed to static compaction (Figure 5.9).

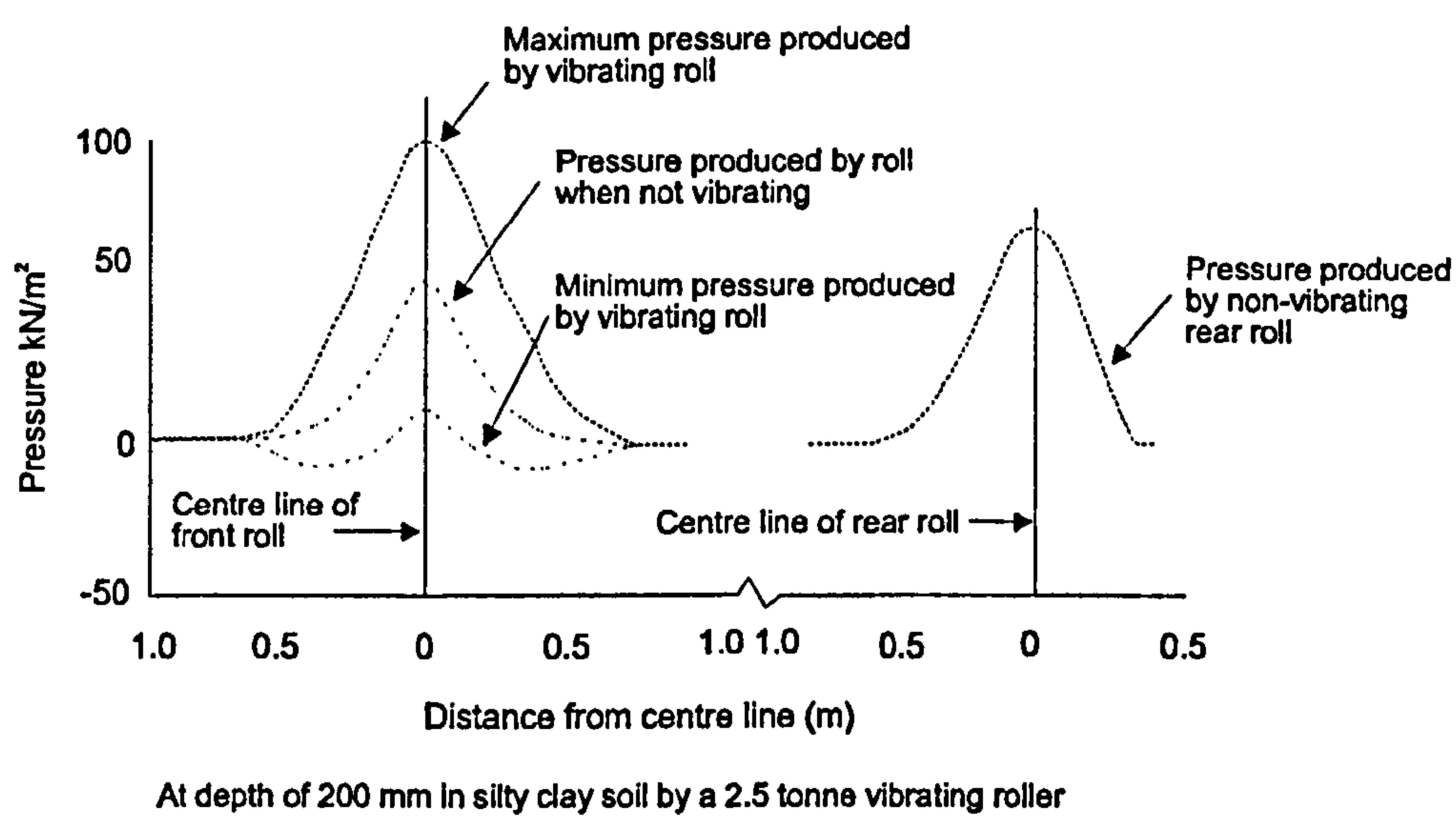


Figure 5.8 Influence of Technique upon Compaction of Silty Clay Soil (O'Flaherty, 1974)

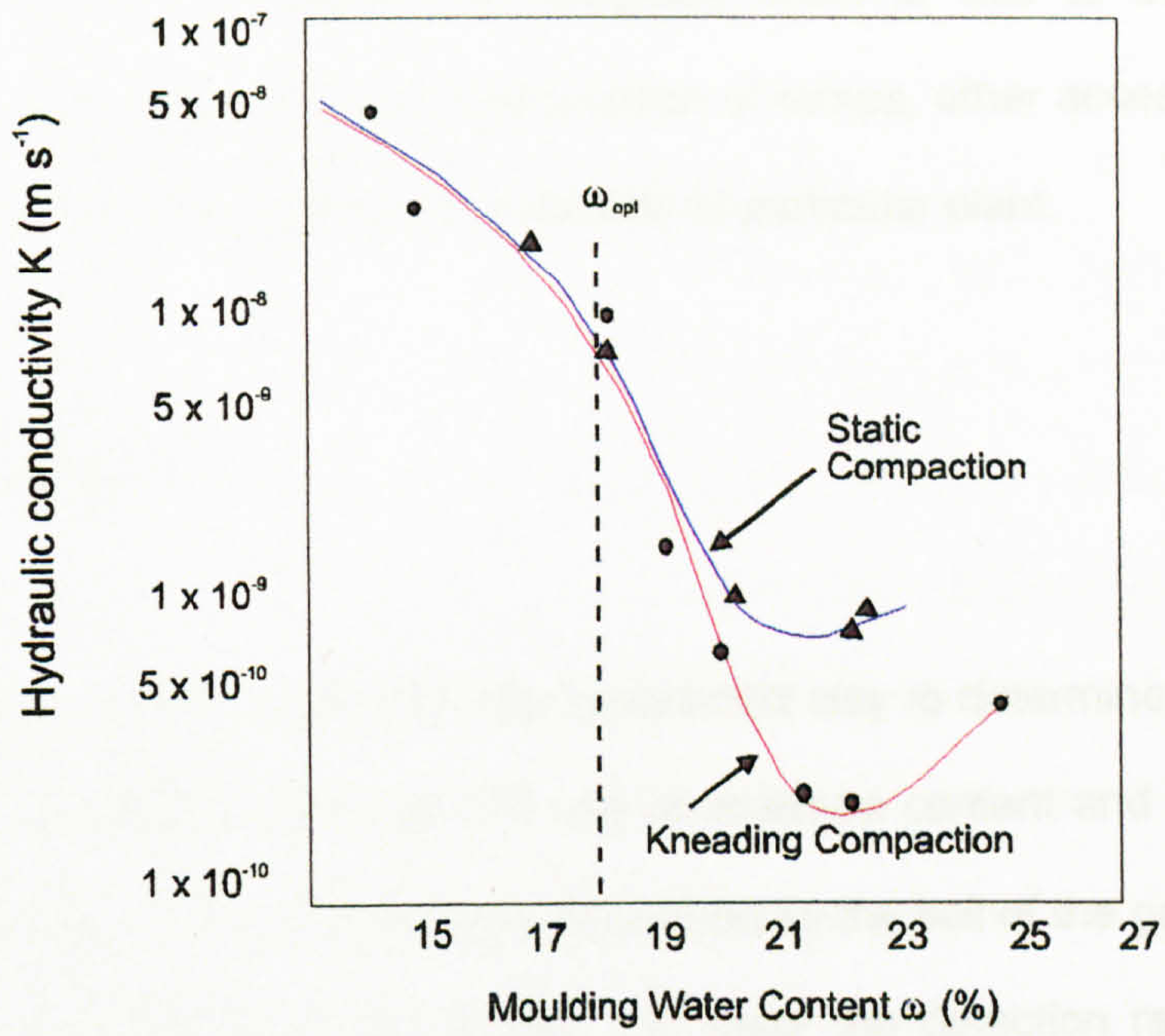


Figure 5.9 Results from Kneading and Static Compaction (Rowe *et al.*, 1995)

The compaction technique is defined by Daniel (1993) as, '*one pass of the compactor, not just an axle, over a given area*'. The number of passes may be altered throughout the works, as it will be dependent upon the moisture content of the clay, to achieve an accepted level of compaction.

The smooth compactor has drawbacks in that it compacts the clay in layers as it is spread. Each clay lift placed by the bulldozer is therefore not combined with the next as well as it might be with the sheepsfoot. The club (as opposed to taper) sheepsfoot compactor could be vibrated in order to compact the clay further. This also provides the keying-in mechanism for the next lift, thus reducing the possibilities for interlift migration of leachates and increasing shear strength at the interface (Whyte & Vakalis, 1988).

The suitability of a particular piece of kit may be determined financially, although, of greatest importance is the ability of the kit to achieve the designers specifications. This is explained in Section 4.5.7 where the subgrade finish is vital to the integrity of the completed composite liner. The size and location of ramps, other access points and even the liner itself can be influenced by the suitability of particular plant.

5.11.5 Field Testing

The Nuclear Density Meter is used on the compacted clay to determine the compaction of the engineered mineral liner through the use of moisture content and bulk density. The method depends upon the scattering and absorption by the soil of the gamma rays emitted by the kit, i.e. the higher the bulk density, the lower the detection rate of gamma rays (Parsons, 1992). The most popular nuclear density probe (Figure 5.10) used today is the portable kit measuring density by direct transmission. Moisture content is measured in the

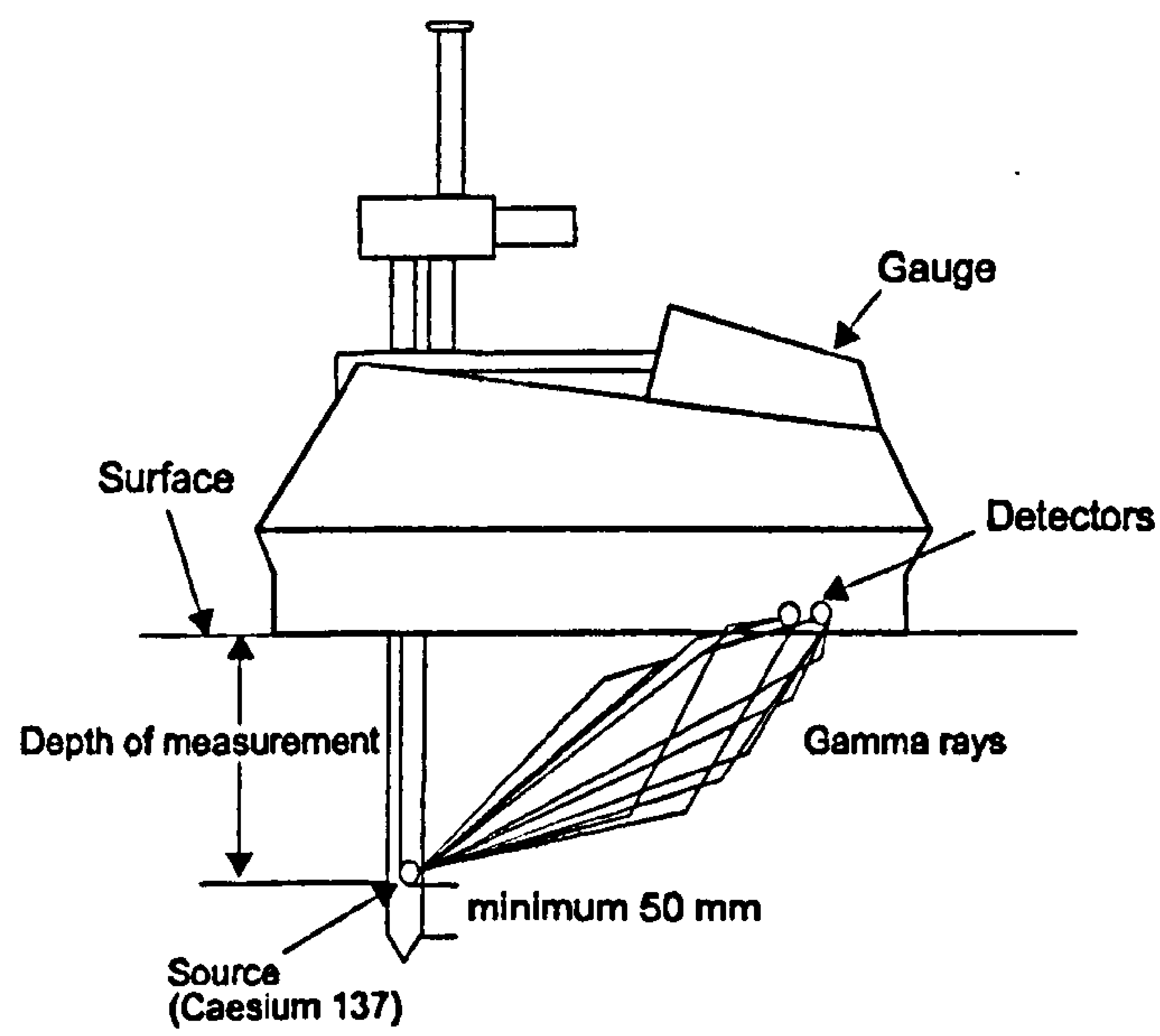


Figure 5.10 Nuclear Density Probe (after Parsons, 1992)

same way using neutron radiation.

This kit uses a nuclear probe which is extended into a hole made by hitting a metal pin of similar dimensions into the ground. This has the potential for error, particularly since the hole made is irregular, being larger than the pin in depth and diameter. The probe must be pushed against the side to achieve a reputable result. Parsons (1992) noted that this method created greater disturbance in sandy materials, decreasing density in the immediate locality. There may be limitations in the use of a probe, although it will achieve more representative results than the back scatter measurement apparatus which only measures gamma rays at ground surface level upon rebound from the soil.

New, faster and more robust methods for on-site testing are therefore necessary to provide accurate field techniques for the determination of the prescriptive requirements for compaction, moisture content and other required measurements. Methods, such as the density probe, require further laboratory confirmation of results, using test controls and samples, which are time consuming to acquire. A technique is required which needs only one control test of the material at the start of the project, or even, during the site investigation in order to determine the degree of required suitability. Murray *et al.* (1992) state that a performance specification for permeability is preferred. However, due to the time required for such on-site tests, it would be preferable to relate the permeability to other parameters (density and moisture content) which can be monitored more easily. In addition, confirmation would perhaps still be required through more detailed laboratory testing.

5.12 THE MOISTURE CONDITION VALUE TEST

5.12.1 Introduction

Importance is placed upon determining a suitable hydraulic conductivity testing procedure in order to reduce the time and costs incurred in the construction of a compacted clay liner or placement of subgrade. It was with this aim that an alternative approach the Moisture Condition Value (MCV) was researched in order to investigate the possibilities and practicalities for its use on-site.

Dennehy (1988) states the principal advantages of the MCV test are the speed of result availability and the simplistic nature of both the technique and the application of results. Originally developed by the Transport and Road Research Laboratory (TRRL) (now TRL) (DoE, 1952) as a modification of the aggregate impact test apparatus, the MCV is a test for the rapid and reproducible measurement of the moisture condition of material for earthworks (DoT, (1991), Clayton, (1979) and Parsons & Boden, (1979)). The technique has been used routinely in Scotland, both in the laboratory and in the field, to assess the acceptability of soils for earthworks (Smith *et al.*, 1993). In the UK it is primarily used in order to control compaction of lime stabilised clays (DoT, 1991 and Cobbe & Threadgold, 1988). It could replace other methods, for example triaxial permeability testing, through a definition of the effectiveness of a material in terms of the upper limit of the moisture content (Scottish Development Department (SDD), 1983).

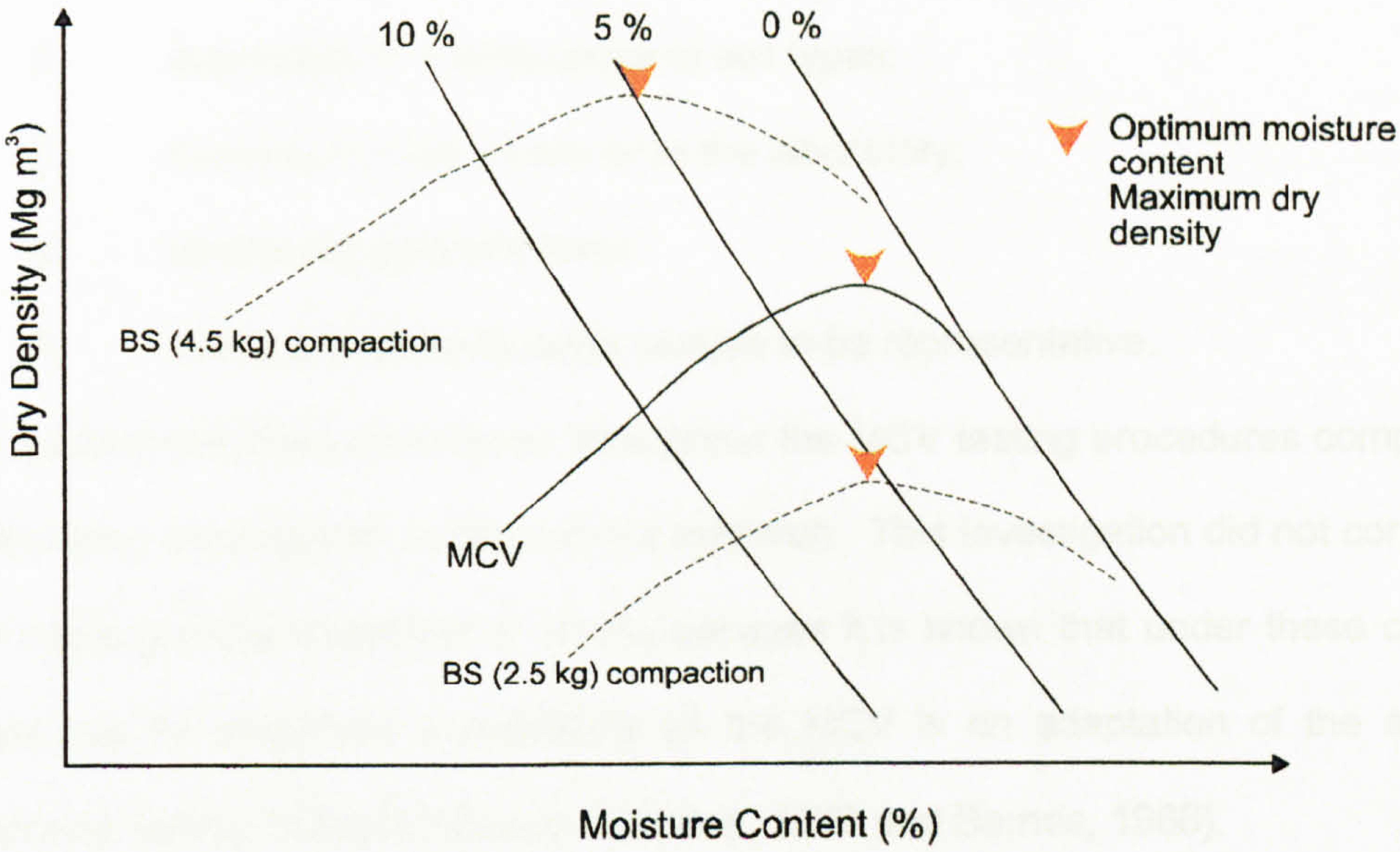


Figure 5.11 Typical Proctor and MCV Compaction Curves.
Adapted from Murray *et al.*, 1996.

The method is integrated in the Specification for Highway Work (DoT, 1991), the critical Clauses being Cl. 612: Compaction of Fills, and Cl. 632: Determination of MCV of Earthworks Materials. The former denotes a maximum MCV of 12.5 for cohesive soils which is approximately equivalent to a moisture content at which ≥ 10 % air voids is achieved whereas at ≥ 5 % air voids the MCV would be 11.5 or less.

The MCV assesses the suitability of a material in relation to specified limits of moisture limits or strength (Parsons & Boden, 1979). It provides a density (γ) versus moisture content (ω) relationship which lies between the BS 2.5 kg Standard (light) Proctor and BS 4.5 kg Heavy Proctor as illustrated by Figure 5.11.

Green & Hawkins (1987) outlined the primary objectives for the MCV test as those below:

1. Providing a rapid result;
2. Applicable to a wide range of soil types;
3. Suitable for use on-site or in the laboratory;
4. Minimising operator error;
5. Using a sufficiently large sample to be representative.

These parameters were considered throughout the MCV testing procedures completed for the laboratory investigation in this current research. This investigation did not consider the use of more granular materials or chalks because it is known that under these conditions the test can be employed successfully as the MCV is an adaptation of the aggregate compaction testing method (Parsons & Boden, 1979 and Barnes, 1988).

Parsons & Darley (1982) devised a formula in order to determine the MCV of the sample, which was applicable for plant, such as motorised scrapers and dump trucks with rigid chassis, operational at any speed. Research by Parsons (1979) and Parsons & Boden (1979) also proved a relationship between the bulk density, compactive effort and moisture content, and, that shear strength can be an effective measure of suitability (SDD, 1983). The MCV test is limited between the permeability requirement for landfill liners of $K = 1 \times 10^{-9}$ m s^{-1} and an undrained shear strength of no less than 40 to 50 kN m^{-2} which is required for earthworks (Murray *et al.*, 1992).

5.12.2 MCV Apparatus Specifications

5.12.2.1 Description

The MCV apparatus is a manual device which was designed for operation either in the field or in the laboratory. The apparatus has a base with a weight of approximately 31 kg

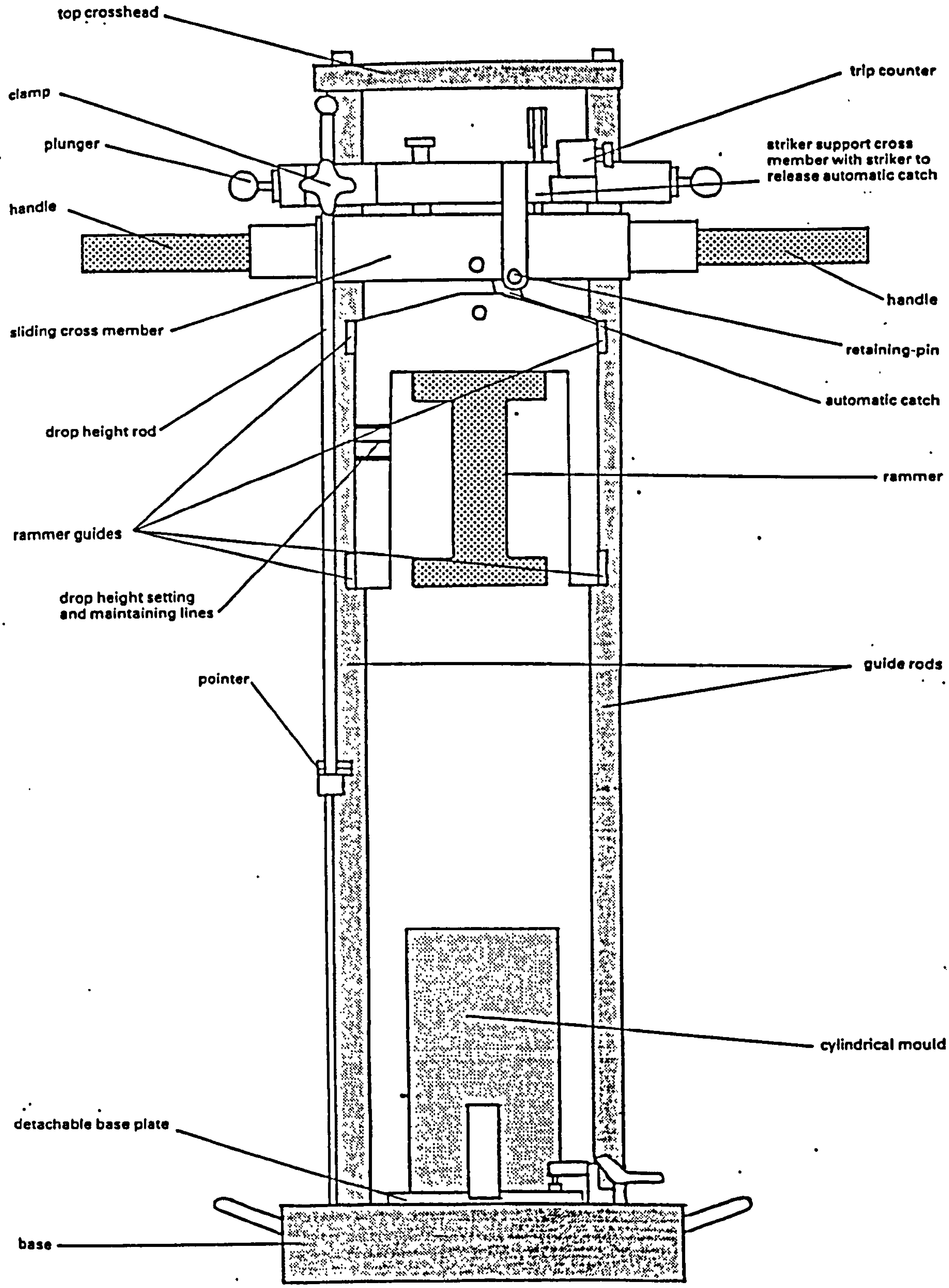


Figure 5.12 Moisture Condition Value Test Apparatus (ELE Manual, 1993).

in order that it can operate effectively in unfavourable site conditions. Figure 5.12 portrays the apparatus in simplistic form and Table 5.8 gives the different parts of the apparatus and their measurement.

Apparatus	Measurement
Dimensions Height Base diameter	 950 mm 300 mm
Mass of rammer assembly	7 kg
Diameter of cylindrical rammer	97 mm
Height of drop	250mm
Mould internal diameter	100 mm
Mould internal height	200 mm
Total mass of apparatus including Empty mould	60 kg
Mass of soil sample	1.5 kg

Table 5.8 Moisture Condition Value Apparatus and Associated Measurements.

5.12.2.2 Sample collection and preparation

Samples were taken from each of the two case study sites in Chapter Four. The material at both Site Alpha and Beta was homogenous in terms of geotechnical characteristics, although there was some degree of variation for *in situ* moisture contents. This was to be expected as explained in Section 5.9.4, and, ultimately, would not detrimentally affect the final MCV result.

The soil sample was first passed through a 20 mm BS test sieve, to separate the larger particles and clods, which were discarded (BS 1377: Part 1 (BSI, 1990)). In the London

Clay samples all the material passed, while the small amount of gravels from the Mercia Mudstone was removed. Problems may arise when the materials are dry, as hard clods can form which can only be removed by crushing. Immediate testing on-site would reduce the probability of this since the material would generally be at or near to its natural moisture content providing more ease of workability.

The Moisture Condition Value was taken at varying moisture contents necessitating addition of moisture (water) to the samples. Upon the addition of moisture, the samples were placed in a sealed container to encourage uniformity of moisture content (Parsons & Toombs, 1987). The characteristics of the clay minerals ensured that there was no immediate homogenous distribution of moisture, therefore the wetted clays were allowed to stand for a minimum of 24 hours before the testing was completed. This test was, as a result, time consuming in the laboratory due to the limitations of ensuring even moisture distribution. However, in the field this procedure would be unnecessary since laboratory calibration of the samples means that materials could be tested immediately at their *in situ* moisture contents (Dennehy, 1988).

5.12.2.3 MCV Test

Tests on 1.5 kg samples of London Clay and Mercia Mudstone were completed in accordance with BS 1377: Part 4, as instructed by Cl.: 632 of the Specification for Highway Works (DoT, 1991).

The test method uses the record of *n* (typically 1 - 128) attempts required for a 7 kg rammer, dropped over a distance of 25 cm, to compact a specific sample weight until its density can no longer be reduced, i.e., a full state of compaction has been achieved. This state is established when no change in depth of the sample, within the mould, is recorded for at least two consecutive measurements. This is in contrast to the Proctor measurements which are based upon given amounts of compactive effort being applied to a sample.

Moisture content is determined using a representative sample of the tested material (compacted soil) which has been removed form the mould. The weight of the sample is taken before and after drying (minimum of 24 hours), as instructed by BS 1377: Part 1, (BSI, 1990) and the moisture content expressed as a percentage.

The MCV test may be completed at increasing moisture contents controlled by the operator in order to determine the MCV moisture calibration. The form of the test is given by Parsons (1979) who also suggested that it could be used as an earthworks control without the continual use of Atterberg limits or moisture testing (Parsons & Boden, 1979).

Moisture content calibration of the sample is required at the primary stages of kit utilisation in order to determine the envelope of usable material. Once this has been achieved, the upper and lower limits of the MCV can be calculated and further procedures would not, under ideal conditions, require continual moisture content testing for calibration.

5.12.3 Testing Procedure

Prior to testing the samples, calibrations were made on the apparatus in order to check the drop height (Figure 5.12) was exactly 25 cm. This was rechecked at regular intervals throughout the procedure with each different sample.

The samples for MCV testing were placed in the mould and the rammer was used to compact the soil. A sturdy permeable plate, 1 cm in thickness, was placed between the rammer and the sample in the mould. This would prevent contamination of the rammer, i.e. clay sticking to it may cause friction within the mould, and provide a relatively even surface for distribution of the rammer weight.

The measurement of the penetration of the rammer into the mould was then recorded, as opposed to the change in density of the sample, using a Vernier Depth Gauge. The trip counter on the instrument automatically recorded the number of blows (*n*).

5.12.4 Calculations

The penetration of the rammer for each blow at different moisture contents was measured. Calculations are based on the change in penetration between a given number of rammer hits (*n*) and four times as many blows (4*n*) i.e. 1 and 4, 2 and 8 etc. The change is calculated and plotted on a logarithmic scale against *n* (initial number of blows) as in Figure 5.13.

The steepest straight line is that drawn on the graph through the points before or passing through the 5 mm change in penetration mark (Figure 5.13). It must be stated that there is possible margin for error at this point due to variations in the interpretation of the instructions for procedure.

The MCV can be defined from Figure 5.13 as :

$$MCV = 10 \log_{10} B \quad \text{(Parsons \& Boden, 1979)} \qquad \text{(Equation 5.3)}$$

B is the number of rammer blows at which the penetration equals 5 mm, to the nearest 0.1. Since a large number of blows may be required to remove the last remaining air voids in the material, a change in penetration of 5 mm was chosen to *'represent the point beyond which no significant change in density occurs'* (Barnes, 1995).

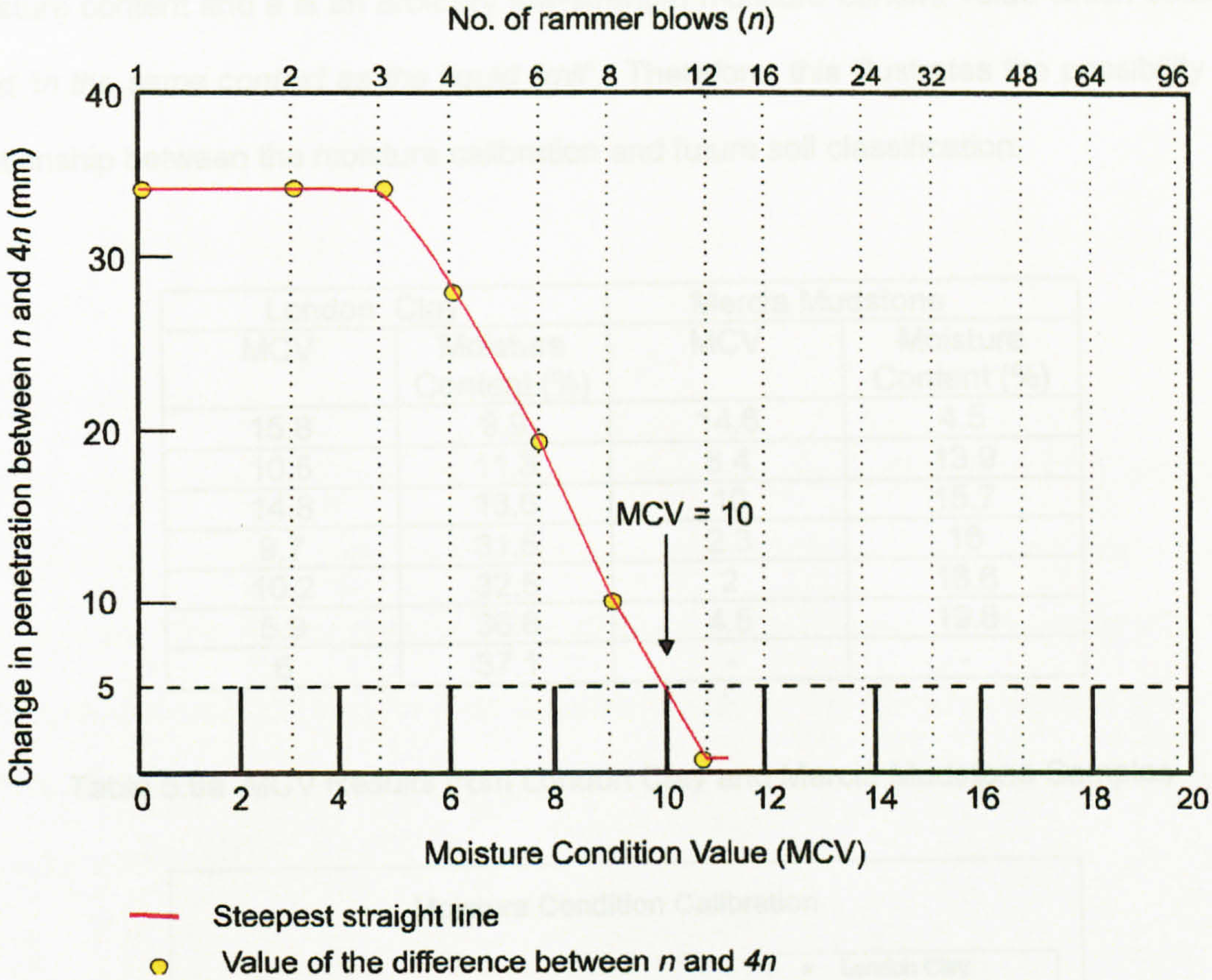


Figure 5.13 Example of a Plot for an MCV calculation.

5.12.5 Moisture Content Calibration

Typical calibration lines can be achieved for the material at various moisture contents. The relationship between the moisture control and the MCV is given by:

w (%) = a - b (MCV) (Parsons & Boden, 1979) (Equation 5.4)

where w is the moisture content

a is the moisture content (%) at MCV = 0, (i.e. the intercept from Table 5.9b) *b* is the slope of the line from trend lines such as those shown in Table 5.9b.

Parsons & Boden (1979) state that *b* is indicative of the sensitivity of the soil to changes in moisture content and *a* is an arbitrary low-strength moisture content value which could be used *'in the same context as the liquid limit'*. Therefore, this illustrates the possibility of a relationship between the moisture calibration and future soil classification.

London Clay		Mercia Mudstone	
MCV	Moisture Content (%)	MCV	Moisture Content (%)
15.8	9.9	14.6	4.5
10.5	11.3	8.4	13.9
14.8	13.6	10	15.7
9.7	31.5	2.3	16
10.2	32.5	2	18.6
5.9	36.8	4.5	19.8
6	37.1	-	-

Table 5.9a MCV Results from London Clay and Mercia Mudstone Samples

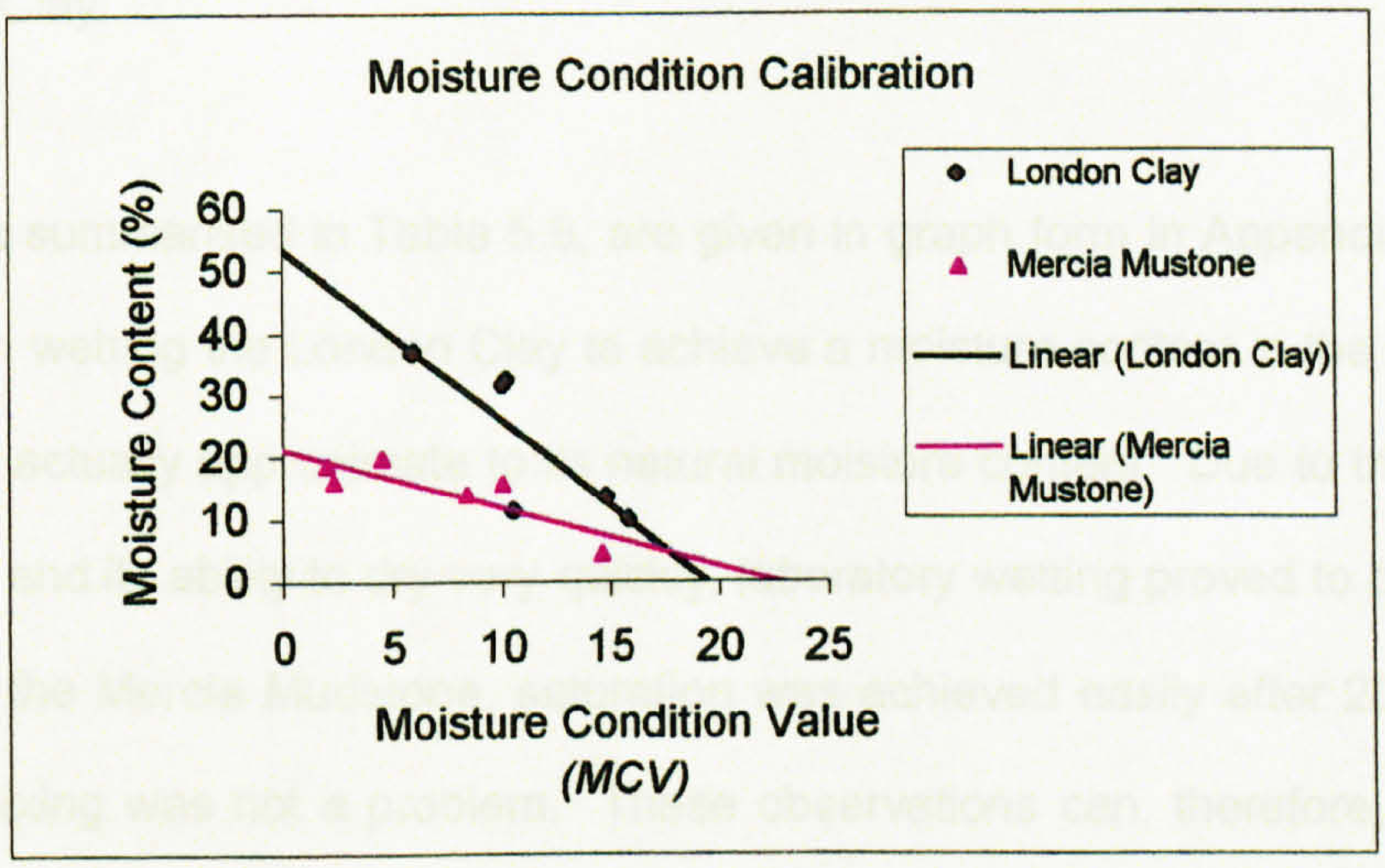


Table 5.9b MCV Versus Moisture Content (%)

Parsons and Boden (1979) put forward a proposal for a method of soil classification based upon the use of parameters *a* and *b*. However, Ewan & West (1983) concluded that soil classification according to the Casagrande system using this method was inconclusive and inefficient. In addition, Green & Hawkins (1987) agree that such a system would be unworkable.

5.12.6 Analysis of Results

5.12.6.1 Results

Throughout the plotting of the difference in penetration measurements (MCV), anomalies and outliers were noted either side of the steepest straight line, particularly in the London Clay sample. The results (Figure 5.9) indicate a general trend in increasing MCV with decreasing moisture content for both samples. This trend is more apparent in the Mercia Mudstone sample for which the moisture content results were not as diverse as compared to the London Clay.

The results, as summarised in Table 5.9, are given in graph form in Appendix 9.4. There was difficulty in wetting the London Clay to achieve a moisture content in the range of 20 - 30 %, which is actually approximate to its natural moisture content. Due to the fine nature of the material and its ability to dry very quickly, laboratory wetting proved to be a problem. In the case of the Mercia Mudstone, saturation was achieved easily after 20 % moisture content and mixing was not a problem. These observations can, therefore, be linked to the on-site difficulties of clay liner compaction. If the material is not at a suitable moisture content for adequate compaction, it would be extremely difficult to wet or dry it, especially if bulk quantities were required.

5.12.6.2 Seepage from apparatus

The *ELE* manual instructions (ELE, 1993) and some research (Dennehy, 1988) state that the point of seepage from the base of the mould, should it occur, must be noted. However, if the test was continued after this point, it would affect the final results of the moisture condition value. For the purposes of this research, testing continued and the seepage point noted (Appendix 9.4). Therefore, this accounted for the anomalous, rogue results which are at the bottom of the MCV compaction curves. If the plotted results were ignored, then there is little reason to continue the test since seepage would then generally continue to occur with each blow, reducing the size of the sample. This problem was more prevalent in the London Clay samples at their higher moisture contents due to the fine nature of the particles. The seepage could be attributed to the fact that there was a loose fitting base on the apparatus to avoid the entrapment of air within or around the sample. This worked well in samples which were drier than OMC but those above optimum proceeded to seep.

5.12.6.3 Evaluation

Cobbe & Threadgold (1988) give data for the MCV test on both London Clay and Mercia Mudstone as shown in Table 5.10. The lower limit for the range of moisture contents over which the Moisture Condition Calibration is reliable is the optimum for maximum dry density under Moisture Condition compaction (Dennehy, 1988). The upper limit is the point at which density ceases to decrease with decreasing ω. Cobbe & Threadgold (1988) state that if the γ_b was used, as opposed to the γ_d, the upper limit can be identified during the test and before moisture determinations and, also, that the upper limit varies greatly with the type of material under test. Table 5.10 illustrates that the OMC will vary with the parameter which is chosen for the test, i.e. measurement of MCV or BS Heavy Proctor and

Soil Type	OMC (BS Heavy Proctor (γ_d))	OMC (γ_d)	MCV	OMC (BS Heavy Proctor (γ_b))	OMC (γ_b)	MCV
Mercia Mudstone	15.5	15.3	16.1	16.5	16.3	14.6
London Clay	18	20.7	15.2	19	22	14.4

OMC: Optimum Moisture Content (%)

Table 5.10 MCV and OMC Results for Dry and Bulk Density.

Adapted from Cobbe & Threadgold (1988).

γ_d or γ_b.

The MCV test results from Table 5.10 indicate that the moisture content of the London Clay should be in the region of 20 - 22 % to achieve an ideal MCV of 15.2 to 14.4. The DoT (1991) stated that a suitable MCV should be in the region of 14.5 for compaction works. Therefore, from the results above this would be 16.3 % OMC for the Mercia Mudstone and 22 % OMC for the London Clay. The results from the samples in the previous chapter indicate a moisture content of 13.6 % for the London Clay and 4.5 % for the Mercia Mudstone. For the London Clay this is too low and for the Mercia Mudstone it is excessively low. Some moisture content results equivalent to that of the above were achieved on-site and compaction completed. However, a suitable degree of compaction was not achieved to concur with the QA.

Barnes (1995) states that the minimum acceptability criterion for the MCV is about 8 *'to the limits of strength for trafficability purposes as well as for the stability of an earth structure'.* Under these circumstances, higher moisture contents for the London Clay (36.8 % +) or Mercia Mudstone (16 % +) would not attain the required specification.

In summary, the results achieved by the investigation in this thesis only partially indicated the true properties of the clays. Therefore, these results could not be relied upon in order to determine the clay material suitability for compaction to construct landfill liners. The following sections investigate possible explanations for this.

5.12.7 Examination of the Apparatus and Procedure

This investigation noted that the apparatus was under considerable strain when testing drier samples. Continued vibration of the smaller parts and guide columns may give rise to loosening of parts over the long term which was confirmed by Green & Hawkins (1987) during prolonged testing.

Since there were problems with the equipment during laboratory testing, (namely due to the interpretation of the procedures and apparatus set-up from the manual), it was seen that these could have been compounded under site conditions. It was also noted that, as with any testing procedure, the likelihood of variation between different laboratories could be high (Parsons & Toombs, 1987), especially since the MCV procedure is not a regularly completed test.

Indeed, the procedural instructions do possess a degree of ambiguity in terms of the interpretation for setting up the apparatus and, additionally, for definition of the results (Dennehy, 1988). This is illustrated in the conflicting background research (Dennehy, 1979 and Parsons, 1979) which was presented at the ICE Conference on Clay Fills (Anon, 1979). The differences exist predominantly in the interpretation of the MCV curve. TRRL Scotland have adopted a different approach to that of the TRRL in England.

5.12.8 Analysis of MCV Interpretation Techniques

There may be differing interpretations of the MCV calculation due to variations in the steepest line through the 5 mm change in penetration axis. The ELE manual (1993) solely states that *'the steepest possible straight line shall be drawn through the points immediately before or passing through the 5 mm change in penetration value'.* This appears to be ambiguous in that there is no indication of whether this is a best-fit line of all the points, or whether it should include two values either side of the 5 mm value. TRRL Scotland (LR 750) (SDD, 1983) states that the line must go through *all* the test points to intercept the 5mm line. Conversely, the TRRL in England state that the test curve must be *projected* through the change in penetration line. In the event, this could lead to variations in results with a difference in value of as much as 2 (Green & Hawkins, 1987). Interpretation for this investigation employed the steepest line was in line with the trend of the data on a point by point basis in line with TRRL Scottish guidelines (SH 7/83) (SDD, 1983).

Figure 5.14 Illustrates the differences in MCV which may occur, in this case a difference of 1.8. This plot was taken from results achieved during this investigation. The final example interpretation (red line) indicates a best fit trend line between point immediately each side of the 5 mm change in penetration line. MCV interpretation is, therefore, an important consideration when using Codes of Practice and guidelines which stipulate a minimum or maximum MCV for earthworks.

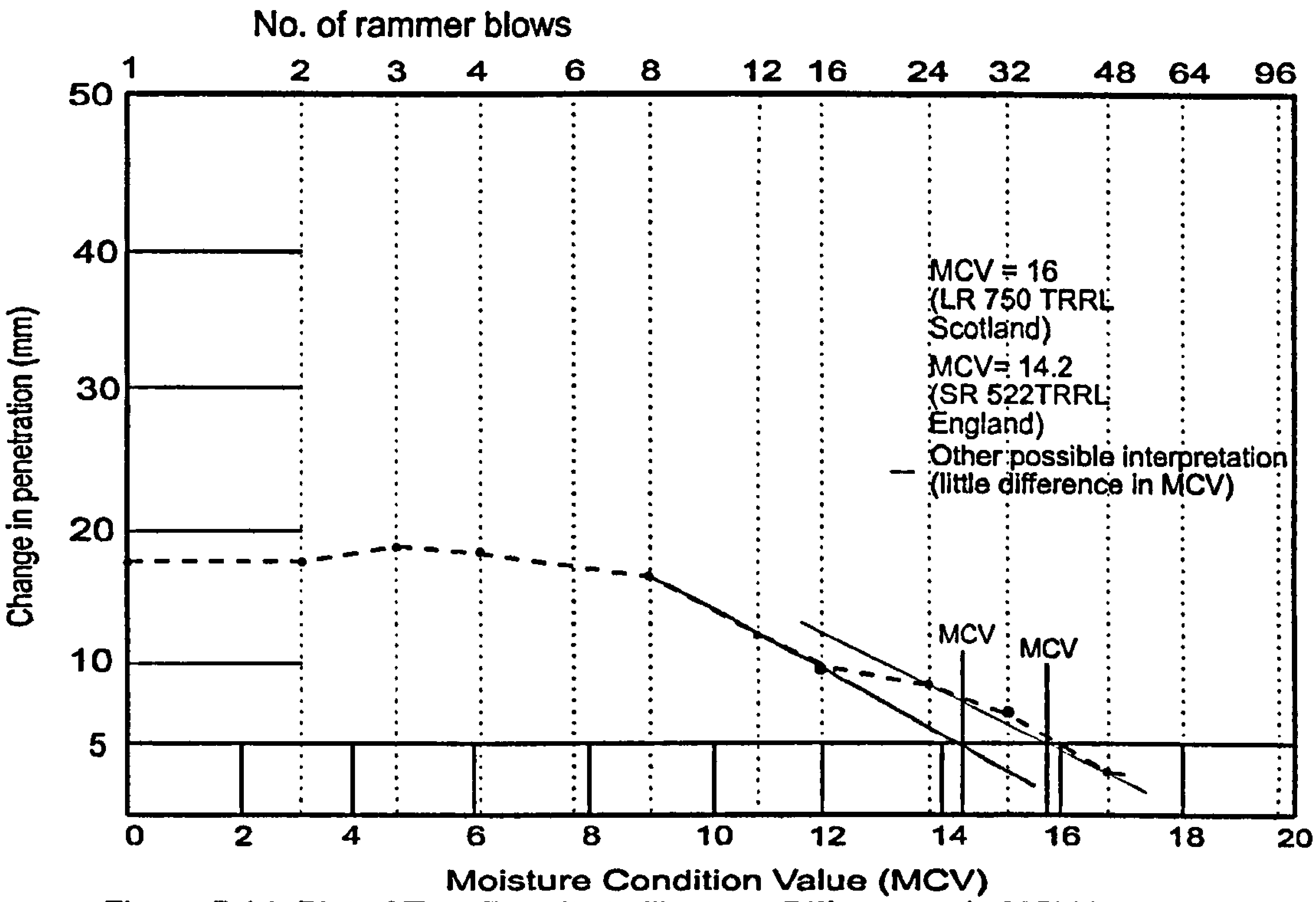
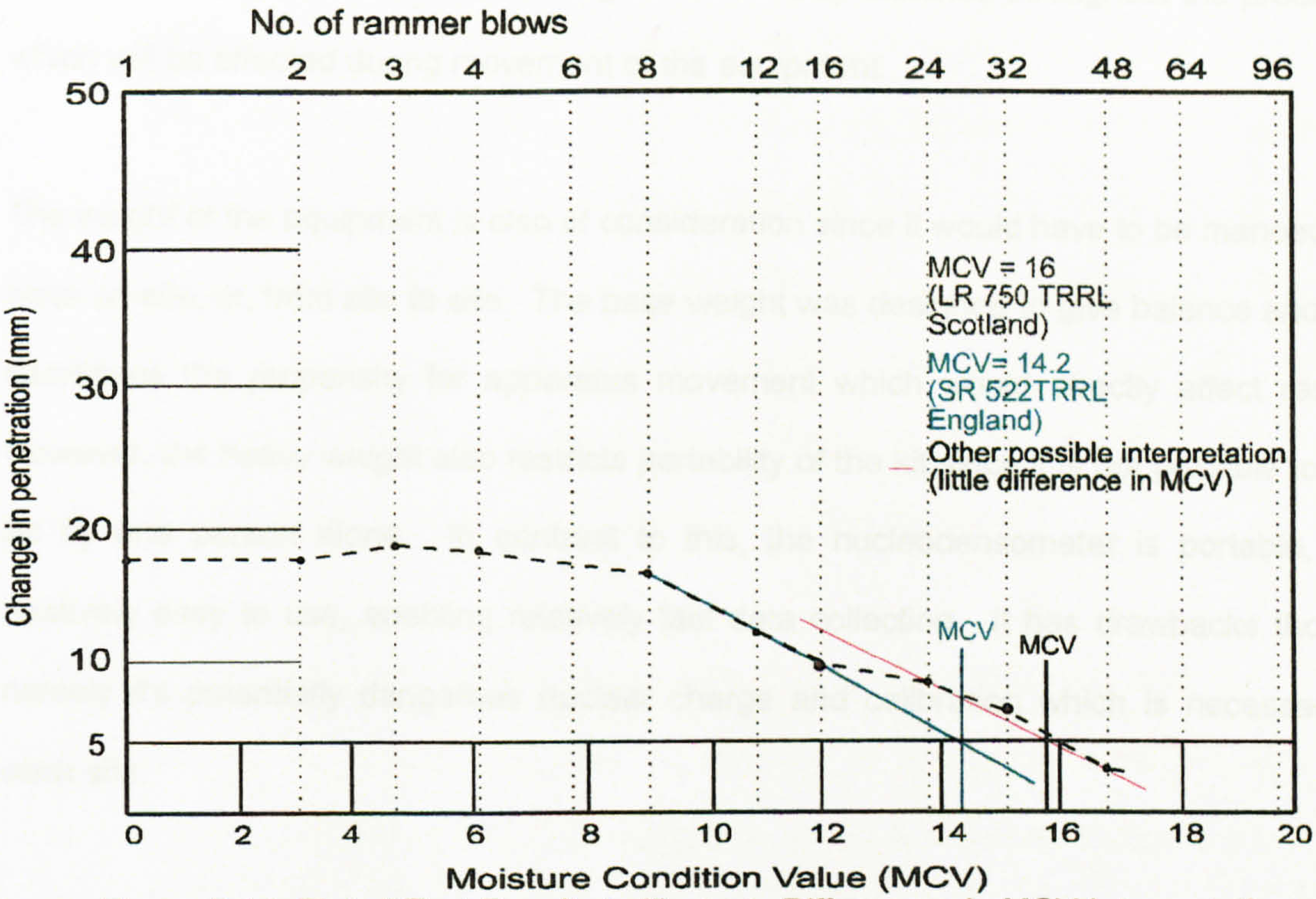


Figure 5.14 Plot of Test Results to Illustrate Differences in MCV Interpretation

Parsons and Toombs' (1987) study on the 'Precision of the Moisture Condition Test' employed ten laboratories in order to determine the repeatability and reproducibility of the MCV test. Their report determined that there could be procedural errors involved with the test, such as those oultined previously, and efforts have since been made to reduce these. The main problems arose with the apparatus, specifically the rammer, where its free-fall may have been inhibited to produce undetectable errors, primarily due to the build up of friction.

This current investigation revealed the apparatus was primarily suitable for use in the laboratory as opposed to on-site. Site conditions are not always favourable, requiring apparatus which is not too sensitive to movement and to conditions which may be experienced throughout earthworks and construction. For example, Parsons (1976)



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This current investigation revealed the apparatus was primarily suitable for use in the laboratory as opposed to on-site. Site conditions are not always favourable, requiring apparatus which is not too sensitive to movement and to conditions which may be experienced throughout earthworks and construction. For example, Parsons (1976) indicated the importance of maintaining the same drop distance throughout the procedure which will be affected during movement of the equipment.

The weight of the equipment is also of consideration since it would have to be manoeuvred once on-site, or, from site to site. The base weight was designed to give balance and also decreases the propensity for apparatus movement which would directly affect results. However, the heavy weight also restricts portability of the kit since it is not possible to pick up by one person alone. In contrast to this, the nucleodensometer is portable, and relatively easy to use, enabling relatively fast data collection. It has drawbacks though, namely it's potentially dangerous nuclear charge and calibration which is necessary at each site.

5.13 DISCUSSION

This research has addressed the main requirements for geotechnical testing of clays used in the construction of engineered landfill liners. It has demonstrated the main problems associated with current testing procedures and, also, highlighted possible areas for concern with regard to ensuring the best possible construction practice on-site.

Present methods of landfill liner construction monitoring are limited. For example, evidence has been presented to indicate that preferential flow paths exist in engineered clay liners, even after stringent QA. These flow paths restrict the precise measurement of permeability in both the short and the long term proven through laboratory and field trials. However, there is a potential for these pathways to become blocked and, therefore, less influential through time, provided chemical and biological precipitation and attenuation occurs.

Landfill liner suitability is predetermined through prescriptive controls on the permeability and thickness, for example. Performance controls may provide a more real approach, based on the characteristics of the individual materials which must be verified throughout construction procedures. Performance controls also enable the assurance of a degree of QA throughout the construction of the site. The MCV test provides such an example, although to date it has not proved successful for on-site liner construction monitoring. It clearly has a great deal of potential as a rapid monitoring approach.

This investigation has given an indication of the validity of the MCV test and, also, a view of its practicality for on-site verification of clays. The results achieved indicated that difficulties may be experienced with the apparatus, which is reiterated by the fact that tests in different laboratories provided a range of results. The current available guidelines are not sufficiently stringent for the testing of clays for landfill applications. Therefore, there is a recognised need for stipulated Codes of Practice which can be employed by site engineers.

The prime concern of this research is directed towards the operation and workability of the apparatus. Currently, it is portable but heavy and cumbersome, and, if used on-site as a regular testing procedure it would need to be refined. However, once on-site and in use, the technique could be applied to samples at varying moisture contents to provide an envelope of workable material which fits within the prescriptive permeability limitations. It may be true that a thinner liner can achieve the permeability requirements, however present Codes of Practice and guidelines, as employed by regulators, still require the minimum of 1 m for a single clay liner.

Since current methods, including the nucleodensometer, still give a degree of understanding of the materials characteristics, new testing procedures must prove that they provide a more reliable result or are faster and easier to use. In addition to this, the methods must be widely applied in order to encourage use and to assist in the uniformity of testing methods, the results of which can be reliably compared. Importantly, it must be stated that monitoring methods, such as the MCV, do not provide an alternative to detailed laboratory testing procedures for permeability. In addition, the MCV cannot guarantee that the permeability has finally been achieved, since this is ultimately related to the compactive process and lift thicknesses, for example. This last point highlights possible areas for future research, using MCV test results to relate to lift thickness, compactive effort and to compare results obtained with permeability measurements.

This research has highlighted existing discrepancies since the MCV test was originally proposed in order to facilitate the five criteria outlined by Green & Hawkins (1987) in Section 5.12.1. With reference to these points, in general, operator error is still a problem although this does not pose a great problem. The apparatus can be used on clays, chalks and aggregates, illustrating its use for a range of materials. Immediate results may be achieved on site but their acceptance is still debatable and, finally, the sample may be larger but there is an increased propensity for seepage at higher moisture contents.

The conclusions drawn from the MCV testing directly illustrate the requirement for applied research in this field. The application may, in the future, be developed in order to fulfil the demands of the landfill construction industry. It would reduce the need for regular on-site permeability monitoring which could substantially reduce the construction time for larger projects. The test is cheap, fast and not operator demanding, giving it advantages over other testing procedures once the protocol has been defined. The MCV must also gain reputability as a QA method, through inclusion within recognised Codes of Practice.

The concept of Design Realisation can be applied to the use of the MCV test on landfill sites. Theoretically, the idea would appear relatively sound, however, difficulties with the apparatus and the samples themselves, i.e. seepage, have in practice demonstrated that this was not necessarily so. Design Realisation is, therefore, a suitable concept to illustrate the differences which exist with respect to the theory, laboratory and on-site practice.

5.14 SUMMARY

- Soil variability is one of the fundamental criteria affecting engineering geological investigations. As such, thorough detailed procedures are required for site and ground investigation surveys (Fookes, 1997) in order to minimise future risk to landfill projects.

- There is a recognised requirement for a standard suitability monitoring method for soil liners which can be applied on-site providing fast, effective results. The MCV has the potential to achieve this, however, this current investigation has proven that shortcomings related to both the apparatus and the procedure are still apparent.

- Further refinement of the MCV is necessary if it is to be adopted by the landfill construction industry. The association between prescriptive permeability requirements and limits of MCV suitability must be established in relation to stipulations for landfill liner construction. In its present form it is not recommended for monitoring clay suitability for landfill barriers although it clearly has the potential as a cheap and accurate method of performance monitoring.

- Many of the concepts relating to the geotechnical properties required of clays for landfill liners have been addressed. This can be applied within the framework of Design Realisation in order to demonstrate how the relative theoretical nature of some techniques means that they cannot always be simply applied to on-site construction practices.

6.0 NON-INVASIVE CONTAMINANT MONITORING

6.1 INTRODUCTION

Monitoring has become established as a critical component in the assessment of the integrity of landfill sites through operational to post-closure phases. Landfills require continual monitoring in order to assess:

- The extent and mobility of the contaminant plumes;
- The type and quantification of pollutants;
- Future environmental risk.

Monitoring is a strict requirement stipulated by regulations and legislation necessitating detailed, planned regimes at each site (Reynolds & Taylor, 1996) in order to ensure the criteria outlined by Bagchi (1990) and NWWDO (1995) in Chapter Three.

Research by Griffiths *et al.* (1996) and Well *et al.* (1994) has revealed that there is a fundamental need for strategies which reduce the inevitable time delay between actual sampling and result reporting as identified in Chapter Five. In recognition of this, a technique is proposed encompassing technology which has now advanced to reach promising stages of development, thus enabling possible application in landfill studies.

In this chapter, the main operational monitoring techniques available to date are outlined and an alternative non-invasive approach is suggested. The method proposed is low altitude multispectral airborne remote sensing which utilises the detection of vegetation damage as an indicator of landfill contaminant migration. Importantly, in the early stages of this investigation, it was recognised that the technique must meet unequivocal requirements placed upon it by the waste management industry which would enable its deployment. The criteria can be broken down into three fundamental categories, including:

Planning and costs:

- Economies of scale, i.e. cost effectiveness in terms of financing (initial outlay) and deployment of staff;
- Applicability as a short and / or long term project;
- Time taken for data turnaround, i.e. sampling to reporting;
- Possible training costs.

System operation:

- Ease of use, i.e. would a specialist or highly trained user be required;
- Supply of a backup system, possibly even an invasive sampling method, in the event of failure of the remote sensing technique;
- Ability to detect chronic or acute damage and produce a damage classification.

Environment:

- A non-invasive technique that would not be detrimental to the environment;
- It would not change the existing environmental systems. For example, with existing approaches, groundwater regimes may be altered by uncased boreholes which could facilitate cross contamination.

The aim of the research is to investigate the possibility of an alternative to current basic forms of invasive monitoring i.e., predominantly surface and borehole recordings as illustrated by Figure 3.12. Section 3.13 has outlined the main objectives and requirements for monitoring of landfill sites in the UK. Increasing pressures from regulatory bodies for effective, holistic monitoring systems, designed to operate well after restoration, have instigated advances in the technology employed in monitoring systems. Indeed, the growing necessity for detailed landfill monitoring has encouraged a review of current methods and an investigation of new ones.

This proposed application could reduce overall monitoring time due to the relative ease of data collection. It has been estimated, that data could possibly be collected and analysed over the period of one day in a refined system. This is in direct contrast to the current intensive data collection techniques at ground level which involve sampling at each borehole or surface water source, data entry, data analyses and, finally remediation if the results so required. Remote sensing would not be restricted by problems at ground level, (e.g., land ownership). Furthermore, the technique remains unaffected by man-made features, such as aerial power cables, buried utilities, roads and fencing, some of which can affect ground-based geophysical investigative methods.

The prerequisite for improvement of environmental standards has encouraged the development of highly sensitive and inexpensive equipment (Campbell, 1985). The need for monitoring has been heightened by the concern for the welfare, in terms of health and safety, of operatives on site and nearby inhabitants. Furthermore, the application for new construction projects upon restored landfills, particularly in urban areas, has considerably increased in the past decade, necessitating refined monitoring techniques in order to prove the suitability of the land. Site Alpha, (Chapter Four), provides an ideal example where the site was restored and integrated as part of a business development park shortly after completion of restoration.

A survey of approximately 4,000 UK landfill sites by Roche (1996) indicated that there is a very significant incidence of problematic sites in existence (18 % of *'around 1000'* sites from the survey). The main problems involved LFG migration (48 %), groundwater (15 %) and surface water (27 %) contamination, with less important ones resulting from fires (4 %) and slope instability (6 %). Interestingly, the survey illustrated that almost a third of the problem sites were containment landfills in comparison with the remainder which were attenuate and disperse sites. 5 % of the total sites were constructed after 1990 which indicates that changes within the industry, i.e. stricter controls on landfill design, construction and monitoring have probably contributed to the operation of more effective sites.

6.2 LEACHATE AND LANDFILL GAS MIGRATION

Since migration of gaseous and aqueous solutions from within the 'confines' of a landfill site is to be expected, consideration and classification of the potential risk to the environment is significant and cannot be understated. Predominantly, this risk comprises the contamination of potable groundwater and localised contamination of vegetation and soils. Case study sites (Neumann & Christensen, 1996) give indications of damage occurring 150 m from the waste body and 100 m away from one landfill, the latter of which could be attributed to migration through old mine workings. Additionally, Flower *et al.* (1981) noted gases up to 305 m from the landfill, in the subsurface soils, leading to the widespread death of vegetation. IWM (1998b) details other cases indicating the importance of monitoring through routine or on-the-spot procedures.

An emphasis is now placed upon managing the released gases and leachates through long term control schemes (DoE, 1995b). Under these circumstances, control should imply both the physical and financial steps to eliminate, reduce or transfer the risk upon identification. Principally, the aim is to prevent a repeat of the scenario experienced in 1986 at Loscoe (UK), as described in Chapter Three (Section 3.2.7) (Williams & Aitkenhead, 1991 and WEPC, 1995).

The majority of this research completed on the effects of pollutants from landfill sites, with regard to soil and vegetation damage, concerns the effects of landfill gases. The effects of leachates are mainly linked with groundwater contamination, which, to a lesser extent may also result from migrating landfill gases. Leachate contamination can also be monitored through the surface water pollution it may create. Perched leachate in lenses above the height of the water table may be penetrated by plant roots, particularly the main tap roots, which may lead to future vegetation damage. Discussion in this area is current since recent research has provided evidence that plant roots do not penetrate landfill capping layers. Instead, they extend at shallow depths along the length of the cap, which may comprise either engineered clay or geomembrane sealing layers (DoE, 1996b).

6.3 LEACHATE AND LFG MIGRATION ROUTES

The behaviour of dispersing pollutants from landfill sites is highly complex (IWM, 1998b). Kjeldsen (1996) describes in detail the migrational features of gases through the soil which are mainly dependent upon the surrounding strata (Campbell, 1989b), anthropogenically induced pathways (Clay & Norman, 1989), (e.g. mine shafts), meteorological conditions (Kjeldsen & Fischer, 1995) and barometric pressure gradients (DoE, 1995b). A framework for the migration characteristics of landfill gas (Kjeldsen, 1996), is shown in Figure 6.1.

Gas migration may occur vertically or laterally from a landfill under diffusion or pressure gradients, but is highly dependent upon the ground conditions and the stage of site operation (IWM, 1998b). Capping may decrease the likelihood of vertical migration, possibly placing increasing stresses upon the lateral boundaries of the landfill. LFG migration will also depend upon the stage of waste decomposition which affects the percentage components in the gas as illustrated in Figure 3.1 (Farquar & Rovers, 1973). For example, in initial phases of decomposition, comparatively high rates of Oxygen and Nitrogen will be produced, as opposed to, twenty years on when Carbon Dioxide and Methane would probably be the most prevalent. Geological features, such as fissures, bedding planes, fault planes, fractures and joints are also potentially influential and have

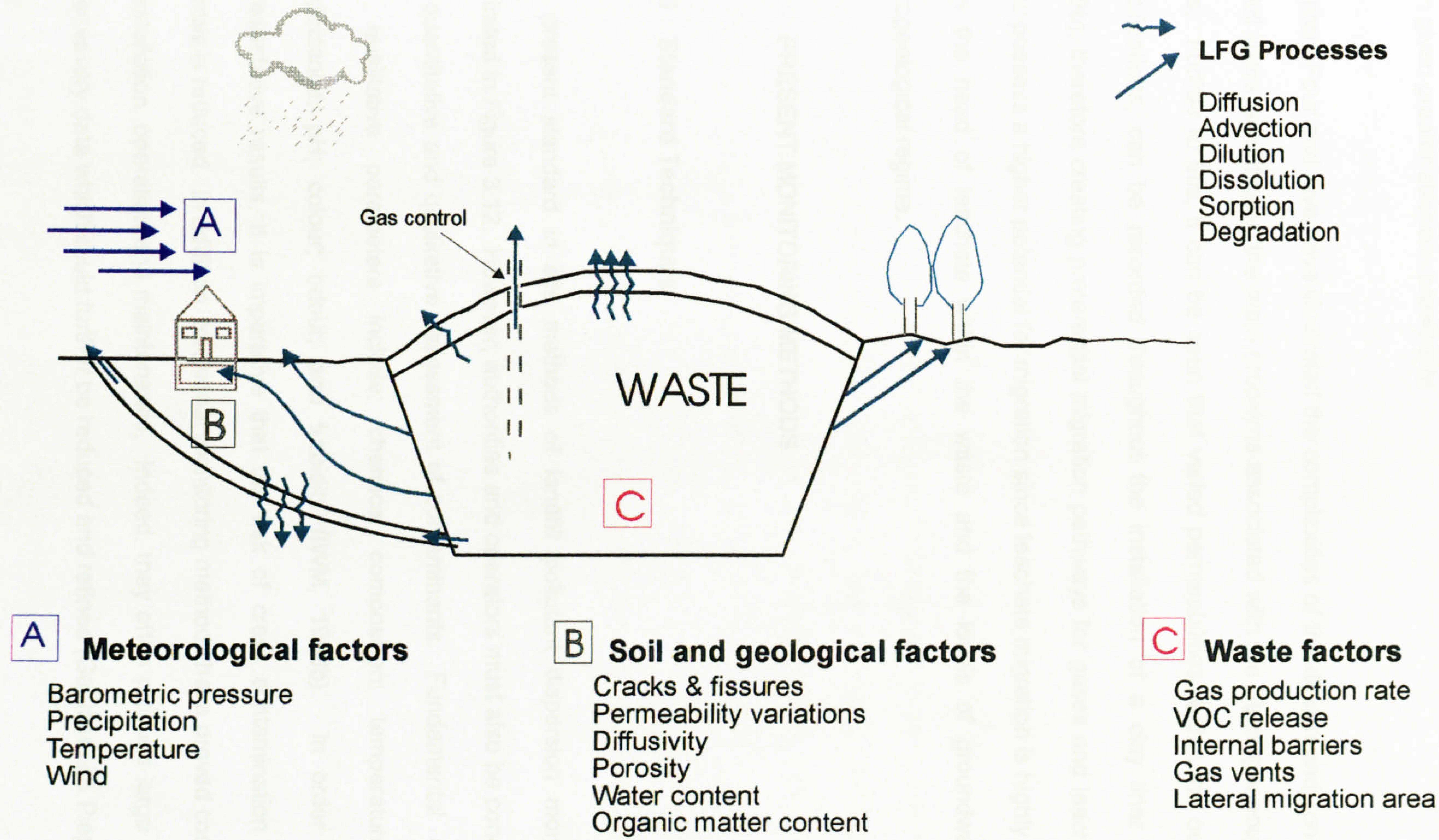


Figure 6.1 Framework for Landfill Gas Migration. (Adapted from Kjeldsen, 1996)

been given greater attention previously.

Chapters Four and Five have illustrated the complexities of the design and construction of landfill liners, specifically, the main problems associated with the heterogeneous nature of clays. Further to this, it can be seen that varied permeabilities, within the outlined liner specifications, can be recorded throughout the installation of a clay liner (Campbell, 1989b), therefore creating preferential migration pathways for gases and leachates. The LFGs possess a higher potential for migration since leachate migration is highly dependent upon the head of leachate within the waste and the levels of groundwater in the hydrogeological regime.

6.4 PRESENT MONITORING METHODS

6.4.1 Standard Techniques

The present standard *in situ* methods of landfill pollutant dispersion monitoring are illustrated in Figure 3.12. However, authorities and operators must also be concerned with the quantitative and qualitative assessment of contaminants. Fundamental quantitative and qualitative parameters include: chemical composition; temperature; specific conductance; pH; colour; odour; and turbidity (IWM, 1998b). In order to provide representative results, it is imperative that the risk of cross contamination during this process is reduced. In addition, traditional monitoring methods have proved costly in terms of installation, operation and maintenance. Indeed, they often produce large amounts of unnecessary data which could further be reduced and refined (Gervasoni & Piepoli, 1989).

Knowledge of the extent of the contaminant transport is of continued importance throughout the lifetime of the site. The existence of recently developed modelling systems provide the ability to estimate quantification of future production and simulate possible migrational pathways for both LFGs and leachates (Metcalfe & Farquar, 1987). Cernuschi & Giugliano (1989) describe two different approaches to estimation which include:

(i) The use of empirical and/or theoretical models of gas generation and migration processes from the landfill;

(ii) Calculation of the emission from measurement of the pollutant concentration above and/or within the surroundings of the waste body.

In fact, perhaps it is a combination of both which is necessary to achieve a representative figure for expected pollutant generation. In addition, the International IAEG Symposium Geoconfine '93 (Arnould *et al.*, 1993) identified *'modelling (either predictive or during the operation of the facilities), together with the in situ monitoring (hydrogeological or geochemical measurements)'* as the key to the assessment and control of safety of confinement systems (Griffiths *et al.*, 1996).

Groundwater sampling is generally completed with the aid of boreholes at variable depths and with multilevel monitoring abilities. These subsurface boreholes have become highly specialised since their secondment from the fields of water abstraction and geotechnical drilling (Kent & Hemingway, 1993).

Cross contamination is reduced by flushing the boreholes up to four times (Bagchi, 1990) before sampling is completed, as is the case during leachate sampling. However, the main complication associated with this type of monitoring is that the well must intercept the point of pollution (leakage plume) in order to detect it (Lee & Jones, 1992b). This is determined by the hydraulic gradients in the underlying strata. The well, therefore, must be down gradient and also take into consideration that the leachates may be higher in density and can sink upon mixing with groundwater (Lee & Jones, 1992b). The frequency of this monitoring is generally quarterly (3 monthly) in order to provide an assurance that there is no contamination of groundwaters and to monitor the progress of the contaminant plume.

Similarly, LFG is measured using probes in wells of varying depths at intervals of 30 to 50 m distance around the site perimeter (DoE, 1996b). Since gas travels in the top layers of soil, shallow probes may be installed alongside deeper ones, beyond the base of the liner. Hand held probes also provide means for gas detection on an 'as required basis', in the event of reported odours, and for spot checks (IWM, 1998b). These probes are generally limited as they are only able to detect a single gas at any one time. Gas concentrations may disperse before the probe is able to detect them thus illustrating a further limitation of the equipment.

LFGs will be produced in higher concentrations over a specified period, possibly between 10-30 years in the lifetime of the site, and production may start anywhere form three months to a year (DoE, 1998b). It is at this stage, therefore, that vegetation will be most susceptible to damage. Once contaminant production is minimised and subject to management strategies and controls, migration is less likely from the site and damage will be reduced dramatically. Studies of bioreactor landfills employing high rate leachate recirculation methods have successfully achieved a faster process of methane production (Blakey *et al.*, 1997), effectively reducing the time taken to achieve the gas production phases as recognised by Farquar & Rovers (1973). The period for the production of leachate and LFG could then be calculated and an intense monitoring programme employed throughout this time. The investigation by Blakey *et al.* (1997), however, was limited due to the short nature of the trials and perhaps by atypical low temperatures recorded within the landfill (19 - 15°C), as acknowledged by the authors.

6.4.2 Geophysical Methods

The application of geophysical techniques in the field of environmental monitoring in the UK has proved to be slow in comparison with the rest of Europe and North America (Reynolds, 1996). However, on the whole, techniques have become more sophisticated, possibly demanding execution by fully trained operators with integration at the conceptual stages of landfill design.

Variable electric conductivites may result from leachate in groundwaters, thus enabling detection and differentiation of contamination at depth. Indeed, higher conductivities may be indicative of zones of contaminated waters (Matias *et al.*, 1994). This technique is of a highly qualitative nature, dependent upon changes in conductivities which, for example, cannot be linked to a particular contaminant. Methods of detection include; ground penetrating radar (Forde, 1996), seismic reflection and refraction, electrical resistivity (Reynolds & Taylor, 1996). Matias *et al.* (1994) highlight the variables involved in geophysical techniques which cannot be overlooked. These include the degree and depth of contamination; the geology of the site; lateral variations; and inhomgeneities within the material. Such knowledge would therefore be required in order to employ a suitable method correctly, although, new ones are available for which this may not necessarily apply (Anon, 1997b).

To date it has not been possible to identify areas of LFG concentration under operational or post-closure conditions using geophysical techniques. However, it may be feasible to use differences in moisture content in order to determine concentration levels of leachates. Geophysical methods are potentially influential for monitoring landfills since they could be comprehensive, relatively easy to operate and cost effective.

Performance monitoring concerns the overseeing of the site construction and operation, in accordance with the operational design and Codes of Practice. It overlaps with contaminant monitoring in some instances. For example, large decreases in leachate head could indicate a catastrophic failure of the liner which may lead to contaminant migration. Performance monitoring could therefore, in the majority of cases, be a primary indicator of possible contaminant migration from a landfill site.

Some geophysical systems can be built into the liner design, therefore providing a constant monitoring mechanism of the integrity geomembrane (Anon, 1997b). As a result, leak detection will occur before the leachate is able to cause contamination to any significant degree. It is based on the detection of differing resistivities which may occur across the liner where it is damaged. Figure 6.2 illustrates an example of a monitoring system which

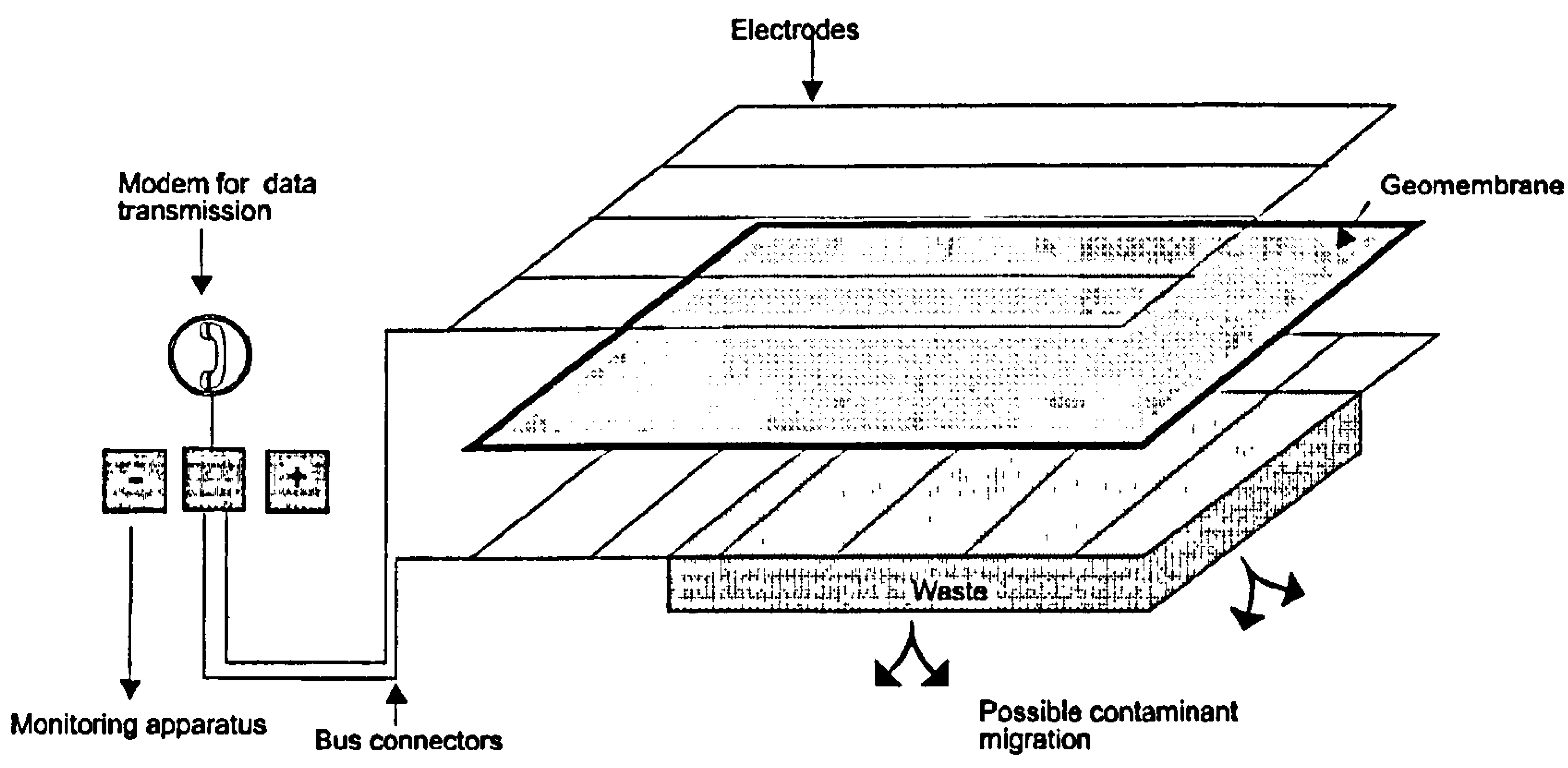


Figure 6.2 A Schematic Diagram of an Integrated Geophysical Monitoring System. (Adapted from Anon, 1997b).

is used alongside a single lining system. These systems are becoming prevalent since they can be integrated into the construction of the site and are predicted to have a relatively long operational lifetime. The latter point is, therefore, also linked to the lifetime of the landfill lining system. It is expected that both systems will operate efficiently until the polluting potential for the waste has been reduced, approximately in excess of 30 years.

6.4.3 Current Remote Sensing Methods

Some waste management companies already integrate basic aerial remote sensing techniques within their standard monitoring strategies. The remote sensing includes techniques such as; black and white photography (Sangrey & Philipson, 1979 and Haynes *et al.*, 1981); aerial thermography (Titman, 1996 and Irvine *et al.*, 1997); infrared photography or a combination of techniques (Well *et. al.*, 1994 and Vincent, 1994) for the identification of stressed vegetation or thermal pollution. Leachates are generally warmer (by several degrees) than ground or surface waters which has enabled their recognition and verification. All of the aforementioned require less detailed knowledge of processing and analytical skills than the methods employing multispectral airborne remote sensing. Currently, they have the ability to present real time data turn around in comparison with other applications. That is, the data acquisition and analyses could be completed in less than a day, in ideal circumstances.

6.5 AIRBORNE REMOTE SENSING OF LANDFILLS

6.5.1 Remote Sensing Systems

Multispectral airborne remote sensing is spatially expansive and non-invasive, having no effect upon the environment being surveyed (Figure 6.3). Thus, it proves able to effectively cover extensive areas, including those which may be difficult to access at ground level. Steven & Jaggard (1995) state that as early as 1972, with the launch of the *al.*, 1980), land classification, planning (Green *et al.,* 1994) and agricultural monitoring (Collins, 1978, Jago & Curran, 1996 and Puhr & Donnoghue, 1996). However, the main influence on the entire use of remote sensing derives from the technological developments used in military applications (Griffiths *et al.*, 1996).

Since the application is effective at covering extensive areas, it has proved to be successful over fragmented study areas. This is particularly important since remote sensing can be used to identify specific locations over an entire area which may later require further detailed ground sampling.

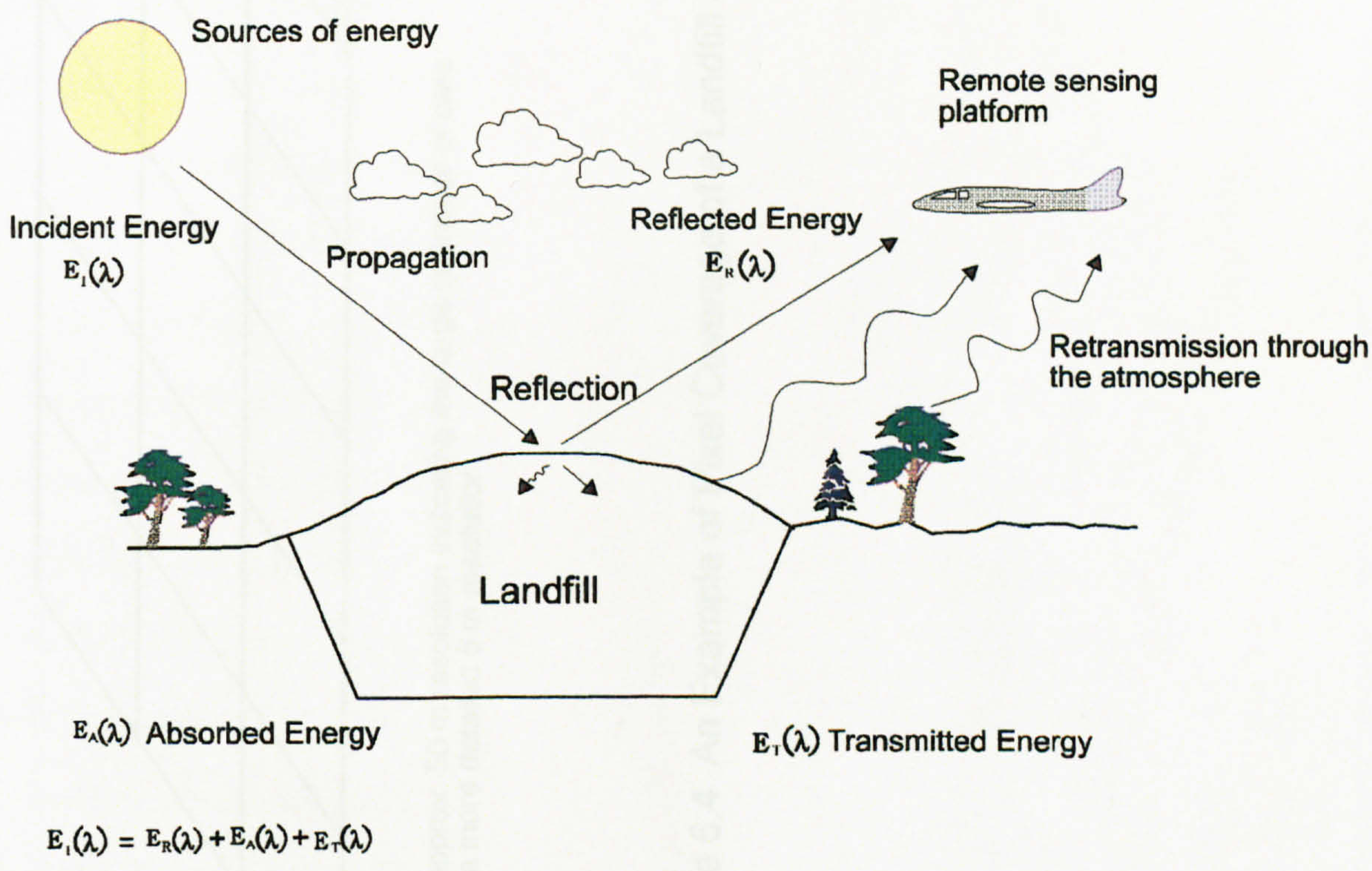


Figure 6.3 A Passive Receptor Airborne Remote Sensing System.

Remote sensing of landfill sites is proposed as a monitoring application which could be applied on both a microscale and a macroscale. Data is recorded in pixels which reflect the resolution of the recorded data as illustrated in Figure 6.4. Therefore, data can be

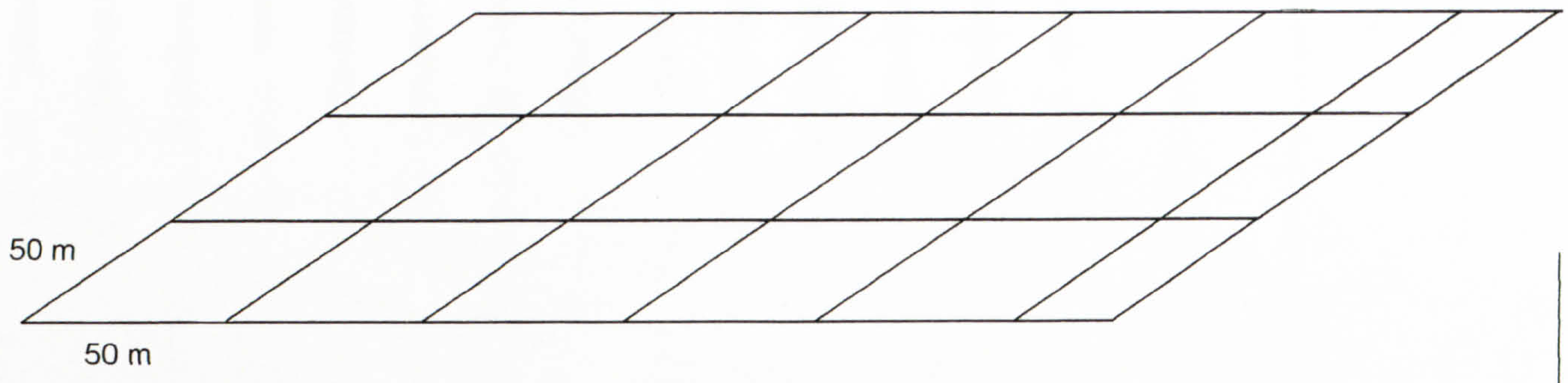


Figure 6.4a Pixel Layout

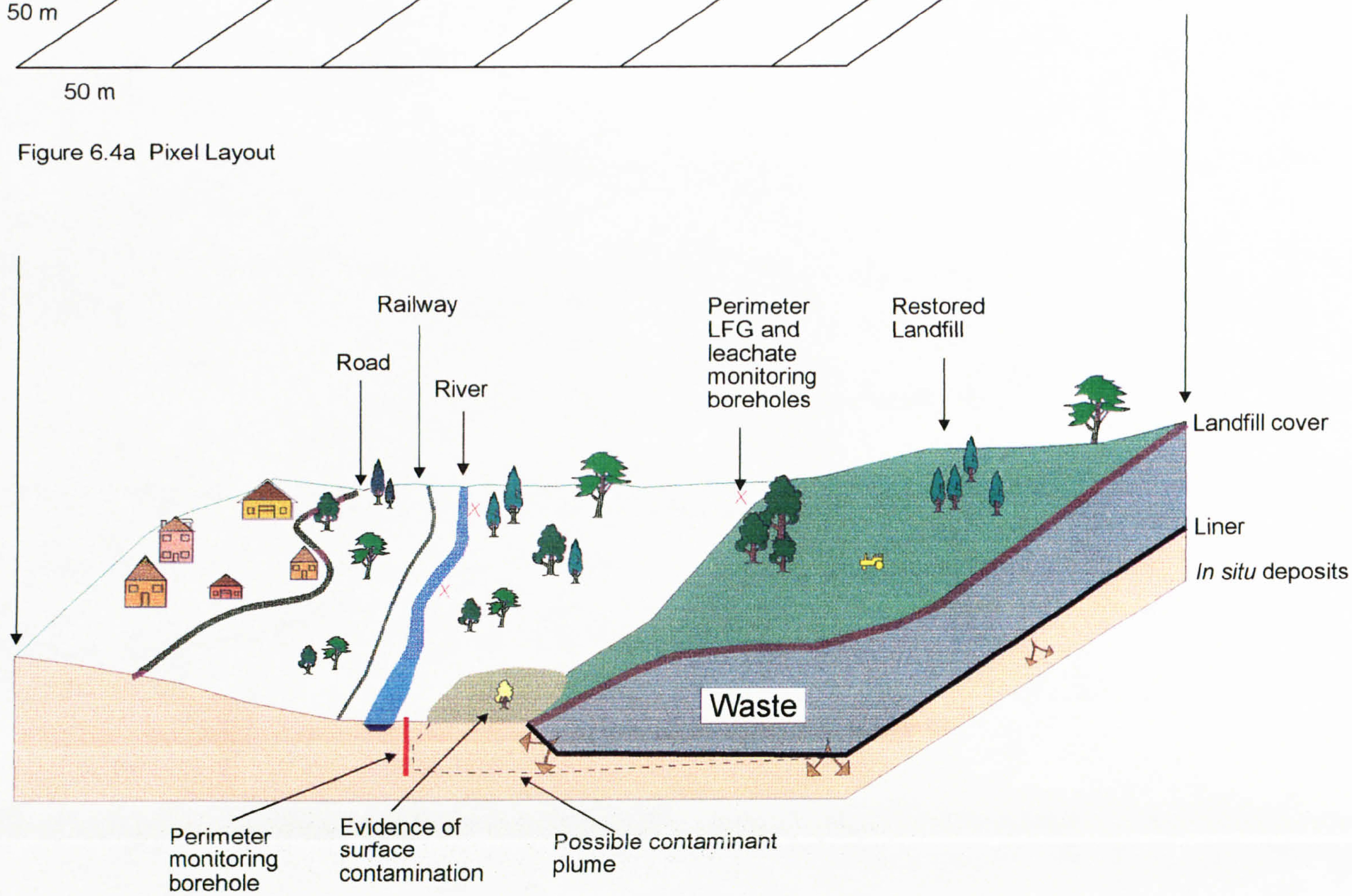


Figure 6.4b Surface Features

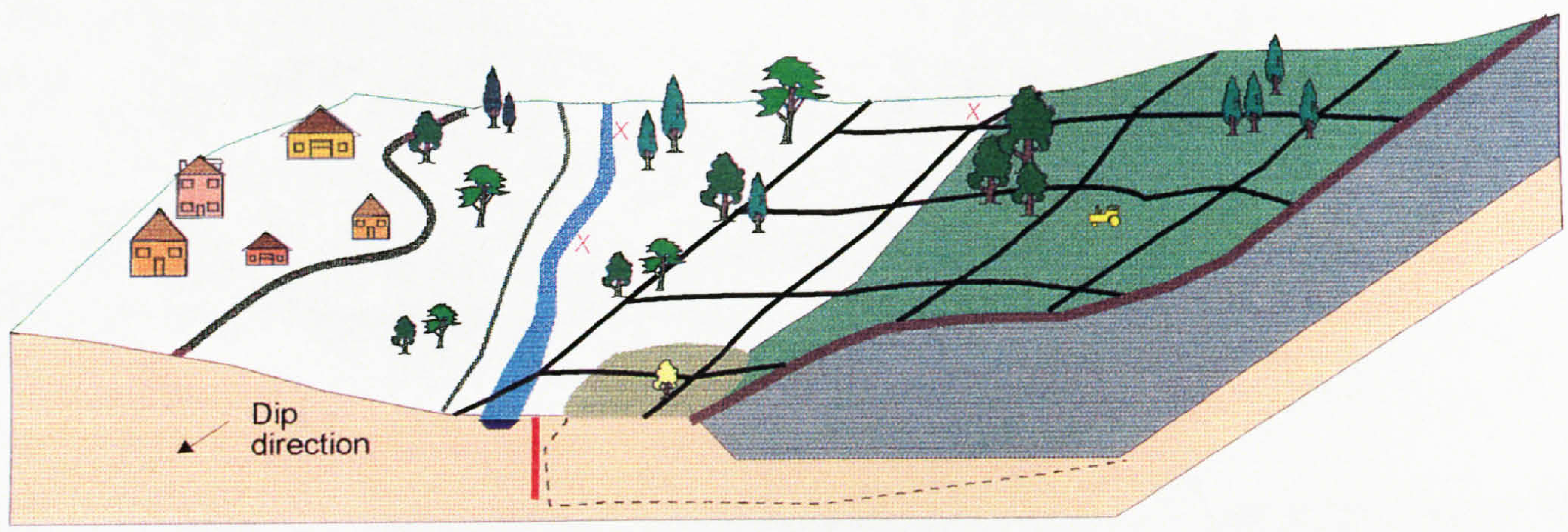


Figure 6.3c Actual Pixel Coverage at Ground Level

Pixel scale approx. 50 m resolution indicating the large quantities of data available at a more detailed 5 m resolution.

Figure 6.4 An Example of Pixel Coverage of a Landfill Site and Surrounding Area the resolution of the recorded data as illustrated in Figure 6.4. Therefore, data can be interpreted at an individual pixel level (for this investigation 5 m by 5 m), or as a whole, in terms of groups or clusters of pixels. Pixels enable interpretation of the most dominant reflectance. Therefore, if a small area of vegetation within the 5 m ground space is damaged, the effect may be cancelled out by the rest of the healthy vegetation. In the future, data may be available at a resolution of 1 m which would enable detection of vegetation damage at individual canopy level.

6.5.2 Previous Applications

Remote sensing can be applied in many fields from the environmental sciences to agriculture and civil engineering. Indeed, Goetz *et al.* (1983) outlined the possibilities for economic exploration and, Rock (1984) further describes its use in geobotanical mapping as an indicator of hydrocarbon microseepage. Horler *et al.*, (1983c) investigated the relationship between a decreased concentration of chlorophyll in leaves and increases in the visible wavelength of plants indicative of geochemical anomalies. Collins *et al.* (1983) and Chang & Collins (1983) have completed studies into the mapping of forest canopies affected by metal-induced stress. The application could be applied to areas of dense forestation, which previously demanded costly and tedious exploration surveys, therefore identifying locations of formerly unknown mineral reserves. These types of geobotanical studies have been influential in proving the ability for the discrimination of vegetation according to specified parameters. They have enabled initial categorisation of the manifestations of stress on vegetation whilst also enabling calculations of the degree of damage. In this way, future studies could assist in locating contamination whilst also enabling monitoring of the extent of the problem.

Garofolo & Wobber (1974) have outlined the results of small-scale studies using aerial photography. Solid waste quantities on landfills could be estimated from high-altitude *generated by a waste source unit'*. The results of their work would contribute towards the planning stages of landfill sites through the demonstration of spatial relationships in a *'single viable format'*. Garofolo & Wobber (1974) recognised the value of their research but realised that progress could only be achieved in co-operation with the waste management industry, a focal point for this current investigation.

6.6 REMOTE SENSING

6.6.1 Theory

The general concept of remote sensing for a non-user is explained by Curran (1985) as the *'observation and measurement of an object without touching it ...it usually refers to the use of electromagnetic radiation sensors to record images of the environment which can be interpreted to yield useful information'*.

The art of remote sensing comprises two basic activities, data acquisition and the then subsequent analysis for interpretation. The former is associated with available technology

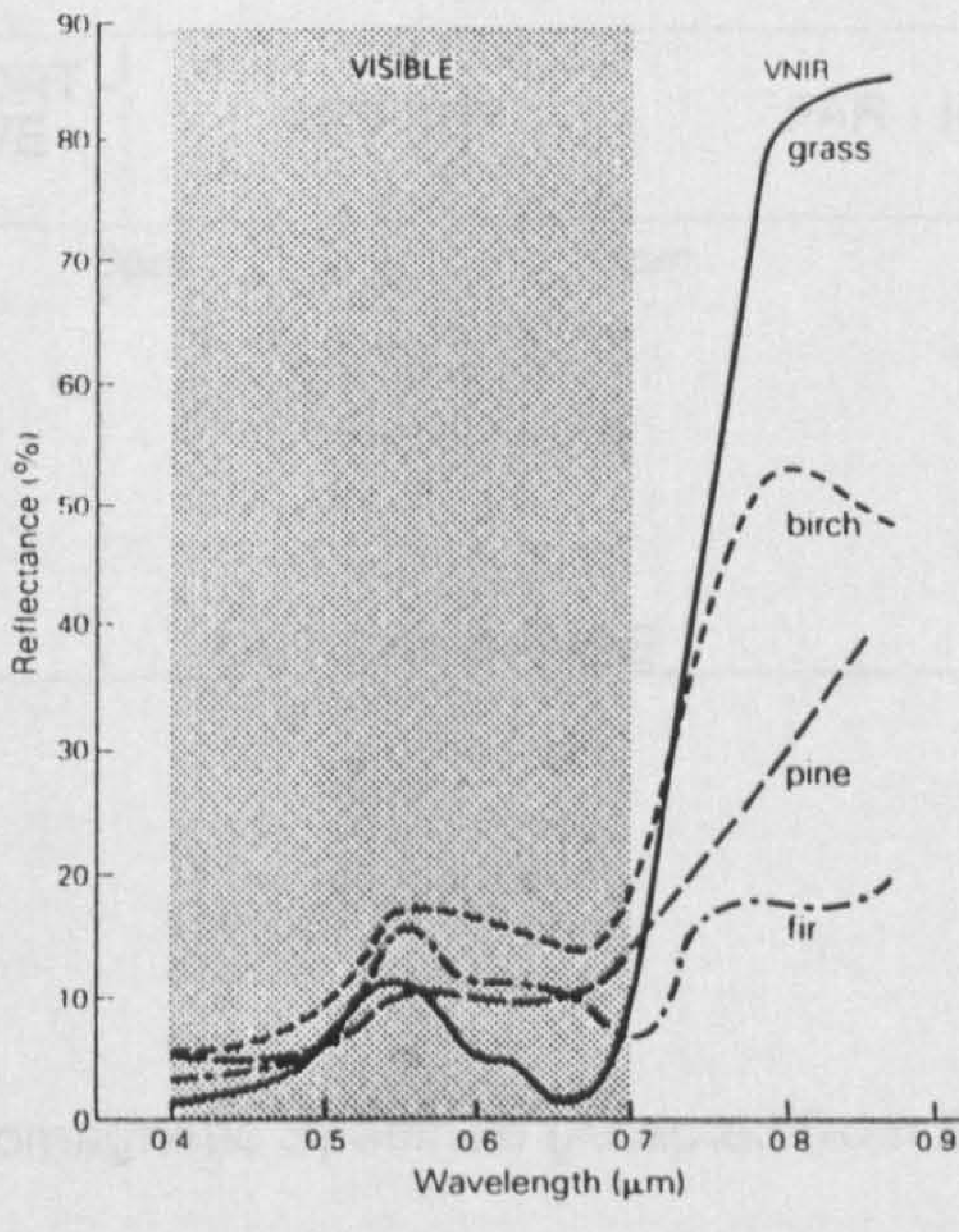


Figure 6.5 The Spectral Reflectance of Various Types of Vegetation (Drury, 1990).

for the remote collection of data and both are inextricably linked. Remote sensing may alternatively be explained as the measurement of how materials reflect and absorb radiation according to the wavelength in the different Electromagnetic (EM) regions (Drury, 1990). The measurement of reflected radiation produces a spectral reflectance curve which is unique for all materials (Figure 6.5) and can enable identification.

6.6.2 Electromagnetic (EM) Spectrum

The electromagnetic (EM) spectrum, as portrayed in Figure 6.6, illustrates the classification of the energy in terms of radiation from 0.02 micrometers (µm) to 100 m wavelengths. The spectrum can be divided between the extremes, comprising cosmic rays and radio waves (Gupta, 1991) into the optical range and the microwave range. The most important

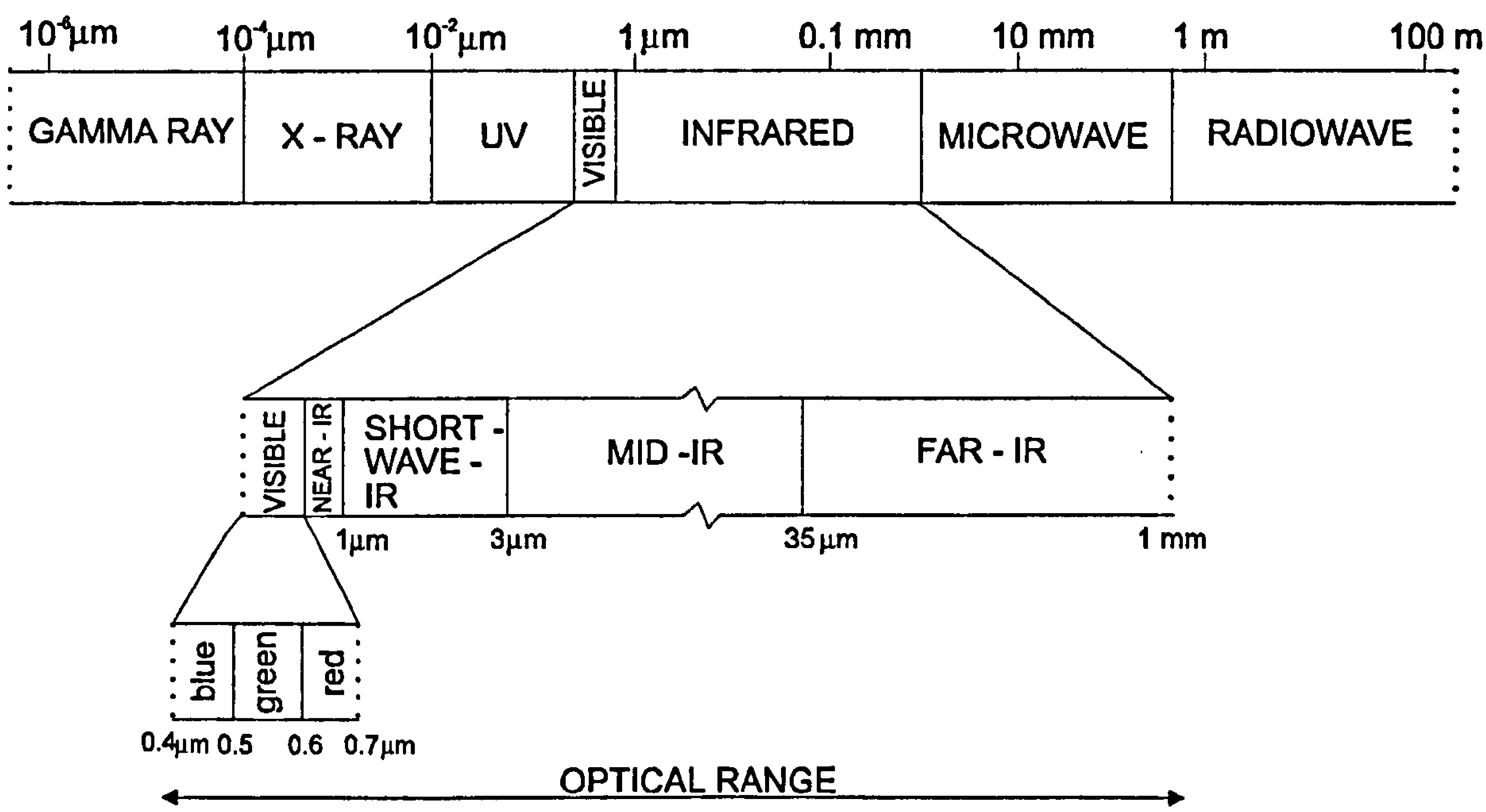


Figure 6.6 The Electromagnetic Spectrum (Adapted from Lillesand & Kiefer, 1994)

general wavebands used in remote sensing are; 0.4 - 14μm (optical; visible to mid Infra red) and 2 mm - 0.8 m (microwave).

6.6.3 Spectral Reflectance (ρλ)

Electromagnetic energy is incident upon features on the earth, resulting in various fractions being reflected (E_R (λ)), absorbed (E_A (λ)), or transmitted (E_T (λ)). The interrelationship

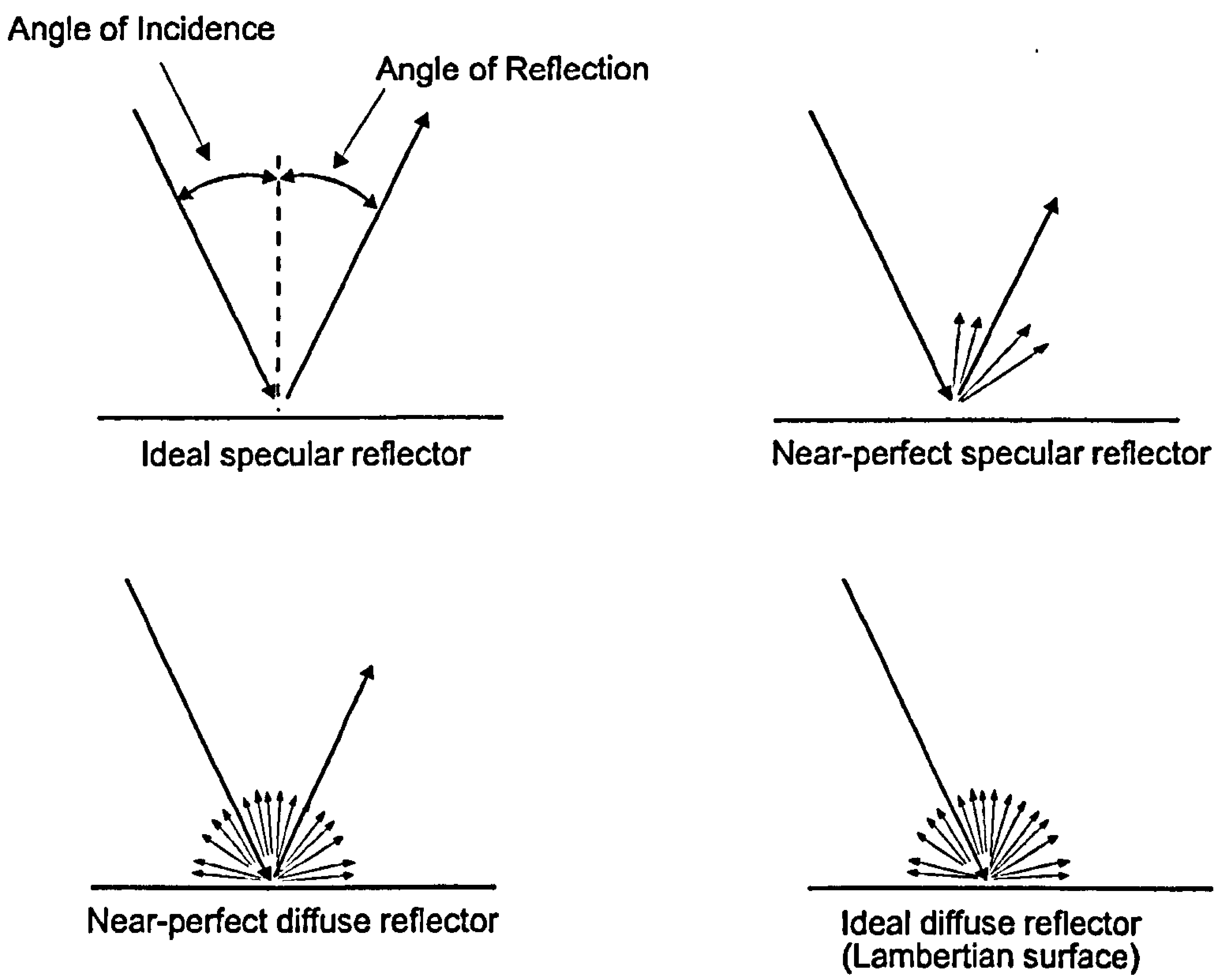


Figure 6.7 Specular Versus Diffuse Reflectance (Lillesand & Kiefer, 1994)

between these can be described as in Equation 6.1 (also in Figure 6.3):

$$E_I(\lambda) = E_R(\lambda) + E_A(\lambda) + E_T(\lambda) \qquad \text{Equation 6.1}$$

The proportions of these, which can be recorded, are influenced by the type and condition of the sensed features. In order to record the energy which is reflected (E_R (λ)), the geometric manner of reflectance from an element must be considered, i.e., specular reflectors (flat surfaces) and diffuse (Lambertian) reflectors from rough surfaces shown in Figure 6.7 (Lillesand & Kiefer, 1994).

Reflected incident energy (E_R (λ)), from the Earths surface can be quantified from the reflectance characteristics of the earths surface features. The measurement, the spectral reflectance (ρ_λ), is measured as a function of the wavelength (λ) and can be defined as the following:

$$\rho_\lambda = \frac{E_R(\lambda)}{E_I(\lambda)} \times 100$$

$$\frac{\text{Energy of } \lambda \text{ (wavelength) reflected from the object}}{\text{energy of } \lambda \text{ (wavelength) incident upon the object}} \times 100$$

Where ρ_λ is expressed as a percentage.

Equation 6.2 Spectral Reflectance Measurement.

6.6.4 Vegetation Reflectance

In order to assess vegetation damage using remote sensing, the spectral regions must be

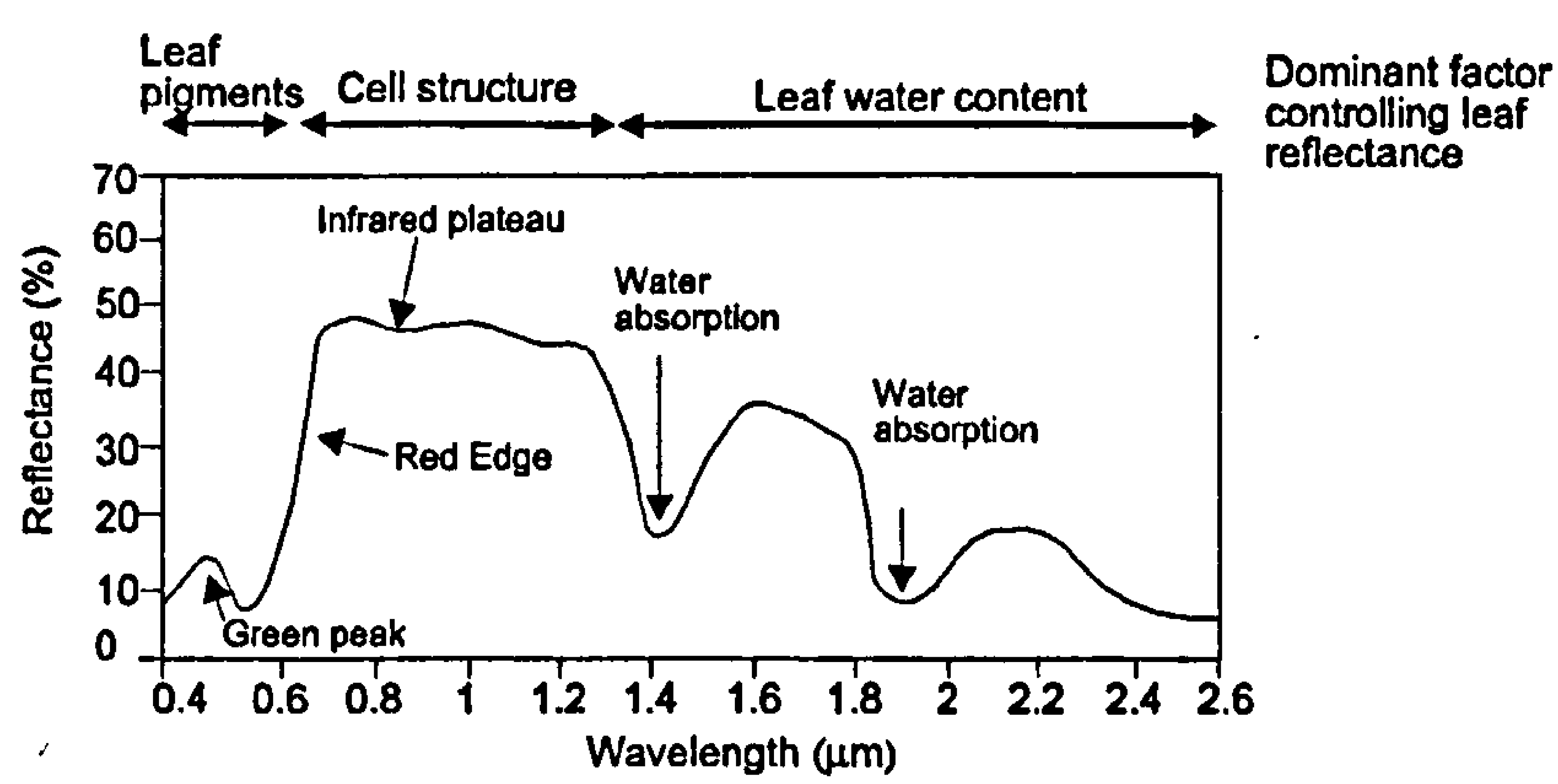


Figure 6.8. Typical Reflectance Curve of Green Vegetation.
(Adapted from Rogers, 1997).

identified in which vegetation is most responsive to unfavourable growth conditions. It is primarily the interaction of both the physiological and chemical which produces the typical reflectance curve for vegetation as illustrated in Figure 6.8.

Vegetation reflectance provides a good indicator of the structure, character and health of plants (Boochs *et al.,* 1990). Carter & Miller (1994) state that the best indication of stress within the 0.4 - 2.5 μm range is an increased reflectance in the visible (0.4 - 0.7 μm).

Difficulties in obtaining representative results may be incurred if the reflectance of the background features, excluding the vegetation, are similar to that of the plants. However, Horler *et al.* (1983a) disproved this using studies involving opaque rock background which, in the spectral region of 0.68 - 0.74 μm, is similar to many soils. The study used simulated natural vegetation on this background which was scanned in order to locate the representative red edge. The investigation disproved the possibility of interference in reflectances recorded from vegetation with that of background soil features. This was achieved by sampling reflectance spectra from pea and maize leaves using a spectrophotometer, backed by a slice of opaque rock which simulated 100 % vegetation cover, in the laboratory. This was completed again with only 80, 60, 40 and 20 % of the sample aperture covered by the leaf. Horler *et al.* (1983a) found that, even at the lowest coverage, the red edge was still identifiable and its wavelength λ_{re} remained the same. Thus, the effects of ground cover in field applications would be unaffected.

6.6.5. Red Edge

Research by Horler *et al.* (1983a & 1983b), Boochs *et al.* (1990) and Rock *et al.* (1988) have proved that a 'red-edge' exists in the reflectance spectra of vegetation in the range of 0.68 - 0.75 μm (Figure 6.8). It is a unique feature of green vegetation as a result of two optical properties of plant tissue (Horler *et al.*, 1983a):

- High internal leaf scattering to cause large Near Infrared (NIR) reflectance;
- Chlorophyll absorption giving low red reflectance.

Reflectance in the 0.68 - 0.75 μm range is sensitive to early stress-induced decreases in chlorophyll content and is represented by a blue shift in the red edge as illustrated by Hoque & Hutzler (1992). Hoque & Hutzlers (1992) research, using beech tree leaves, indicated a blue-shift in the maximum inflection point of the red edge. This was statistically proven to be synonymous with damage which was defined as leaf loss and discolouration. Therefore, chlorophyll content and visible damage are closely related to blue-shifts in the reflectance red edge curve. In addition, Boochs *et al.* (1990) state that the red edge derived from high resolution spectral data may even be enough to ascertain small differences in morphology and the chemical structure of the vegetation.

6.7 CHARACTERISATION AND ASSESSMENT OF VEGETATION DAMAGE

6.7.1 Vegetation Damage

Studies have been completed since the late 1960's (Murtha, 1976, Murtha, 1978, Gaucher *et al.*, 1978, Pinar & Curran, 1996), on the application of remote sensing as a tool for the detection of vegetation characteristics. Furthermore, research by Jago & Curren (1996), Jones & Elgy (1994), Collins *et al.* (1983) and Chang & Collins (1983) has identified the use of damaged vegetation detected through remote sensing as a method for locating areas of contamination. The applications formulated as a result of such research projects have since been applied to landfill case studies in order to determine their effectiveness as monitoring techniques. Indeed, specifically chosen case study sites have also been used for this current investigation.

As early as 1972, when damage assessment was only based on data from aerial photography, Murtha identified the need for more than just the simplistic aerial estimations of vegetation damage (Murtha, 1978). Quantitative and qualitative spectral and spatial measurements could then be used in conjunction with each other and in association with the advances in technology and data recording to produce more definitive results.

Definition of the term '*damage*' is of primary importance for the purposes of this investigation since it may lead to confusion over dead and dying vegetation. Murtha (1978) regards damage as a *'detrimental change in form'* of the vegetation. Changes are therefore expected in both the morphology and spectral reflectance patterns. The most suitable definition, however, was from Murtha (1976) who classified damage as the following;
'any type and intensity of an effect on one or more plants, or parts thereof, produced by an external agent, that temporarily or permanently reduces the financial or aesthetic value, or impairs or removes the biological capacity for growth and reproduction or both'.
Therefore, damage will include dead and dying species detectable through a variation in spectral reflectance or signature.

For a detailed assessment of migration distances, specific site information is vital. The following provide examples which are specific to landfills; the location of high permeability pathways, capping and liner thicknesses. In terms of the damage created, it is also important to consider the type of vegetation and its health prior to contact with the pollutants. Environmental Impact Assessments (EIAs), prior to the commencement of the landfill, will provide details of the pre-existing vegetation types and health. These data can then be incorporated into a long term plan to facilitate an assessment of vegetation over the entire period of landfilling and post completion monitoring.

6.7.2 Damage Manifestations

The use of remote sensing to monitor landfill sites is based upon the identification of stressed or damaged vegetation which may manifest itself in different forms as indicated below (from Lyon, 1987):

- A decrease in size and vigour;
- A decrease in the number or variety of species present;
- Absence of characteristic plant species;
- The presence of dead vegetation (in extreme cases);
- The presence of plant species adapted for growth on contaminated land.

For the purposes of a ground investigation, it requires a trained eye in order to determine the different vegetation characteristics, even at ground level. This investigation now recognises the requirement for specialised knowledge in this area, although, at the beginning of the current study, it was not deemed to be of such importance. It was assumed that damaged vegetation could be identified solely through remote sensing regardless of species type. This may be true in extensive areas of damage concentration but with regards to the identification of specific plant types, classification of varying spectral reflectance patterns according to species is necessary.

Murtha (1978) divides the damage into an assessment of the change in morphology or physiology of the vegetation. A change in morphology could be explained as a change in the shape or outline of the vegetation which could be defined further as cellular collapse or defoliation. In contrast, a changing physiology would be expressed as a deviation from the normal over time, for instance growth reduction or top dieback. Damaged vegetation in the form of chlorosis i.e. yellowing of the leaves, stunted growth and die back are all visible forms of damage associated with landfill contaminants. The interest lies in whether the landfill pollutants cause damage in either of these ways or possibly both. These can be seen during ground monitoring and will provide evidence for the presence of contaminants.

It is important to note the possible problems which may also be associated at this stage in anticipation of some representative results. Progressive analysis is necessary to determine changes in vegetation patterns throughout the year which occur with seasonal variation as a result of senescence, alterations in chemical composition and changes in chlorophyll accumulation, (Boochs *et al.*, 1990), that are in turn related to plant type. Reflectance spectra are affected by vegetation growth patterns throughout the year, indicating that damage to vegetation may also be related to seasonal change.

Ground investigation is also imperative once analysis of the remote sensing data has taken place. This determines whether the vegetation damage can be denoted by the migration of either leachate or LFG. A flame gas de-ioniser field kit can register the presence of LFG in minute quantities in the subsurface of the soil. It would be necessary to carry out fieldwork on problem areas where vegetation damage is identified by remote sensing analysis.

Importantly, the damaging agents from landfills, leachate and LFGs, need to be differentiated from other agents such: as fire; disease; insect damage; and human activities (Jones, 1991). This stage should be completed through ground surveys at the same time as the remote sensing data is recorded. Most landfills will already possess a detailed knowledge of the environment in the vicinity and records could even be updated from previous environmental impact assessments and site investigation surveys.

It is also possible to define the manifestations of damage in terms of their acute or chronic nature. Acute can be defined as a high input of pollutants over a short time, in contrast to chronic which denotes an exposure to lower concentrations over a longer period. Larcher

(1995) suggests that acute lethal damage, seen in the immediate vicinity, may be recognised in the following forms: chlorosis; leaf discolouration; necrosis of tissues; and death. In contrast, chronic symptoms are less distinctive: reduced productivity; defective fertility; less vigorous growth of trees; and sparser foliage. Only the immediately apparent features would be recognisable in this case, since a comprehensive study of the local vegetation was beyond the scope of the investigation. However, a comparison over time would increase the possibility of classification in these terms.

6.7.3 Chlorosis and Vegetation Dieback

Chlorosis exhibits itself as a yellowing of the plant leaves and is a symptom of Virus Yellow infection which affects both efficiency and yield (Steven & Jaggard, 1995). As a result, chlorosis in plants will affect the reflectance pattern which deviates from that of normal, healthy vegetation.

The extent of damage through vegetation dieback is a function of:

1. Species type, since some species may be more tolerant of the components of LFG, namely methane and carbon dioxide along with the reduction in oxygen content;
2. Soil type and thickness;
3. Moisture content of the soil;
4. Temperature;
5. Retention time of pollutants within the soil itself.

(WEPC, 1995)

It is important to consider that the above may not always be directly attributed to landfilling activities, so, this must be proved to be the case. In addition to the first point, landfill restoration procedures may take advantage of the potentially resistant species during the aftercare planting.

6.7.3 Causation factors

Damage to vegetation in the vicinity of a waste body will generally occur primarily as a result of root damage. The damage therefore may be attributed predominantly to the distribution of gas through the subsurface layers of the soil strata, although poor quality of groundwater may make some contribution. The presence of the gas leads to an anaerobic environment in which plants are unable to grow. This may be due to;

1. A lack of oxygen in the root zone (asphyxiation). Most plants demand 5-10 % oxygen in soil air, rising to 12-14 % for woody species, although this fact depends on species. Shallow root systems and dwarf growth (Neumann & Christensen, 1996) give an indication that aeration has occurred from the atmosphere on the surface layer of the soil;
2. The high toxicity of carbon dioxide leading to phytotoxic conditions. Under normal conditions, the amount of CO_2 present within the soil will vary according to the amount of organic matter degradation. CO_2 tolerance is again variable between species although plants can grow in 5 % CO_2, Kjeldsen (1996) stating 20 % CO_2 to be a high concentration. The presence of methane (CH_4) may be beneficial to plants although in high concentrations (45 %) minor damage may occur due to oxygen depletion caused by microbial oxidation of methane (Neumann & Christensen, 1996);
3. The anaerobic conditions facilitate the collection of heavy metals, such as iron and manganese in higher, poisonous levels (Flower *et al.*, 1981). Neumann & Christensen (1996) consider this to be a minimal factor for consideration, since asphyxiation is the main cause of damage resulting in possible death.

6.8 AIRBORNE REMOTE SENSING DATA ACQUISITION

6.8.1 Investigation Outline

The research completed for this investigation assumed that the data analyst had no previous knowledge of remote sensing, possessing solely a background in landfill engineering and management. The criteria comprised the production of a systematic method for data collection and processing and, in addition, that the system could immediately be applied by the waste management industry. The latter may have been a demanding prerequisite. However, some progress has been made in the achievement of this, since fundamental difficulties have arisen especially during data collection which could be corrected at initial stages of the system development.

6.8.2 Data Collection

For this study, data was obtained from sensors mounted on a NERC Piper Chieftain plane which was specifically equipped as shown in Figure 6.9. The data collection was stipulated for 1995, March / April time at the start of the growth season. On the day of the flight the weather was mainly clear although cloud was recorded in some of the data. In the event, the data for Chelson Meadow was re-recorded on another flight (April, 1996). The second acquisition, along the same flight line, was completed a year later in 1996 using the identical data collection specifications in order to provide a temporal comparison.

6.8.2.1 Airborne Thematic Mapper (ATM)

Data was collected using a Daedalus 1268 - 11 channel Multispectral Scanner or Airborne Thematic Mapper (ATM). The ground resolution was 5 m and the wavebands recorded as in Table 6.1.

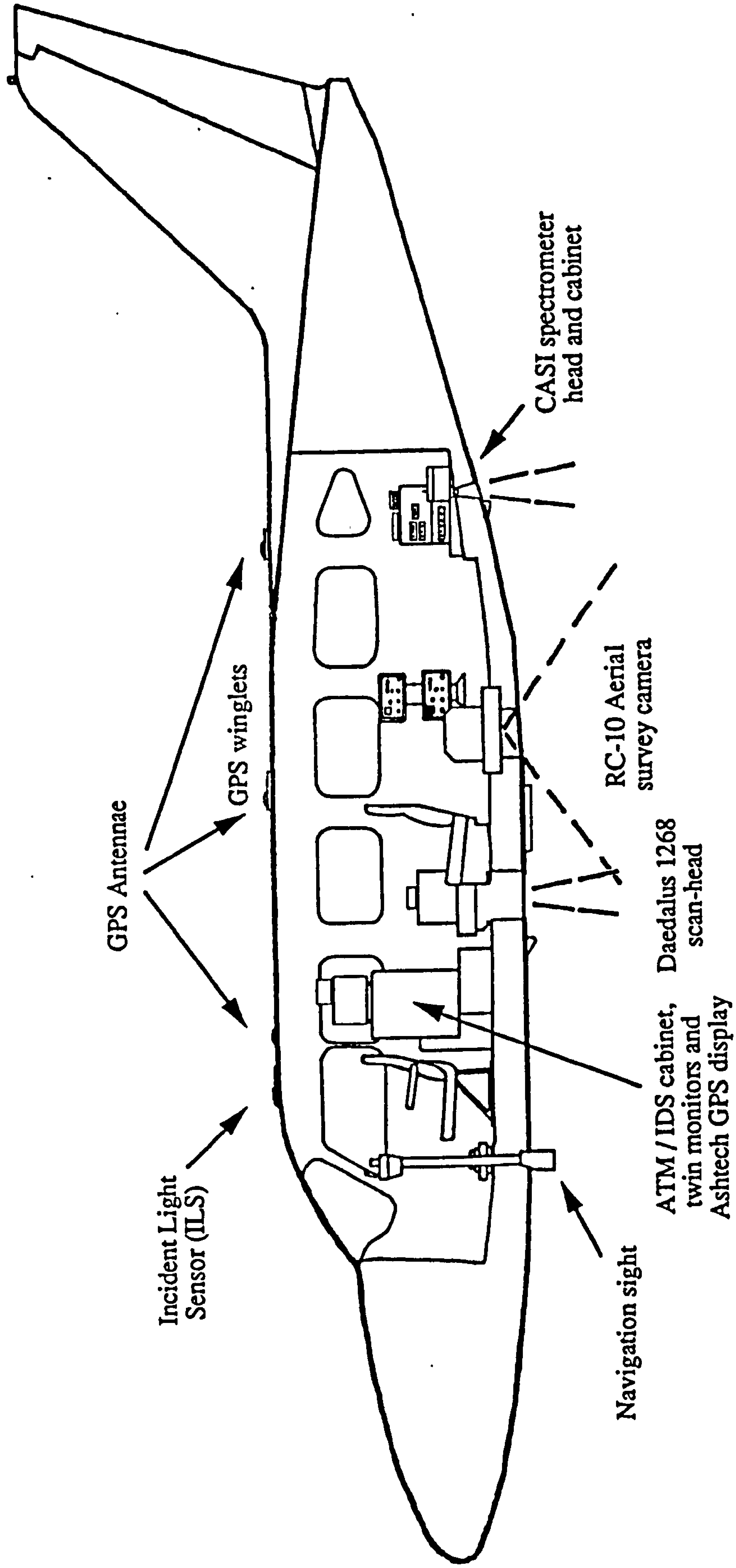


Figure 6.9 Cross-sectional Schematic of the NERC Piper Aircraft illustrating the General Equipment Layout (NSS, 1996)

Band	Start (nm)	End (nm)	Purpose
1	420	450	Water penetration
2	450	520	Vegetation discrimination
3	520	600	Peak green vegetation reflectance
4	605	625	Water quality
5	630	690	Max. chlorophyll absorption
6	695	750	Vegetation red edge curve
7	760	900	Vegetation max reflectance
8	910	1050	Near Infra-red (NIR)
9	1550	1750	Vegetation moisture
10	2080	2350	Rock discrimination
11	8500	13000	Surface temp, moisture

Table 6.1 ATM Wavebands Recorded (NSS, 1996).

6.8.2.2 Compact Airborne Spectrographic Imager (CASI)

The second technique for the airborne data collection was the Compact Airborne Spectrographic Imager (CASI) at a ground resolution of 5 m. It is a Canadian high performance pushbroom sensor which was specifically designed to enable the acquisition of low cost multispectral data for both aquatic and terrestrial purposes (Franklin, 1994 and Babey & Anger, 1989). Multispectral scanners enable the collection of data in many narrow bands through 200 channels or more thus encouraging discrimination of surface features in terms of absorption and reflectance.

CASI covers a spectral range typically from 450 - 950 nanometers (nm) (0.45 - 0.95 μm) which in turn can be further minimised to identify specific interests. This range is divided between 0.4 and 0.9 μm at 1.8 nm spectral intervals (Lillesand & Kiefer, 1994). The CASI can be operated in two modes; a spatial and / or a spectral one operational in 288 channels. However, the spectral modes are programmable in the spatial ones i.e. spectral widths and ground cell resolutions (Gong *et al.*, 1995).

Spatial resolution: 578 pixels.

Spectral resolution: 288 pixels (1.8 nm each).

Band	Start nm (Channel No.)	End nm (Channel No.)	Purpose
1	441.53 (264)	459.17 (254)	Blue vegetation response
2	480.37 (242)	499.84 (231)	Vegetation response
3	547.74 (204)	556.63 (199)	Max .green absorption
4	665.57 (138)	674.54 (133)	Max. Vegetation absorption
5	694.28 (122)	703.27 (94)	Red-edge
6	705.07 (116)	711.06 (89)	Red-edge
7	735.66 (99)	744.67 (94)	Red-edge
8	746.47 (93)	753.68 (89)	Red-edge
9	760.90 (85)	764.51 (83)	Oxygen absorption
10	775.34 (77)	784.37 (72)	Max. vegetation reflectance
11	815.13 (55)	824.18 (50)	Water absorption
12	860.46 (30)	869.54 (25)	Near Infra-red plateau

Table 6.2 CASI Wavebands Recorded (NSS, 1996).

This application directly recorded information on a preset bandset of 11 channels specifically related to the spectral reflectances of vegetation (Table 6.2).

The wavebands are directly relevant to the detection of vegetation quality and type and a comparison with the ATM data shows that the CASI covers a more specific area of the electromagnetic spectrum. Therefore, the CASI tool is possibly the most applicable in this area although, until recently, its use was minimal due to difficulties with the data correction techniques.

6.8.2.3 Aerial Photography

A Wild RC-10 Survey Camera was used to record data at a ground resolution of 1:1600 m and 1:1000 m in the form of visible colour vertical aerial photographs. A set of photographs was received from both of the NERC flights (1995 and 1996) for the case study in Plymouth, but only one set for the Heathfield site (1995). This made it possible for a temporal comparison of operations on the former site whilst also providing an overview of the environment adjacent to the sites. The photographs also provided means for contrast whilst working on the manipulated ATM data.

6.8.3 Acquisition Problems

The foremost complication was the time taken for the acquisition of data. An initial attempt was made to prove that the application could be planned, instigated and results achieved in a maximum of 24 hours. However, the raw data for this research was received in excess of one year after it was flown. In addition to this, the data received was not geometrically corrected and there was no geometric correction equation available for the relatively new CASI technique and one would have to be devised. At the date of submission of this thesis, this stage of the data processing has not been completed three and a half years after the original NERC flight, rendering the CASI data unusable for the purposes of this study.

6.8.4 Data Correction

Pre-processing of airborne data requires specific geometric and radiometric corrections. Airborne imagery possesses problems which are not experienced in satellite imagery. The main difficulties arise as a result of geometric variations. For example, differences in earth curvature, atmospheric refraction, altitude, velocity, pitch and roll of the remote sensing platform and nonlinearities in the Instantaneous Field of View (IFOV) possessed by the sensor. Geometric variations can be corrected by finding out the relationship between the pixels and the corresponding area on the ground which is achieved using a geometrically corrected map. Geometric correction is especially critical for the analyses of multi-temporal data.

Radiometric problems also occur, namely errors occurring in the recorded brightness of the pixels. For example, atmospheric conditions, viewing geometry and instrument response characteristics (Lillesand & Kiefer, 1994). Unpredictable interference (scattering) in the atmosphere will affect the reflected and emitted energy. This scattering takes two forms, Rayleigh and Mie. The former occurs when the radiation interacts with atmospheric particles (and other smaller ones) which are smaller than the wavelength of the recorded radiation. Mie scattering occurs when the size of the particles and the remote sensing wavelengths are of similar magnitude. Data must be corrected for scattering before it is analysed further to reduce error.

These corrections are dependent upon the use of the imagery. Therefore, it was mainly the geometric corrections that were necessary for this study. For the purposes of this study, data correction was completed prior to receipt of the imagery from NERC.

6.9 CASE STUDY SITES

6.9.1 Introduction

The study sites located in South West England (Figure 6.10) were chosen for the collection of three forms of airborne remote sensing data. The choice of site was a function of:

- The location of the site;
- The form of landfill design philosophy employed.

Both of the above are related since the characteristics of the landfill location will influence the design as described in both Chapters Three and Four. The two sites therefore provide an ideal contrast from which to draw results. They were both operational throughout the entire period of data collection.

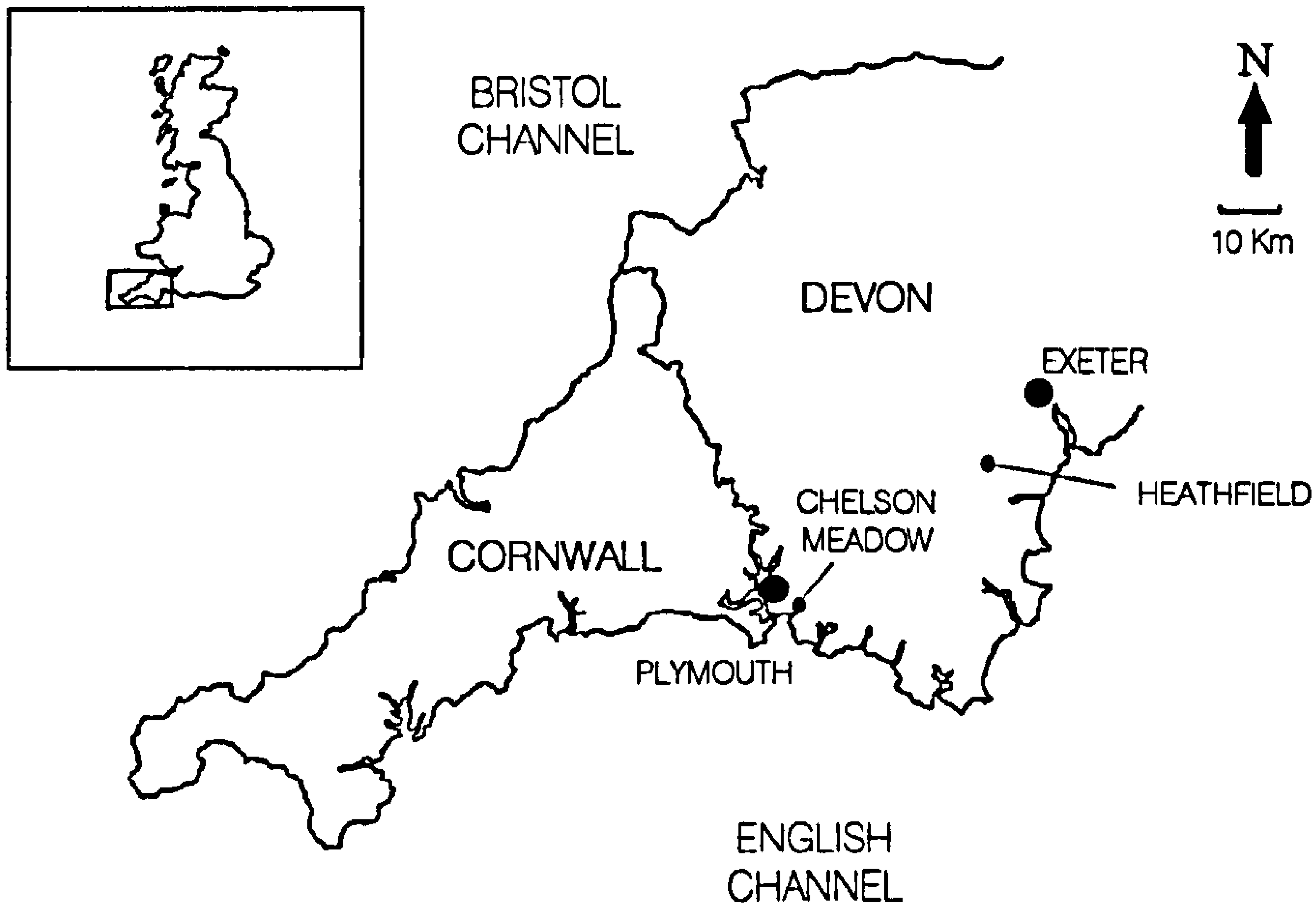


Figure 6.10 Location of the Case Study Sites. (Hopper, 1996)

6.9.2 Chelson Meadow, Plymouth

The first case study site is the Chelson Meadow landfill in Plymouth, operated by Devon Waste Management (DWM), the Local Authority Waste Disposal Company (LAWDC). It is based upon attenuate and disperse principles, relying on the unsaturated geological strata to attenuate pollutants, thus minimising effects on the underlying groundwater aquifer (Bagchi, 1990). However, there is an engineered leachate drain at a level of 7.5 m AOD and several leachate cut off drains which discharge to the lagoon. It is a combination land fill and raise, the majority of the waste being placed above the height of the flood plain.

Prior to development, the location was originally part of the River Plym tidal estuary, a ria infilled by both natural sedimentation, following the post-glacial rise in sea level, and tailings from the former kaolin quarries located in the headwaters of the River Plym. The sequence of deposits presented in Table 6.3 occurs at the site.

STRATA	DESCRIPTION
Landfill/raise	Domestic and inert wastes, some asbestos. This is ongoing fill to date.
Reclamation Fill	Tipped wastes and sludges (Max. thickness 15m)
Alluvial Deposits	Sandy, silty clayey soils. The clays reduce recharge to the underlying aquifers and the likelihood of leachate migration.
Bedrock	Upper Devonian strata comprising grey fissured slates and mudstones which range in permeability from $K = 1.2 \times 10^{-8}$ to 5.3×10^{-8} ms^{-1}, i.e. moderate to low, which will impede leachate migration. Except in the South Western corner where limestones form interbedded with the slates. The limestones are a minor aquifer owing to fractures in the upper weathered zones.

Table 6.3 Underlying Strata of Chelson Meadow Landfill Site (Adapted from DWM, 1996).

Chelson Meadow was reclaimed in 1807 through the construction of an 890 m long embankment, 'The Ride', approximately 4.9 m above the level of the estuarine mud, to enclose an area of 73 hectares (180 acres). The area has been used as a racecourse, a World War 1 Airfield (Otter, 1994) and was developed as a landfill site from 1968.

This landfill is of specific interest due to its licence which enables it to accept liquid and solid wastes (Table 6.4) as a co-disposal site. On-site collection and shredding of organic wastes enables composting in linear windrows (Figure 6.11). Chelson Meadow is the main repository for waste in Devon, although most of the waste is derived from the surrounding Plymouth areas. The site is expected to be operational until 2002. This has therefore encouraged the development of other proposals and strategies for the disposal of wastes from the area. Particular attention is given for the disposal requirements of domestic wastes, since they comprise the greatest waste intake, as indicated in Table 6.4, and liquid wastes.

Waste Type	Quantity in Tonnes
Covering Material	94,595.290
Hardcore	25,383.820
Domestic	102,969.600
Commercial	41,364.440
Civic Amenity	26,926.290
Liquid	3,737.700 (22, 000m^3)
Total Input	**294,977.140**

Table 6.4 Chelson Meadow Landfill Site Input Jan. to Dec. 1996 (DWM, 1997).

Upon the completion of waste infilling, it is proposed that the landraise will have reached 15 m AOD, approximately. Continuing partial restoration has been completed at the site in accordance with the licence (Waste Management Licensing Regulations, 1994) and Codes of Practice (DoE, 1996b). At present, the north of the site is partially restored to a golf course.

Compacted clay bunds partially surround the site. At the river side of the site (North East and East) these bunds are lined with an impervious liner. It was noted that this could be a location for interest since break outs of both leachate and LFG had been acknowledged by the operators and flares installed to control the gas. Leats, previously surrounding the site, have since been diverted in order to reduce the possibility of surface water contamination. They now drain the meadow to the river Plym along the North and South sides.

The site is located on the edge of the River Plym estuary (Figure 6.11), into which runoff and leachate were pumped on a falling tide until November 1996. However, an automated leachate treatment plant (LTP), at a cost of £1.25 million, is currently in operation and will remain so post-closure. Operation of the LTP will be abandoned when the production of pollutants is nil or no longer of environmental consequence, the former being highly improbable in the decades immediately after completion of filling. Prior to the introduction of this system, leachate ammonia levels were in the region of 200 mg l^{-1} in contrast with the 50 mg l^{-1} specified by the EA (DWM, 1996). The employment of four sequence batch reactors using nitrifying bacteria to consume the ammonia has resulted in the reduction of levels to approximately 0.5 mg l^{-1}. From the plant, the leachate is pumped out into the estuary half an hour after low tide for a maximum of two consecutive hours. Regular monitoring of the estuarine environment in the vicinity of the outfall pipe has indicated no detrimental results to date.

Present gas treatment for this site occurs in the form of passive venting through two flares which are to be replaced by an extensive gas utilisation scheme in the near future.

Chelson Meadow is located adjacent to an operational limestone quarry (Figures 6.11 and 6.12) which operates an on-site cement works. It is important for the purposes of this research to consider the possible effects of quarrying on the local groundwater regime and also as a potential source of background contamination of the results of this study.

6.9.3 Heathfield, Newton Abbot

The second site, Heathfield, is a more recent landfill which has had three operational fill and raise phases, each necessitating the placement of a form of engineered liner. It is now starting the fourth phase and there is a planned fifth. The site, owned by Haul Waste (a private waste management company), is located at Chudleigh Knighton (Figure 6.10),

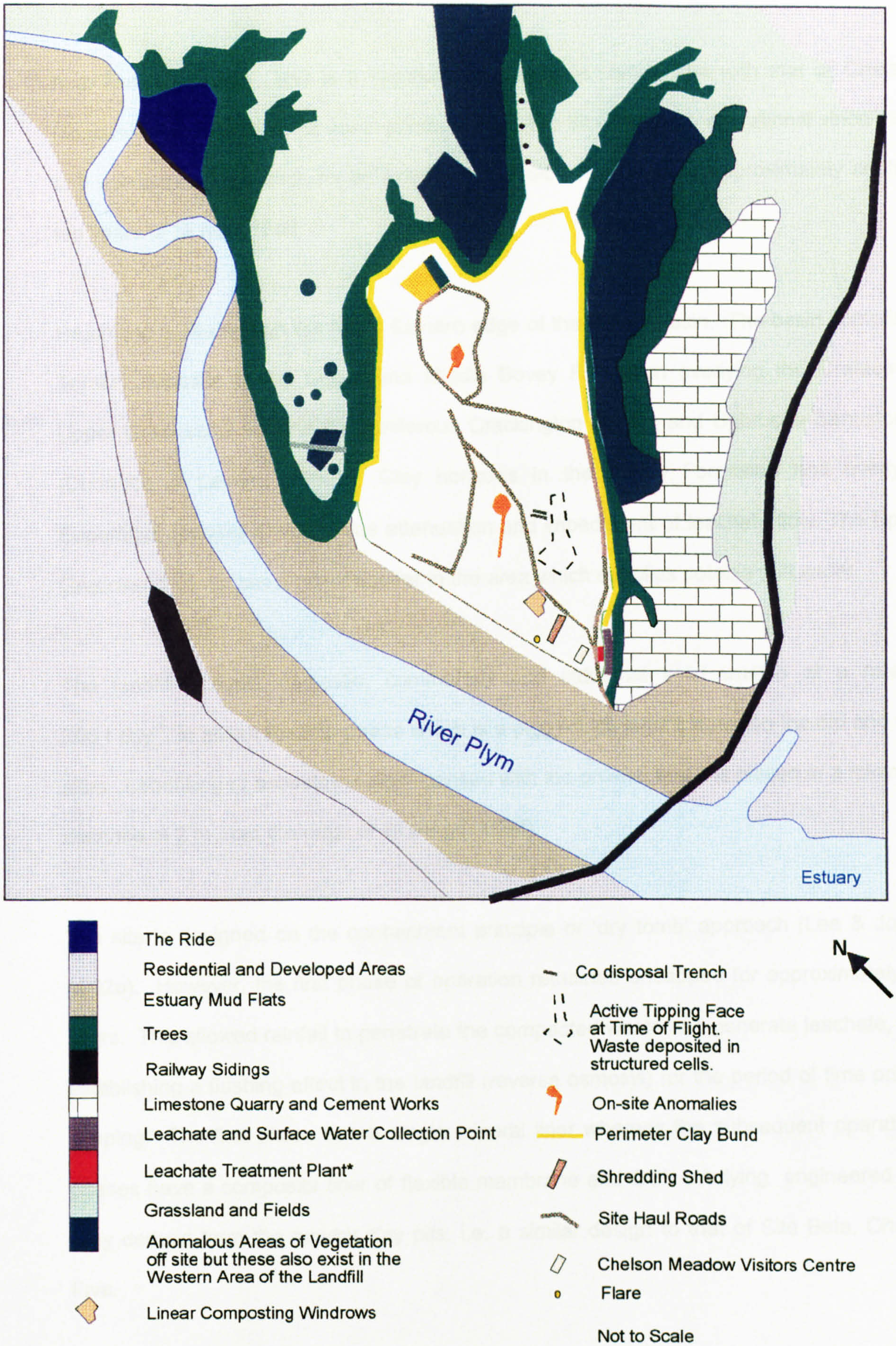


Figure 6.11 Schematic Plan of Chelson Meadow Landfill Site from 1995 NERC data.
* From 1997 data.

near Newton Abbot. This is a relatively rural area in comparison with that of Chelson Meadow as illustrated in the aerial photographs. The site has been operational since 1980 and was granted a licence for an extension in 1990 which enables approximately another ten years of fill from 1996.

Heathfield is situated on the North Eastern edge of the Bovey Basin. The basin comprises Tertiary deposits of the Upper and Middle Bovey Formation overlying the Cretaceous Upper Greensand and the Carboniferous Crackington Shales and Ugbrooke Sandstones (Durrance & Laming, 1982). Clay horizons in the Bovey Formation and overlying Superficial deposits enable some attenuation and impediment of leachate flow. The Upper Greensand comprises a minor aquifer in the area which supplies potable soft water.

The landfill accepts domestic, commercial and industrial solid wastes at a rate of 700 t day^{-1}, in all but the fifth phase which is a piggy-back landfill between the old and new sites. Landfilling of asbestos is also licensed with the proviso that it is placed at a minimum distance of 2 m from the edge of fill (Anon, 1994).

The site is designed on the containment principle or 'dry tomb' approach (Lee & Jones, 1992a). However, the first phase of operation remained uncapped for approximately ten years. This allowed rainfall to penetrate the compacted waste and generate leachate, thus establishing a flushing effect in the landfill (reverse osmosis) for the period of time prior to capping. The first phase has a single mineral liner whereas the subsequent operational phases have a composite liner of flexible membrane and GCL overlying engineered Ball Clay derived from the nearby clay pits, i.e. a similar design to that of Site Beta, Chapter Five.

Long-term management systems have been established in each cell for the provision of leachate treatment and landfill gas extraction. The latter is used to produce electricity for the National Grid on site. This active control system enables the collection of gas channelled to two turbines which produce 0.9 Mega Watts (MW) of electricity in total. Plans are underway to install a further two turbines with the ability to produce a further 1 MW each. Less extensive passive venting systems are also in operation across the site. Passive control systems comprise gas vents along the perimeter of the site and regularly spaced gas monitoring boreholes.

At the time of data collection Phase One was restored and Phase Two partially so. Regular leachate monitoring is completed by the operator through borehole and surface testing at the stipulated monthly and quarterly frequencies along similar procedures to those outlined in Table 4.6 for Site Beta.

6.10 DATA PROCESSING

6.10.1 Initial Stages

The multispectral airborne imagery was initially subject to a range of image processing techniques using Erdas software which enabled processing, analysis and production of corrected imagery. At this stage of the investigation, a specified area from the entire image was identified for use in the analysis. The airborne imagery collected, also recorded locations outside the area of interest for the study. This represented excess data which was unnecessary for processing, therefore it was cut from the main image which was to be used.

6.10.2 Primary Processing Techniques

6.10.2.1 Image enhancement

The initial adjustments employed enhanced areas of low inherent contrast using simple contrast stretching procedures. Contrast stretching can be applied in several forms by adjusting the entire image or individual wavebands. An image histogram is created for each waveband, illustrating the distribution of brightness values for all pixels by plotting the number of pixels with a given brightness against the brightness value (Richards, 1993). The histograms were stretched to achieve a normal or 'Gaussian' distribution by resetting the Digital Number (DN). This is the integer value of an individual pixel which can be converted to radiance or temperature using a conversion factor. At this stage it became apparent that stretching aided the detection of finer spatial details. For example, Figure 6.12 illustrates the different features which can be enhanced through contrast stretching processes. From Figure 6.12a (and reference to Figure 6.11), the co-disposal trenches, non-vegetated areas and on-site haul roads compacted through intense trafficing are identifiable. Figure 6.12b illustrates some of these aforementioned features in more detail. The overlay locates anomalous areas within the site such as the clay bund surrounding the landfill.

6.10.2.2 Image filtration

It may be necessary to filter the image in order to remove some of the noise which occurs. In this dataset, ATM band 1 has a poor signal to noise ratio. Noise is the interference in the image which creates a distortion as a result of limitations in image recording, equipment and signal digitisation (Lillesand & Kiefer, 1994). Noise is determined through a comparison of a pixel with its neighbours. Should the surrounding values exceed the operator specified threshold, the pixel contains noise. It is possible to remove much of the effects of noise through processing, such as periodic noise removal using algorithms, thus

Figure 6.12a Image not Subjected to Contrast Stretching

Figure 6.12b Contrast Stretched Image

Figure 6.12 Original and Contrast Stretched Image of Chelson Meadow, ATM Band 11.

(1995 NERC data).

restoring the image to a closer representation of the real life scene.

A low pass Fourier filter, with a minimum affected frequency of 3 was used to 'smooth' the image. A frequency of 4 was also used but was not as effective in subsequent analyses. Smoothing the image reduces the spatial frequency in order to reduce the variation of grey levels across the image, specifically over a large area of pixels. These particular filters emphasise large area changes in brightness whilst reducing local detail (Lillesand & Kiefer, 1994) as opposed to high pass filters which emphasise the high frequency components.

6.10.2.3 Line Drop

In the imagery there was also some evidence of line drop, i.e. false, unrepresentative pixels in an area of similar DN. However, this was not deemed a major problem for this study since they were generally outside the main area of interest, although it does add to the difficulties which arise in remote sensing processing, before further analyses can take place. In order to compensate for this, an average value can be found from the surrounding pixels, or if ground investigations were completed on the exact area at the same time as the flight, these reflectances could be used. The user must be able to recognise such errors in the data which could detrimentally affect the results unless corrected.

6.10.3 Classification Techniques

Following enhancement, the imagery can then be subjected to detailed analysis using statistical and mathematical techniques. This study has concentrated on the use of the supervised and unsupervised classification. These involve the substitution of the visual data which forms the image with a quantitative identification of the features based on decision rules. Statistical rules are applied in the primary stages of the analysis based on the spectral radiances from each pixel. The result is a thematic map of the image replacing the visual features previously identified to create a non-overlapping classification of the pixels (Lillesand & Kiefer, 1994). Classification of an image involves the grouping together of pixels of similar spectral signatures depending upon an operator specified pathway as indicated in Figure 6.13.

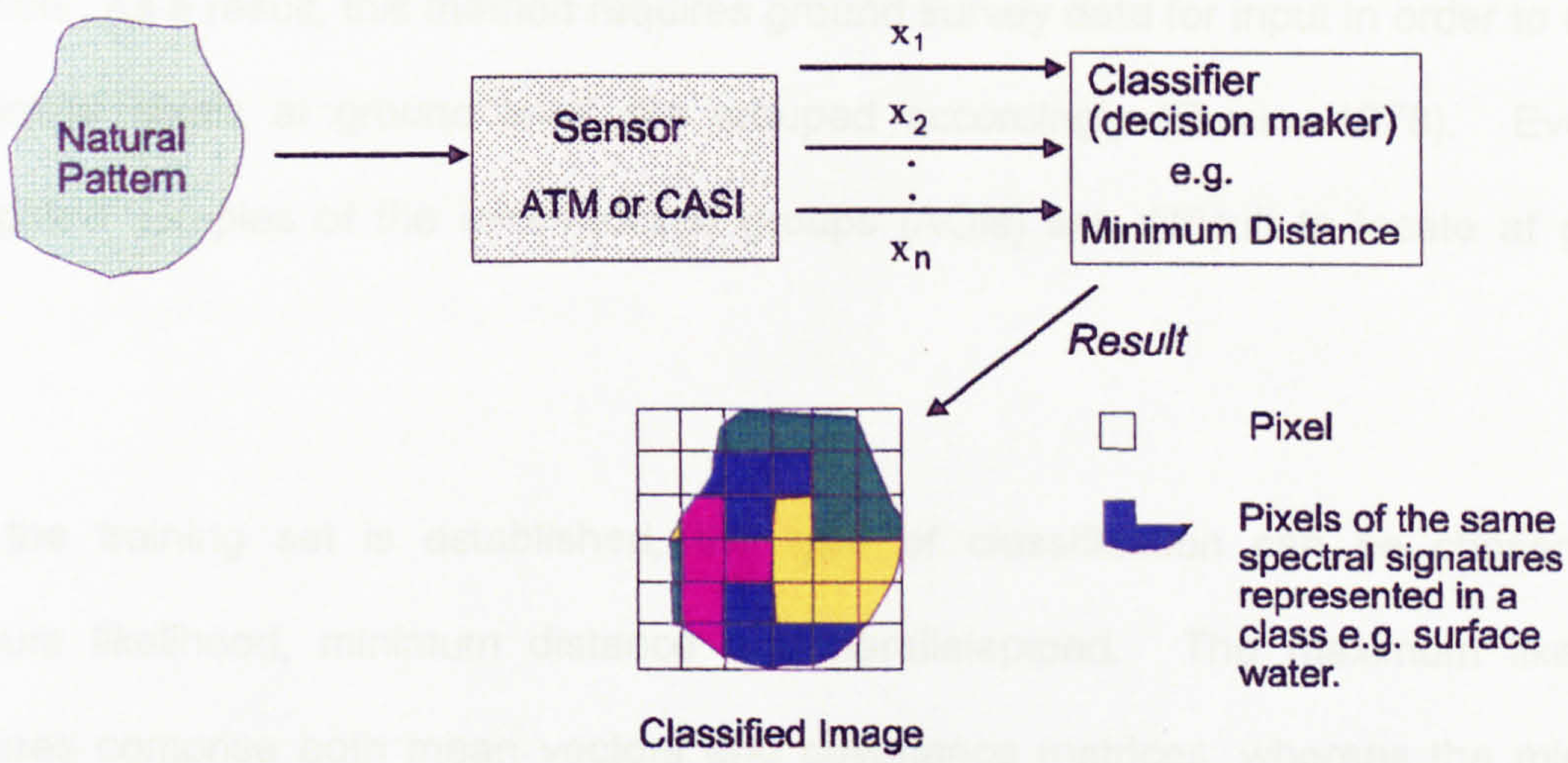


Figure 6.13 Remote Sensing Classification System (Adapted from Swain, 1978)

6.10.3.1 Supervised classification

Supervised classification enables an operator to identify groups of similar pixels in an *Area of Interest* (AOI) which is called a training set, a collection of sets is termed a field. Training patterns therefore represent measurement vectors of known identity. These groups enable the classification of ground cover into groups or 'classes' such as: crop species; soil type; soil moisture; and land use.

Typically, the AOIs should each have a minimum of a couple of hundred pixels (OU, 1989), in order to achieve a representative classification. Conversely, Richards (1993) states that the training set needs to represent less than 1 to 5 % of the total pixels. In this analysis, due to the lack of large clusters of pixels of a similar reflectance, smaller training sets had to be used. In the case of the AOIs from the Heathfield site, classes such as woodland, water and clay-works were chosen and identified by the operator. It was recognised that there may be confusion at a pixel level since there may have been slight deviations in pixel radiances. Furthermore, reliable results can only be achieved if the classes are easily discriminated in the multispectral data. Failure of this leads inevitably to dubious boundary formation. As a result, this method requires ground survey data for input in order to ensure that similar pixels at ground level are grouped accordingly (Swain, 1978). Even so, unmitigated samples of the informational groups (AOIs) are difficult to locate at ground level.

Once the training set is established, the type of classification can be chosen from maximum likelihood, minimum distance and parallelepiped. The maximum likelihood signatures comprise both mean vectors and covariance matrices, whereas the minimum distance classifier comprises only the mean vectors of the training set. The parallelepiped classification signatures are the upper and lower limits of the brightness in each spectral band (Richards, 1993). The minimum distance classifier was mainly used due to the lack of training samples for each class since it depends on the mean positions of the spectral classes and not the covariance information (Richards, 1993).

The choice of bands is then made for the classification. Either the entire range can be used or a specified number. For this study, a range of options were used, although for the initial analysis, the choice of bands was primarily restricted to ATM 9, 7 and 3 and ATM 8, 11 and 2 in the red, green and blue guns on the Visual Display Unit (VDU) respectively. This choice of band combination for the colour composite image was based upon previous work in this field (Jones, 1990 and Sangrey & Phillipson, 1979).

6.10.3.2 Unsupervised classification

Unsupervised classification does not use the training data process. Algorithms are used to group the pixels into classes based on natural groupings or clusters (Lillesand & Kiefer, 1994) which may not be immediately apparent to an analyst completing a supervised classification. An example is shown in Figure 6.14 where the pixel values are plotted to visually identify natural spectral groupings. With reference to ground data, it could be determined that one group corresponds to coniferous trees, one to a plantation of deciduous trees and the final cluster to stressed trees of both varieties. In this case, the classifier has identified distinct spectral differences which may have been missed by the analyst in the supervised classification.

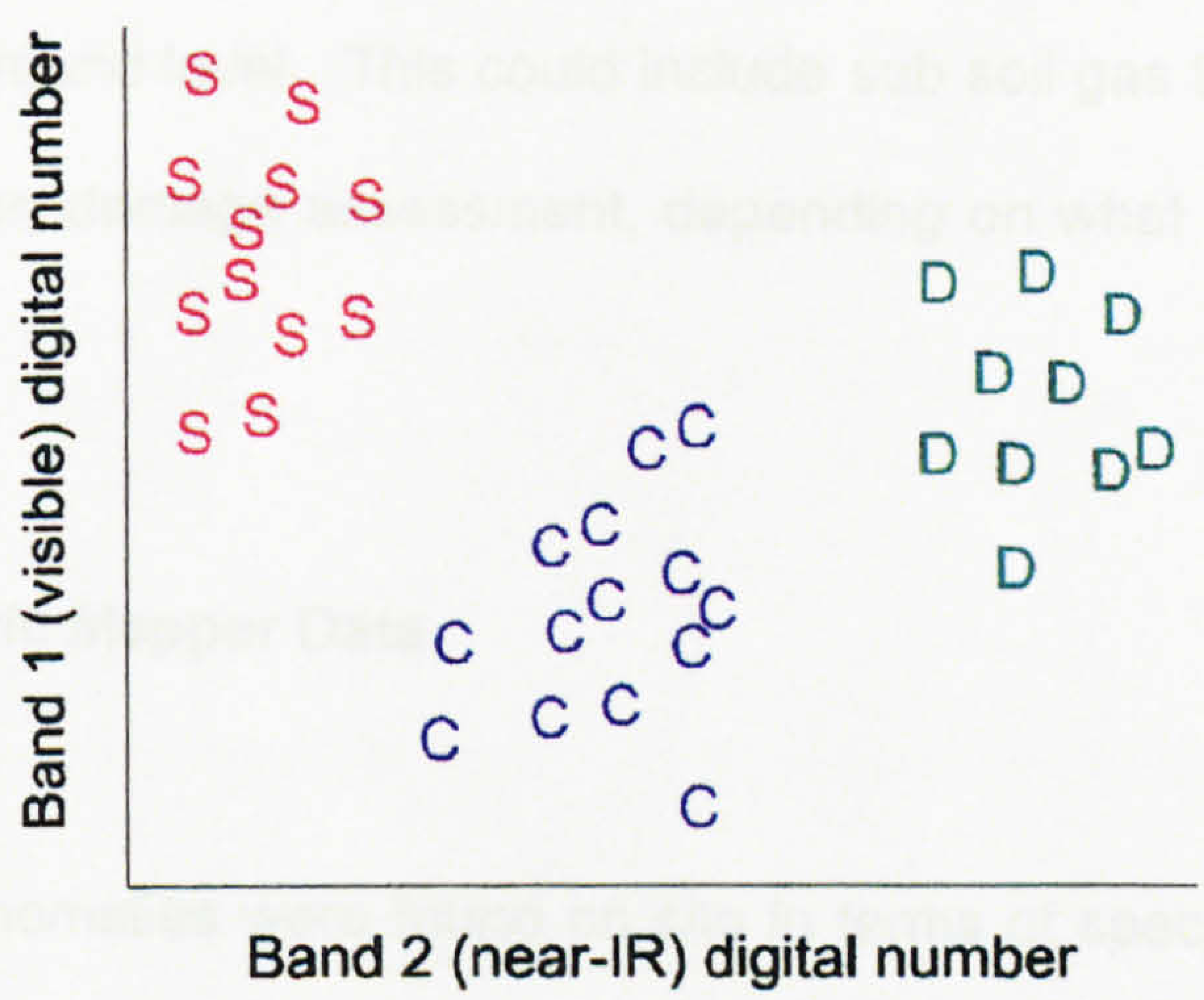


Figure 6.14 Spectral Classes in Two-channel Image Data (Lillesand & Kiefer, 1994).

Unsupervised classification was completed on the same bandsets as the supervised. This is the main type of classification related to this type of study since it is generally used in situations where there is a lack of ground referencing data (Jones, 1991). This investigation specifically did not identify spectral reflectances at ground level in accordance with the data collection flight. Therefore, unsupervised classification was seen to be the most appropriate form. However, unsupervised classification did not enable the use of the identification of specific AOIs made by the investigator, who could stipulate the number of classes. The classification also grouped similar pixels to create an effect of averaging. This could, therefore, have the potential to remove smaller anomalous effects in the data, relating to damaged areas. It implies that over an extensive area, locations of minor damage, or, possibly small areas of concentrated stress may be overlooked.

6.11 DATA ANALYSIS

The principal aim of the study was to give an indication of anomalous areas for interest on and surrounding the landfill sites. Anomalies are hereby defined as those areas of greater contrast to their surroundings for no apparent reason. These locations would then demand further investigation at ground level. This could include sub soil gas testing, surface water monitoring and vegetation damage assessment, depending on what was apparent at site level.

6.11.1 Airborne Thematic Mapper Data

In the enhanced data, anomalies were found on site in terms of spectral signatures which are attached to each pixel. However, no anomalies were found outside the site which could not be attributed to moisture content variations or vegetation type, for example. The clay bund could easily be detected in the Chelson Meadow site which illustrates a possibility for identification of clays through remote sensing techniques.

Figure 6.12b, ATM waveband 11 of Chelson Meadow, illustrates the patchy nature of the vegetation on the site, especially in comparison with the healthier nature of that surrounding the site. The overlay for this figure indicates some of the possibly anomalous areas which would require a walk-over survey and subsoil gas monitoring. It is recognised that both the sites follow a stringent monitoring regime with regards to LFG, both on and around their perimeter. It is likely therefore, that LFG migration is minimal or indeed, adequately controlled, and to date there is little effect on the environment.

The supervised classification completed on the Heathfield site revealed problems in that some pixels with differing ground features appeared to have the same spectral signatures. As a result, these were grouped together and colour coded. For example, in the classification of Heathfield in ATM bands 9, 7 and 11 (Figure 6.15) the HDPE deployed at the site was classified, with vegetation shadow, in the black grouping. Interestingly, the classification highlighted the clay features from both the landfill and the Ball clay pits. Vegetation differentiation was limited to the aerial photographs which were used to choose the specific grouping for the classification. The results of this are highly dependent upon the season since fields may be fallow and plants naturally died back. This demonstrates the requirement for ground reflectance data which had not been acquired for this investigation.

Figure 6.16 portrays Heathfield in ATM bands 8, 11 and 2 respective to the blue, green and red guns in the VDU. Band 8 enables detection of the Near Infra-red, Band 11 the surface temperature and moisture levels and band 2 enables vegetation discrimination. Reflectance measurements would then enable a comparison with the typical reflectance curves found in Figures 6.5 and 6.8. For example, a deviation from the normal reflectance in the range 0.7 -1.3 μm (i.e. 40 - 50 % of the energy incident upon it) would indicate unhealthy vegetation (Lillesand & Kiefer, 1994). A decrease in chlorophyll absorption in the wavelengths 0.45 to 0.67 μm (the visible) is dominantly controlled by the leaf pigment (Figure 6.8). With regard to this stage of the process, the CASI data would provide a superior data source since it has a higher resolution, thus enabling a greater level of channels to be recorded over a similar band width as the ATM. In this way, the specification of CASI data acquisition in the vegetation analyses wavelengths would

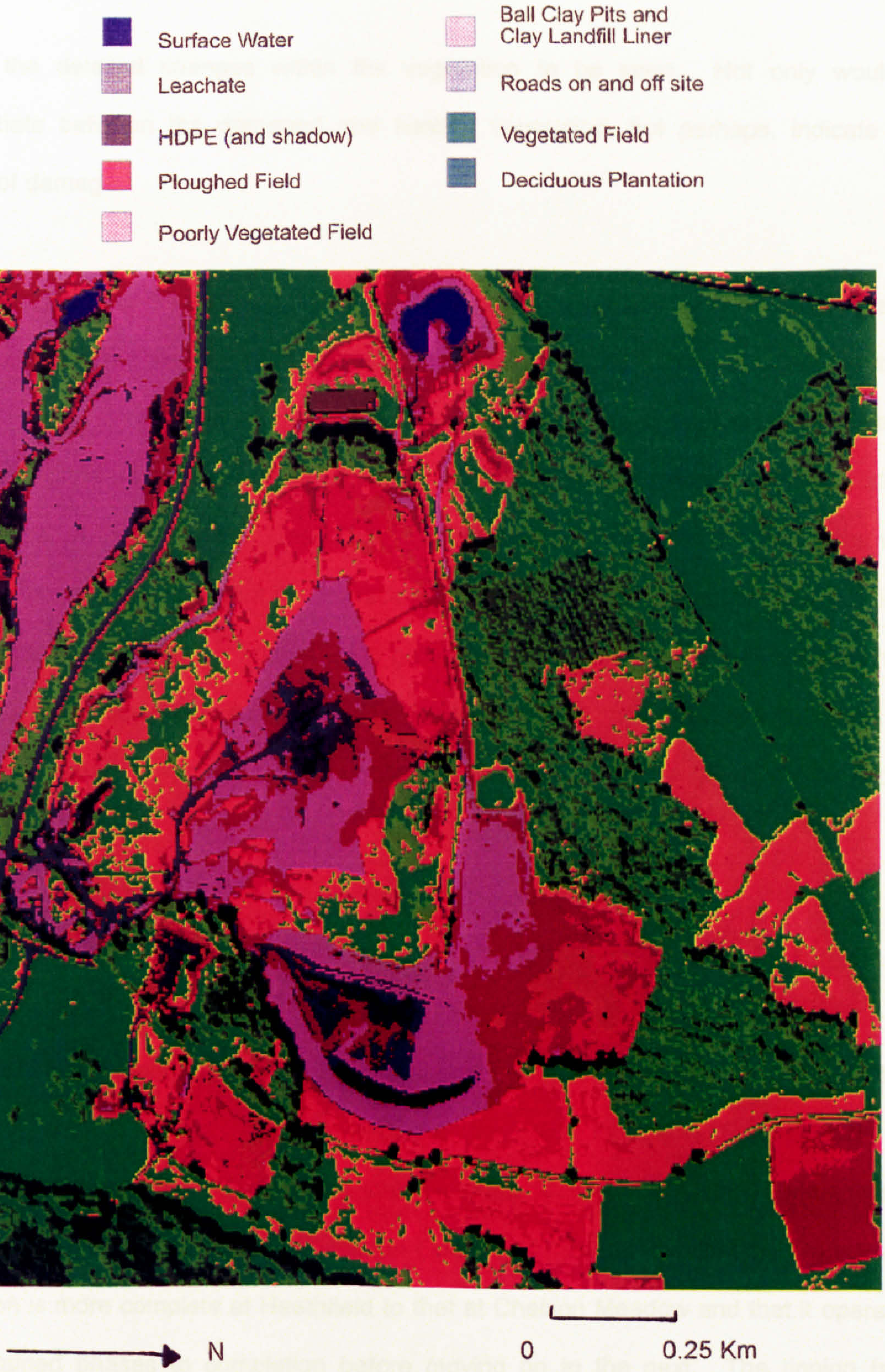


Figure 6.15 Supervised Classification of Heathfield Landfill (ATM Bands 9, 7 and 3) (1995 data).

enable the detailed changes within the vegetation to be seen. Not only would it differentiate between the damaged and healthy vegetation, but perhaps, indicate the degree of damage.

Remote sensing can be applied in order to define areas of surface water. Polluted water, in the form of leachate, will be recognised in the thermal band since it is warmer than surface waters. The reflectance level may also be different to that of unpolluted water, thus enabling the detection of polluting streams which come into contact with river waters. For example, in Figure 6.15 of Heathfield, a differentiation was made between what was known to be a collection point for surface runoff and that for leachate. A supervised classification was run on the image which grouped all water together (blue) and leachate (brown). This illustrated the difference between runoff and leachate in terms of reflectance. Therefore, details of ground features can be used to group similar known pixels.

6.11.2 Aerial Photograph Interpretation

The stereo aerial photographs provided the study with an important visible, real-time comparison to the ATM and CASI. These give an immediate indication of the extent of the Ball Clay and Limestone quarries and their proximity to the landfill sites. Immediately apparent from a comparison of the images in Figures 6.17 and 6.18 is that the progressive restoration is more complete at Heathfield to that at Chelson Meadow and that it operates self contained phases to completion before moving on to the next. The tipping face appears to occupy a much smaller area in comparison and most areas of the site are accessible by track.

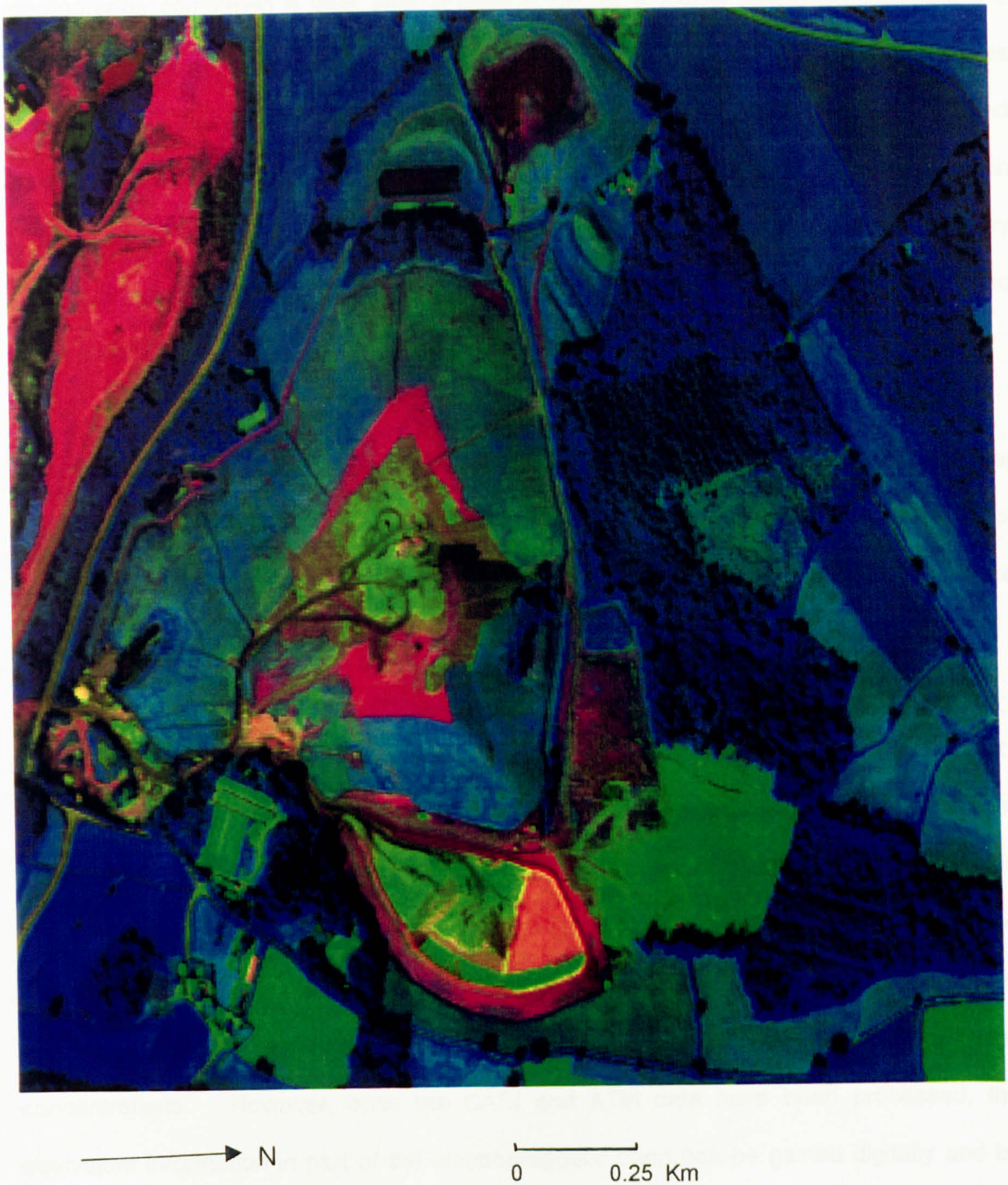


Figure 6.16 Heathfield in ATM Bands 8 (red), 11 (green) & 2 (blue) (1995 data).

Chelson Meadow, conversely, has very little vegetative cover on the surface of the site as indicated by the photograph from the first flight (Figure 6.18). The second set of aerial photographs completed a year later (Figure 6.19), at a higher resolution, illustrate the extent of the restoration process and the location of the cell divisions. This demonstrates the use of the tool to map the development of a site and locates cells which were worked during specific time frames. The proximity of the site to the estuary is clear which highlights the risks of possible surface water pollution. On the other side of the estuary railway works are evident, providing another possible cause, should the estuary be found to be polluted.

The quarrying in process adjacent to the landfill sites may ultimately affect the groundwater regime in the localised area, with even more extensive effects ascertained from larger or deeper sites. This is dependent upon the hydraulic gradient of the groundwater and the height of the water table.

This illustrates the importance of aerial photographs being integrated in a preliminary desk study in order to locate areas of specific interest prior to the airborne imagery collection. In addition, infrared photography could provide a more effective means for data collection since its processing is faster than that of the ATM or CASI. As it is known that damaged vegetation can be detected in this electromagnetic band (Lillesand & Kiefer, 1994), this technique provides a cheap and fast method to immediately ascertain damage concentrations. However, once the CASI and ATM data have been processed, the equivalent information in part of the electromagnetic band can be gained digitally and be subject to a full range of analytical techniques.

Figure 6.17 Aerial Photograph of Heathfield Landfill Site (1995) (Altitude 1600)

Figure 6.18 Aerial Photograph of Chelson Meadow Landfill (1995) (1600 m Altitude)

Figure 6.19 Aerial Photograph of Chelson Meadow (1996) (1000 m Altitude)

6.12 SUMMARISED PROCESS

The summarised flow diagram in Figure 6.20 portrays the stages envisaged for the effective application of this technique. An example of the data acquisition is taken from this chapter in order to illustrate the procedure. It recognises that difficulties may be incurred due to weather conditions and seasonal variations in vegetation patterns which also affected this research. Ground surveying has been included in the model since this current research has indicated its value in terms of linking the contamination specifically to the landfill.

It is important to note that this process is only based on the research completed by the author, with little co-operation from the industry, who at this time mainly feel that the technique is too expensive for field trials. On a broad scale, perhaps on the larger sites in operation in the USA, such field trials would be more efficient in revealing the shortcomings of the application. The sites employed in this investigation were unable to indicate specific areas of interest related to the migration of landfill pollutants.

The most important aspects are now recognised, post investigation, as the ground referencing data and the requirement to reduce the overall data to a manageable level. Remote sensing must now prove to be practical in terms of data acquisition and turn around. This investigation found that a ground survey would prove to be extremely complementary to the ATM and CASI data, both during airborne data acquisition and after, when identifying the reason for the anomalies. Once this system is running, within the monitoring strategy, relationships between ground surveying and the remote sensing can be used to pin-point damage locations.

1 Aim: To investigate the possibility of the landfill producing LFG and leachate and locate anomalous features.

Note other possible influencing activities near the landfill.

Identify the nature and extent of the problem.

↓

2 **GROUND SURVEY AND ROUTINE MONITORING**

Organise the survey to:
1. Locate areas of known vegetation damage;
2. Determine those attributed to the landfill contaminants.

Quantify and qualify the soil gas.

↓

3 Formulate plan:

Identify locations of vegetation damage related to other sources and not landfilling.

Devise the flight plan and decide type of data required:
e.g. scale, coverage and determine financial cost.

4 **RAW DATA AQUISITION**

For example, ATM & Stereophotography.

Possibly collect ground reflectance data.

Flight: dependent upon weather conditions and also seasonal variation of vegetation

↓

→ Transfer to work station
Identify necessary software, e.g. Erdas Imagine.

5 **IMAGE CORRECTION**
Geometric and radiometric

↓

6 **IMAGE PROCESSING AND ANALYSIS**

Image histograms, classification and noise reduction analyses, reflectance corrections.
Identification of anomalous areas, i.e., those indicating possible vegetation damage.
Classify according to location and extent of problem.

→ e.g. is the damage concentrated in specific areas, is it on-site or in perimeter locations? Relate to geological and ecological survey data

↓

7 Further ground surveying to prove LFG and leachate migration through existence of damaged vegetation. (Possibly only in the initial stage of model development.)

↓

8 **REMEDIATION**

Continual monitoring through closure stages for a minimum of 30 years in order to prove the landfill has not potential to pollute.

If necessary, install gas migration controls.

Refine the data acquistion to become site specific e.g. target areas where stress has already been located

It would be preferable to complete phases 2 and 4 in conjuction after the initial trials.

Once refined, the technique may take a maximum total of two working days in order to provide extensive results, combined with ground survey data based on data from the whole site.

Figure 6.20 Summarised Process of a Remote Sensing Monitoring System for Landfill

6.13 CONCLUSIONS AND DISCUSSION

The difficulties in data collection and processing, namely the time taken have indicated that the technology is presently unavailable to facilitate the development of a remote sensing application on a broader scale. This aspect has therefore proved the central concept to the investigation in that theoretical premises verify the technique but current technology restricts its use. The completed technique must demonstrate an ability to produce a faster data turn around and long term cost effectiveness in order for its development in the waste management or remediation industries. It must also provide a temporal reference since both chemical and biological interactions with the environment can be directly related to cause and effect events (Warner, 1994). As such, this investigation planned to use two datasets, flown a year apart.

Some sites may encounter problems in the determination of the flight path. For example, permission for air space may be denied if the study area is located in a military zone. However, this would not be a problem on a typical site but was encountered in the flying zone to the South of Chelson Meadow landfill in Plymouth.

Areas of interest (anomalies) have been located through this investigation but complementary evidence from ground surveying, is necessary in order to prove the link between the landfill and the damage. This would have important consequences for the site operators who will then need to discover the cause and remediate the problem as soon as possible. The effect of activities and areas other than the landfill sites may dominate. At both Chelson Meadow and Heathfield sites, outside influences were apparent including: quarries and pits being worked for Plymouth limestone and Ball clay; the tidal River Plym estuary; and less influential anthropogenically related features. This expanded to include:

- Anthropogenic features. For instance, mining activities or processing plants which pump effluent into surface water courses;

- Uncharted areas of contaminated land.

It may be possible to define the pollutants derived from the aforementioned and attribute them to specific polluters due to their chemical constituencies, i.e. a type of chemical fingerprinting.

One of the aims of this research was to assess the viability of the project without time consuming and costly ground referencing which resulted in a failure to assess the exact reflectances for the sites. Furthermore, if the latter had been acceptable, the data would have to be acquired at a much higher resolution in order that the vegetation assessment and characterisation could be completed on a specific level. However, an increase in resolution may present other problems, such as an increase in scene noise. This type of noise may increase variability within a class resulting in a reduction of classification accuracy (Jones, 1991).

The strategy presented in this research has proved not to meet the criteria as proposed by an ideal remote sensing system (Lillesand & Kiefer, 1994). In most cases, this is through no fault in the data acquisition and analyses, e.g., a perfect energy source. An ideal system, not that a typical one exists, would therefore possess the following:

- A perfect energy source;
- A non-interfering atmosphere;
- A unique energy / matter interaction, a super sensor;
- A real-time data handling system;
- Multiple end-users.

The research aimed to complete a comparison of the two landfill sites over a year, since their operational and restoration activities could have afforded this. The CASI data, as indicated previously, would have provided a far superior indication of the damage incurred (if any) by the vegetation, since the shorter concentrated bands of wavelengths are dedicated to provide more information indicating the manifestation of damage to vegetation.

Since the sites employed by this investigation are still in operation, the probability of locating areas affected by pollutant migration would have been reduced. A site with known contaminant control problems would have provided more realistic opportunities in order to test the viability of the proposed system. Due to the timing of this research, the restricted choice of locality for the study, and possible 'political' disadvantages of finding a site with problems in South West England, it was decided to compare operational sites in terms of design strategies.

The relative size of the sites is of additional importance. Chelson Meadow covers a more extensive area and is unlined, therefore possessing a greater capacity for leakage than Heathfield. At Chelson Meadow, the larger tipping faces and finished cells have been left uncovered for longer periods than Heathfield. This would have led to increased leachate production through higher rates of infiltration into the site. Higher rates of leachate generation, to increase the leachate head, will augment the possibility of breakout from the confines of the site.

The proposed application could be an effective method in the evaluation of sites to be recorded in a contaminated land register. Although the proposal for such a register has been criticised, the methodology and techniques for the collection of the data is in place through other applications. Researchers, (Hooker *et al.*, 1996 and Coulson & Bridges, 1984), have acknowledged the importance of the contribution that remote sensing could make towards recording existing sites of contamination. However, at present it has been decided that such a scheme would be impossible to implement nationally since there would be a high possibility of property blight. Once refined, the method proposed in this investigation could enhance possibilities for the detection of such sites and enable their classification in terms of degree of contamination (Simmons, 1998).

Brownfield sites in the UK have been recognised as areas for possible re-use under the principles of the sustainable development strategy (Agenda 21, Rio Conference 1992) (Lewis & Nathanail, 1996). Firstly, Brownfield sites are identified, followed by remediation which is reiterated in the USA in the form of Superfund classification (Herman *et al.*, 1994) and clean up through Federal programs, namely the Brownfields Initiative (Nelson, 1996). Many of the latter have contributed to a degree of environmental detriment which could have been averted with earlier recognition of the situation. The Love Canal incident (1976) (Montgomery, 1992), near New York, provides such an example in which severe toxic contamination was recognised thirty years after waste inception (1942). It must be noted that even in terms of cost, prevention is preferable to remediation. Roche (1996) indicates costs for groundwater remediation in excess of £100, 000, and *'large scale remediation'* costing over £1 million. Groundwater 'clean-up' is probably the most expensive remediation work which may result from landfill contamination.

Combined with a Geographical Information System (GIS) (Ehlers *et al.*, 1989 and Lewin *et al.,* 1997), data evaluation could be enhanced resulting in a user-friendly format to embrace other valuable criteria: hydrology; geology; local highways; residential developments; and anthropogenic features, for example. Such a format would provide a reliable, holistic means for monitoring sites and for use in land use classification applications. Problems in the field of land classification arising to date may in part be due to the lack of records of previous use. Computing systems, such as GIS, provide ideal opportunities to keep such records whilst also providing effective, adaptable means for regular updating and access.

Remote sensing coupled with applications, such as GIS and Environmental Management Systems (for example, ISO 14001, (ISO, 1996), the latter of which are to be integrated within the operational structure of the company, may in the future enable the development of a more integrated monitoring system. Such a strategy would encourage the landfill to meet environmental standards throughout construction, operation and closure.

6.15 SUMMARY

- The application of airborne remote sensing in order to detect and assess the migration of pollutants from a landfill site can be investigated through the variation in reflectances recorded from plant canopies.

- The airborne remote sensing monitoring technique is in early stages of development although the theory was realised as early as the 1970's. However, since then, there have been advances in data acquisition techniques and analysis so expectations for the future may be even greater.

- The CASI technique should provide a more detailed and specific approach to the detection of plant damage since it possesses more wavebands over a smaller part of the EM spectrum than the ATM method.

- Ground referencing must be an integral part of the remote sensing contaminant monitoring process and should be completed in conjunction with the airborne data acquisition (ATM or CASI). Further efforts may be required to identify causes of anomalous results and prove that they emanated from the landfill.

- An economic evaluation must be made to ensure the long-term viability of such a project. An ideal scenario would involve a company which owned a series of sites or required multispectral data collected over an extensive area.

- An approximate cost break down for this remote sensing project (1994 prices) would comprise £2500 for airborne data acquisition and 3 weeks processing at £1000 per week, totalling £5500. This is significantly less than mobilising a rotary coring rig at £5 - 7000 and installing regular boreholes at £2500 (£50 per m). Indeed, eventually the 3 weeks processing could be reduced to a maximum of 3 days (Griffiths, 1998).

7.0 DISCUSSION

7.1 INTRODUCTION

This research has highlighted complex inter-relationships within the field of landfill design, construction and monitoring in the UK. Landfilling may not be the most suitable method of waste disposal, but at the present time it provides the only final solution to certain waste streams. Since there appears to be no practical alternatives, landfilling will remain a widely used method of disposal particularly given the worldwide increase in waste volumes (Cairncross, 1993). There are options available to landfill practice which may enable it to become a safer waste management process, mainly through complex lining and leak detection systems that entomb the material (Anon 1997 & 1997b). However, the effectiveness of modern containment strategies are questionable over the long term. Systems operating with leakage would perhaps be more effective than containment, provided that they can be controlled and monitored to ensure the environmental consequences are minimal.

This thesis has concentrated on evaluating three technical processes that could provide a basis for aspects of future design, operation and monitoring practices in landfilling: on-site Quality Assurance (QA) procedures; use of Moisture Condition Value (MCV) for compaction control and; potential of Airborne Thematic Mapper (ATM) for non-invasive monitoring of landfill sites. The Quality Assurance procedures are well established and have been found to be critical in landfill practice (Cadwallader, 1994). However, MCV and remote sensing techniques require further development before they can be used by the landfill industry.

Figure 1.1 separates aspects of research and development to illustrate the relationship between the original research and development of a technique and its final application. Applied research (i.e. the application of theoretical concepts to real-world situations) is a critical stage in the development of new suites of concepts and techniques in landfill studies. Once the applicability of an approach has been proven through field trials and monitoring, this information can then be fed back to the theory and adjustments made. In the long term, it is the on-site testing and suitability of the methods and techniques that will be the deciding factor in their acceptance. This process is illustrated in Chapters Five and Six where techniques such as the MCV test and remote sensing, which have well established theoretical backgrounds, are shown to have the potential for use on-site in landfill operations but at present are not yet sufficiently robust for use in practice.

Landfilling is a major environmental concern and applied research in this area is particularly important. The waste management industry recognises this and many of the innovations being made (e.g. in landfill design, contamination mapping, geomembrane deployment) come directly from the landfill designers and operators. Clearly, however, closer links between theorists and practitioners are needed.

7.2 QUALITY ASSURANCE OF LANDFILL DESIGN AND CONSTRUCTION

The thesis has highlighted the importance of a complimentary QA programme, which must be built into the design and construction phases of a landfill to ensure that the end product meets the specification requirements. During the time available, (three months), valuable experience was gained that allowed key problems encountered during the construction of two contrasting landfill sites to be identified and investigated.

Whilst QA procedures are critical to ensure construction is carried out in line with the specification, allowances must be made for changes to be made to meet unexpected ground conditions. This is illustrated at Site Beta (Chapter Four, section 4.5.6) where groundwater infiltration was difficult to control throughout the earthworks. Therefore, regular minor alterations to the design of the ground water control system were required as construction proceeded. At Site Beta, the consequences of the water bearing skerry strata upon the construction of the under drainage system were underestimated. Severe meteorological conditions can also have unexpected consequences. At Site Alpha, high summer temperatures dried the exposed clays, both in the stockpiles for the liner and the placed engineered liner. These conditions may have required the wetting of the clays prior to deployment or even have affected the integrity of the liner. Periods of intense rainfall and high winds also hampered the composite liner placement, further illustrating the effect of meteorological conditions.

Notwithstanding the need for the design to be altered on-site to meet changing conditions, QA techniques are required to ensure that a successful landfill design is implemented in order to guarantee the long-term integrity of the landfill. Such measures provide assurance that the landfill has been constructed in accordance with the design plan and that deviations from this are both explained and recorded (Hopper & Leach, 1997). In addition, should problems arise from the site due to a failure in the liner they can be traced to a particular site location, length of liner material, type of seam and even roll number. During the site works described in Chapter Four, this was more important to achieve at Site Beta, than Alpha, as it would be accepting mainly putrescible wastes which are associated with the production of greater quantities of gases and leachates (IWM, 1998b).

One of the most common variables in QA interpretation is the frequency of on-site testing (Jessberger, 1994). The testing frequency may deviate from the Specifications, Quality Plan, or even Codes of Practice, depending on the homogeneity of the material and the nature of the construction. For example, less rigorous testing may be required by a clay subgrade, (Site Beta), as opposed to a single compacted clay liner, (Site Alpha), since, often the liner system does not include the subgrade. The clay subgrade gives an additional zone of attenuation whilst also providing a smooth, level base for the installation of plastic liners.

7.3 MCV TESTING

The MCV testing procedure, completed on the London Clay from Site Alpha and the Mercia Mudstone from Site Beta (Chapter Five), was originally designed to be a fast method for determining the suitability of materials for use in embankment fill construction (Parsons, 1979). This allows the correct moisture content / compaction combination for the in-placed material to be assessed. In landfill liner construction and placement, the MCV could reduce the need for constant testing, to verify that the liner remains within its prescribed limits (for dry density and moisture content), in accordance with the compaction specification.

It is important to compare results achieved in the laboratory with those on site, since throughout landfill liner construction, site monitoring must prove that the original design specifications have been adhered to. This concept is illustrated by Fookes (1997) in a comparison between '*labrock* and *labsoil*' which may or may not reflect the *in situ* properties of '*siterock*'. Ideally, the MCV method would be suitable for on-site use. However, the investigation into the equipment and the technique revealed that there were problems with its practicality. The nature of the equipment, in particular the possible increased friction on the guidelines, as observed by Green & Hawkins (1987) increased the error margin and may provide a basis for the explanation of the variable results observed in this study (Table 5.9). Ambiguous guidelines for the determination of the final MCV result also raised doubts about the overall results. The MCV has positive attributes but more robust equipment and stricter protocols are required, and indeed are achievable. Therefore, it has been identified that on-site monitoring requires a rapid technique, but that in its present form the MCV does not provide this.

There is a definite necessity for the development of a faster technique for monitoring permeability of placed materials throughout construction. The method must be able to operate simultaneously with construction of the liner. There is a requirement for a test which is easy to use, as well as providing instantaneous results on-site. However, it is recognised that the materials may still require random laboratory testing and comparison with on-site results in order to ensure that homogeneous placement has been attained and maintained throughout construction. This aspect of QA is important in the long term, since it provides evidence that material placement was completed in accordance with the design and construction criteria stipulated by the EA and planners and in Codes of Practice (such as, NWWDO 1995 & 1996).

The final observation of Chapter Five is that the suitability of clays as landfill liners should not only be determined through their physical attributes but also their chemical constituents. The ability for clay minerals to attenuate chemicals in leachates should therefore influence the type of liner or subgrade deployed. In this way, chemical testing should be integrated into both the pre-construction site investigation and the QA procedures in order to assess attenuation properties of clays used at each site, especially when only a single clay liner is being used.

7.4 REMOTE SENSING FOR NON-INVASIVE LANDFILL MONITORING

Non-invasive aerial remote sensing techniques (Chapter Six) could provide landfill monitoring procedures which are environmentally benign and also have significant temporal and spatial advantages. With development they could provide a rapid means of data collection. However, this investigation has outlined some of the current problems in data acquisition and processing.

Aerial remote sensing can be used as a primary identifying mechanism in order to locate areas on the landfill, or in its immediate environment, which require further examination, possibly through ground surveying. Aerial remote sensing also has long-term advantages since the cost of equipment maintenance would probably be less than the siting, operation and regular upkeep of boreholes (Griffiths, 1998). This does not mean, however, that remote sensing will supplant the need for monitoring at ground level. Indeed, remote sensing and ground based monitoring can be combined in order to produce more efficient monitoring results. From the results of this investigation it can be seen that once remote sensing monitoring becomes operational, its advantages, in terms of speed of data collection and results assessment will far outweigh those of invasive techniques, such as ground water borehole or surface water sampling.

This project intended to assess the viability of Airborne Thematic Mapper (ATM) as a technique to produce a rapid data turn around for landfill monitoring on two case study landfills in the South West. In the early phases of this investigation, it was identified that since stressed vegetation was a good indicator of landfill contaminant migration, and could be detected through remote sensing, it could be used as a monitoring tool. Examination of the literature on airborne remote sensing indicated that another technique, the Compact Airborne Spectrographic Imager (CASI) was potentially a more useful approach than the ATM. However, whilst CASI were collected for this study (Chapter Six, section 6.8.2.2) the data were not made available by NERC in time for inclusion in this thesis. The quality of data which can be recorded in the CASI wavebands required to identify vegetation (Table 6.2) is significantly higher than that of the ATM (Table 6.1) as reflectance data are collected on narrower wavebands (NSS, 1996). The narrower spectral wavebands could make it possible to be more specific about the location of the red edge (0.68 - 0.75 μm) (Boochs *et al.*, 1990). For example, a blue shift in the red edge is indicative of early stress-induced decreases in chlorophyll content (Hoque & Hutzler, 1992) The CASI data will therefore provide a valid comparison to the tested ATM techniques. In the future, an assessment can be made on the suitability of this approach.

Some landfill operators currently employ aerial photography within their monitoring strategy since it provides a spatial and temporal interpretation of the site. Should the CASI or ATM techniques fail to prove financially viable, then aerial photography could be enough to provide an immediate indication of changes at ground level, for example a deterioration in vegetation health. Furthermore, false colour Near Infra Red photographs and video thermography (Titman, 1996) provide other methods for assessment at ground level. Video imagery can be used in order to detect leachates since they are generally warmer than ground or surface waters (Titman, 1996).

This investigation did not employ ground-referencing data in an attempt to decrease the turn around time of the data. The original aim was to identify anomalous areas on-site through remote sensing and then to complete a walk over survey in order to provide an explanation. This project has identified that ground truthing is required at the same time as the remote sensing data is recorded. This may be easier on an operational site where the operator or site manager is knowledgeable about the area and current strategies on-site. Since a specialist knowledge base is required for remote sensing imagery acquisition and processing, it is probable that waste management companies would need to contract specialist remote sensing consultants to complete the data analysis.

7.5 DISCUSSION

Throughout the process of landfilling, appropriate controls and requirements must be met in order to ensure the protection of the environment. This is a requirement both in the short term, through construction and operation stages, into the long term where the potential for severe environmental damage may be increased and may result in occurrences such as the Loscoe incident (Williams & Aikenhead, 1991).

Three techniques were identified at the start of this thesis which have been investigated in terms of their applicability to landfill design, construction or practice. These methods, the investigation of on-site QA procedures, the MCV and airborne remote sensing, have had varied level of success as described.

The impact and legacy of landfills upon the environment will continue to be an important issue in the future. Landfill engineers, operators and regulators need to co-operate to facilitate the prevention of contamination from all sites. There are some landfills in current operation for which contamination prevention has not or cannot be achieved, resulting in a requirement for effective remediation and clean-up techniques. It should be a requirement that landfill engineering should prevent damage to the environment as far as possible.

8.0 CONCLUSIONS AND FUTURE WORK

This thesis has illustrated three techniques and evaluated them in terms of their use in landfill practice in the UK. The following summation outlines the key points of the thesis and gives details of possible areas for further research.

Chapter Two evaluates the legislative and policy development which has resulted in the current controls placed on landfill practice by the UK and Europe. Chapter Three assesses the design and construction issues involved in landfill practice in the UK to date and highlights techniques employed during construction. These two chapters set the context for landfilling practice in the UK and illustrate how UK and European legislation (for example, the Water Resources Act (DoE, 1991b)) and policies (for example, the Policy and Practice for the Protection of Groundwater, (NRA, 1992)) influence contemporary landfill construction and operation.

Chapter Four illustrates the importance of continual Quality Assurance (QA) throughout the design and construction of landfill sites. Landfill sites may require diverse approaches to QA, but should provide a recognised, certified level of assurance. A standardised approach to QA would provide a higher overall degree of assurance, whilst also providing the engineer with a framework of working guidelines. In-house consultancy guidelines and others, such as manufacturers manuals (Gundle, 1995) and American guidelines (for example, ASTM, D4437 (ASTM, 1998)), could be replaced by a standardised, integrated approach which allows for varying site conditions and landfill design. Within such a framework, a landfill could be designed and constructed in order to minimise further the risks of contamination.

In order to provide an effective method for deriving a set of QA procedures, data must be collected from different site construction projects. The data should take the form of workable objectives for liner construction in terms of:

- Testing frequency;
- Financial cost to the project;
- Time limitations incurred by testing and awaiting results.

In regard to these points, the MCV test, examined in Chapter Five, provides a potential procedure for faster compaction monitoring whilst also enabling the control of the related parameters (moisture and density) during the construction of a clay liner.

This research has shown that, although the MCV test can be used in other engineering circumstances, such as roadworks (Barnes, 1995), it is not directly applicable to landfill liners as it stands. Importantly, additional investigation is required into:

- The design of the appliance, since seepage occurred both at higher moisture contents and also, when testing the much finare samples, i.e., London Clay.
- The use of the equipment on-site due to the problems of manoeuvrability and stability, i.e. weight and impracticality, which were encounteres evened under laboratory conditions.

The MCV could be integrated in a QA programme for a clay liner, (i.e. using density, moisture content, particle size and Atterberg limits testing), in order to assess its applicability and also, its validity as an on-site testing procedure. Integration of the MCV in this way can only be completed upon restructure of its instruction procedures for use on-site. This research has shown the existence of strategic problems through the interpretation of varying protocols thus appraising the potential of the MCV test.

In Chapter Six, airborne remote sensing has been evaluated as a technique for non-invasive monitoring using two landfill site case studies. The results of this investigation have illustrated that the remote sensing technique should first be applied to sites which are known to have problems relating to Landfill gas (LFG) and leachate migration. In this way, the technique can be directly tested, as opposed to attempting to manipulate a non-specialised technique to locate areas of contamination which may not even exist. Ideally, an unlined site which is closed (and capped), or even, an older uncontrolled 'tip' would provide a more effective study location. Thus the most effective wavebands could be pinpointed through data manipulation. In addition, the collection of ground survey information from vegetation and soil can be combined with meteorological and barometric data, alongside borehole gas measurements, collected at the same time as the remote sensing flight. These additional parameters could assist in eliminating the effects of moisture and variation in vegetation and soil type. Meteorological and barometric data would provide a detailed indication of the effects of localised conditions at the time of data collection.

Development of a full prototype monitoring strategy was therefore not feasible during this phase of research. Indeed, the aim of providing a fast turnaround of data for landfill monitoring was not proven through this investigation due to data acquisition problems. At this current stage, data acquisition and manipulation proved too lengthy a process in order to warrant its use by the waste management industry. This does not imply, however, that the use of remote sensing will not be valid after further research to provide a more precise technique.

The key to the remote sensing monitoring lies with the fact that Compact Airborne Spectrogrpahic Imager (CASI) acquired data possesses a greater number of wavebands over a narrower band width. This enables clarification of results to assess the degree, and possibly, type of vegetation damage. It may even be possible to isolate the type of contamination in occurrence and link this to the actual source. In this way, background sources of contamination can thus be eliminated. In combination with a leak detection system in lined sites, remote sensing using CASI may possibly be able to target the emanation of the contamination.

In future developments, remote sensing could provide a rapid monitoring technique in order to assess:

- Clay landfill capping integrity in the long term -

  Since clay types can be determined through remote sensing and the density of the clay cap may also be possible to assess.

- Those sites which are difficult to access -

  Since aerial remote sensing may not always require ground referencing data imagery of inaccessible locations can be acquired. This is of particular interest for countries such as Australia where remote sensing in areas of the 'Outback' and Subtropical Rainforest would reduce the extensive ground surveying which is required, yet cannot be completed in inhospitable conditions.

- Locations of extensive contamination and areas of contaminated land -

  Sites of unknown contamination can be located and recorded. Traditionally, identification of contaminated land would have required copious amounts of strategically placed boreholes and site surveys. Using the data recorded from one flight it would be possible to assess the extent of the contaminant plume and even produce a qualitative assessment provided stressed vegetation was evident.

It is suggested that limits are set relating to the quantity of monitoring data collected by eventually defining a proven procedure. This is to achieve the enhancement of the overall quality of the data and reduce processing time. There could be problems with data management but these should be addressed through new computer software packages and GIS systems.

The results of this thesis have shown that there is potential for both the MCV and remote sensing techniques. At their current stage of development however, sufficient precision is not directly achievable and therefore, their use cannot be justified. The thesis has demonstrated the need for regulated QA procedures in order to provide working standards for the industry. The author of this thesis believes that with further development within specific aspects of QA monitoring, MCV testing and remote sensing, there is the potential for specified use these techniques in landfill engineering and monitoring.

9.0 PLATES

Plate 8.1. Attenuate and Disperse Landfill.

Plate 8.2. Anchor Trench.

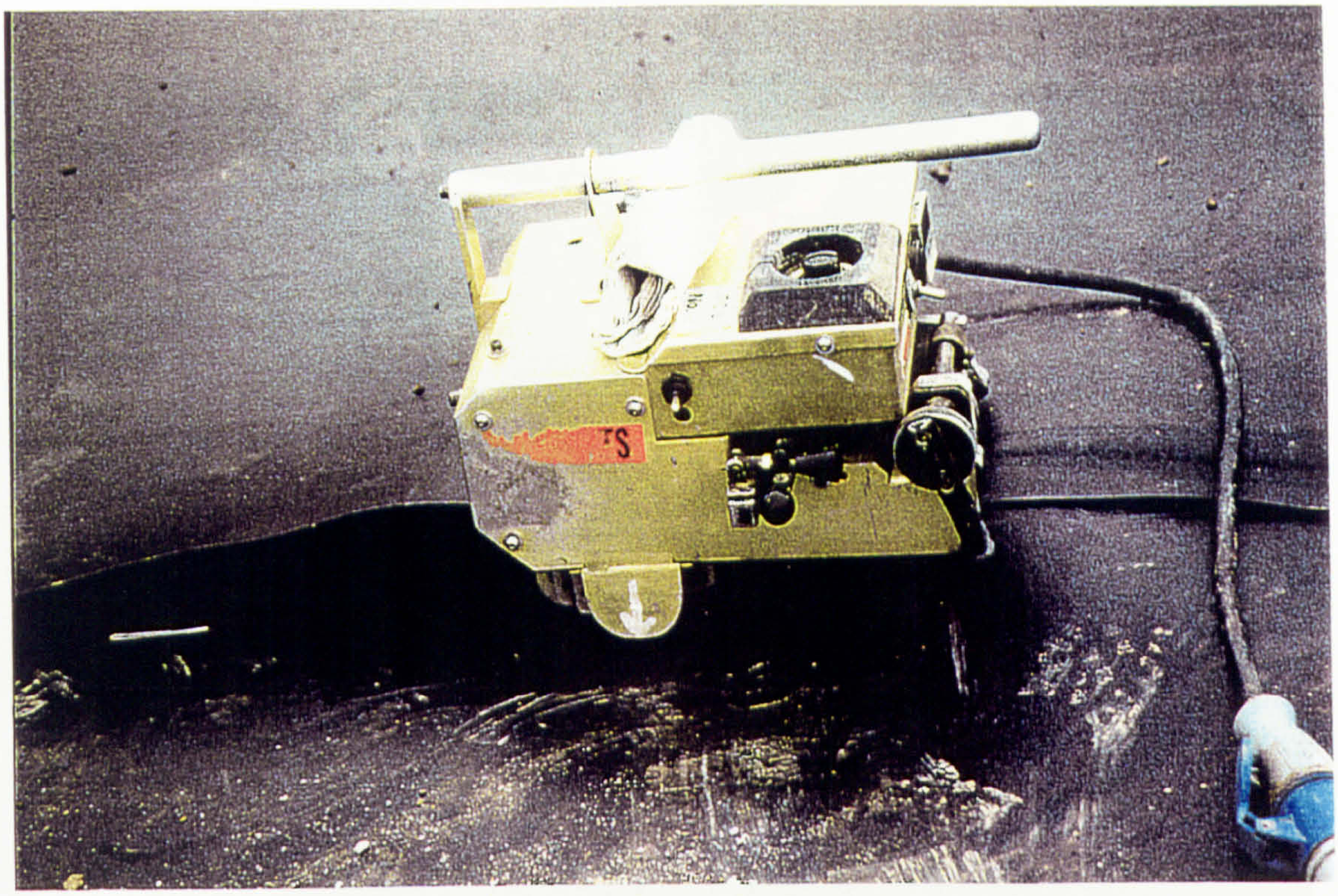


Plate 8.3. Fusion Welding.

Plate 8.4. Pie and Boot Construction.

Plate 8.5. Extrusion Welding.

Plate 8.6. Gravel Deposits at Site Alpha.

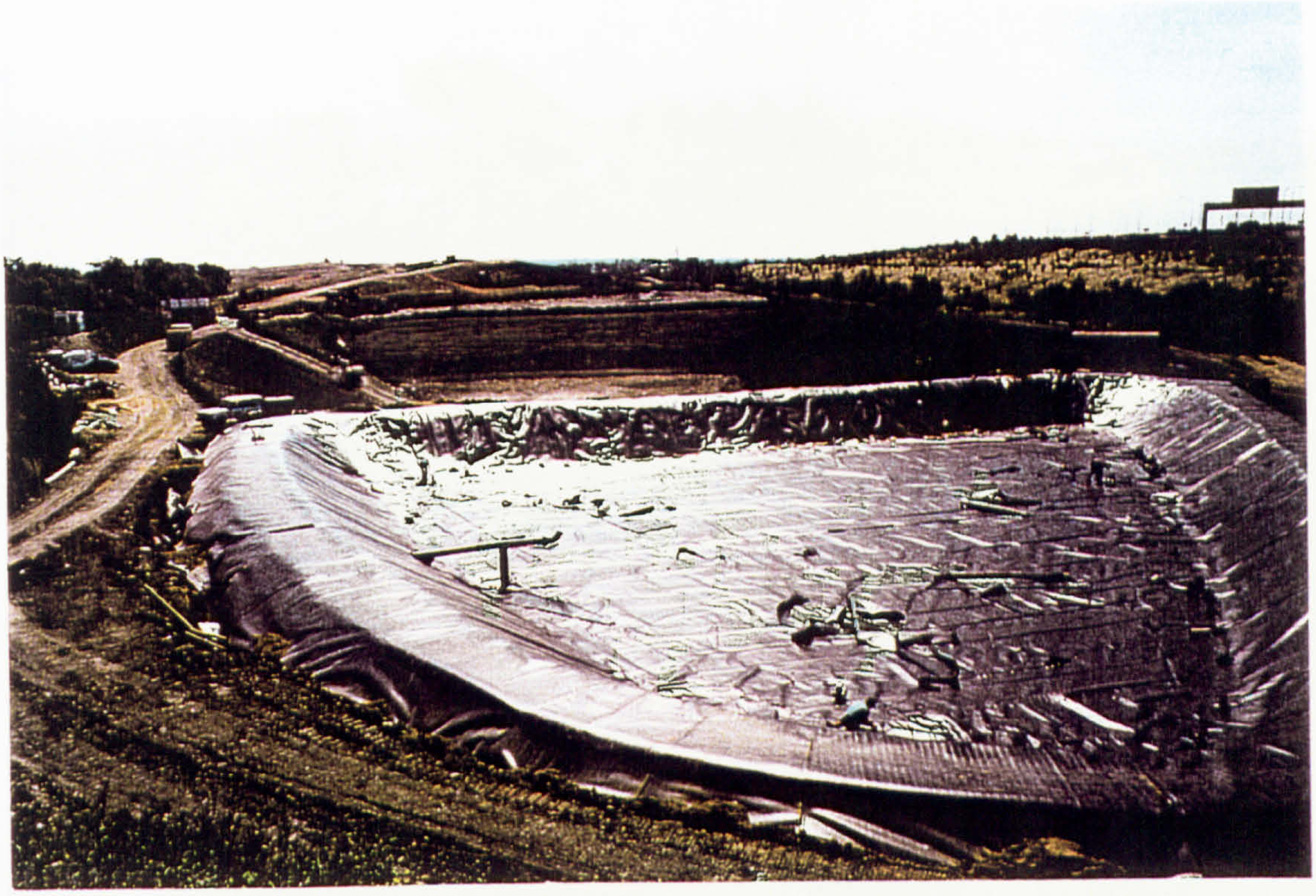


Plate 8.7. HDPE Lined Aeration Lagoon at Site Alpha.

Plate 8.8. D6 Bulldozer and Towed Sheepsfoot Compactor.

Plate 8.9. Mercia Mudstone Trial Pit Exposing Skerry Bands.

Plate 8.10. Herringbone French Drain Layout for Site Beta.

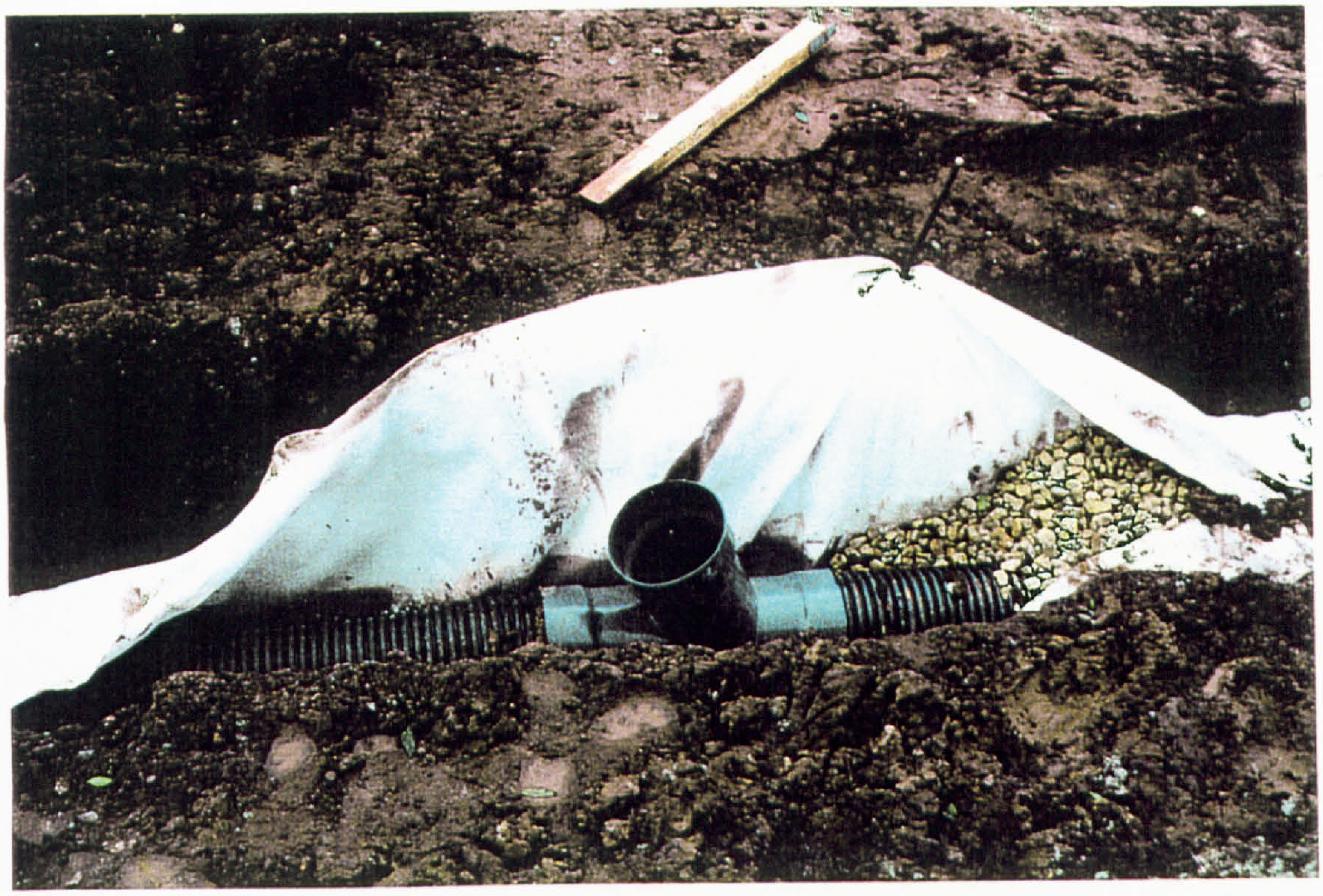


Plate 8.11. French Drain Construction.

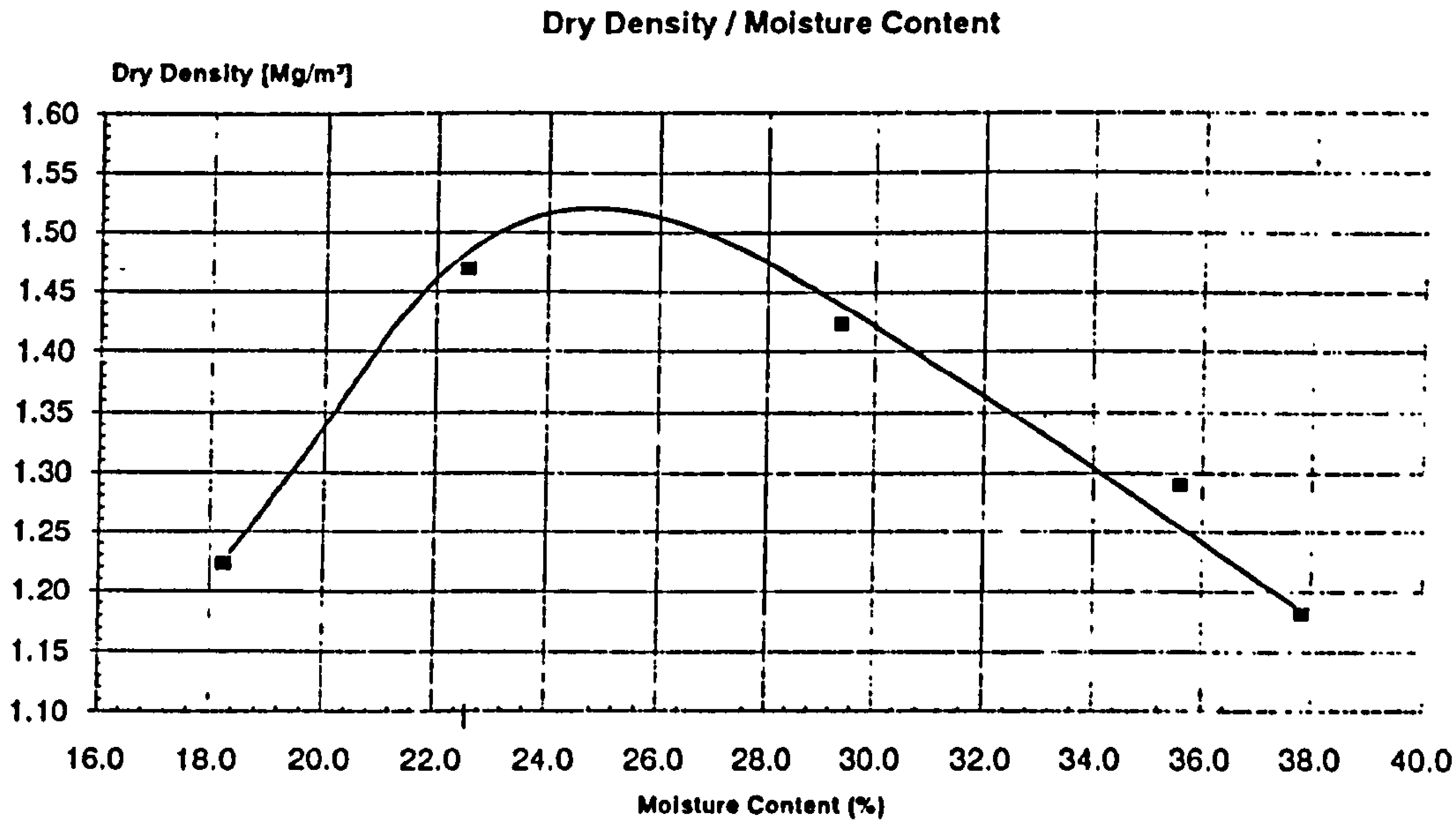
10.0 APPENDICES

APPENDIX 10.1

SITE ALPHAS OPTIMUM DRY DENSITY AND MOISTURE CONTENT TEST RESULTS

Test Results

Maximum Dry Density : 1.53 Mg/m³ Optimum Moisture Content : 25 %



APPENDIX 10.2
A SAMPLE OF SITE ALPHAS *IN SITU* MOISTURE CONTENT AND DENSITY RESULTS

Maximum dry density: 1.53 Mg m^{-3}
Depth of Test: 175 mm

Test No.	Moisture Content (oven dry) (%)	Dry Density Mg/m^3	Degree of Compaction (%)
1.	27	1.48	97.2
2.	27	1.46	95.7
3.	8.1	1.69	110.9
4.	8.1	1.69	110.8
5.	13	1.64	107.6
6.	13	1.64	107.5
7.	13	1.65	108.3
8.	13	1.67	109.2
9.	12	1.67	109.3
10.	28	1.49	97.6
11.	28	1.45	95
12.	28	1.45	95.1
13.	26	1.47	96.4
14.	26	1.52	99.8
15.	8.1	1.82	119.3
16.	8.1	1.79	117.3
17.	20	1.63	106.6
18.	20	1.65	107.9
19.	12	1.75	115
20.	12	1.77	116.4
21.	13	1.64	107.5
22.	13	1.61	105.7
23.	28	1.43	93.9
24.	28	1.43	93.9
25.	23	1.50	98
26.	21	1.55	101.4
27.	24	1.50	97.7
28.	24	1.50	98.3
29.	21	1.58	103.2
30.	21	1.57	102.7
31.	25	1.45	95
32.	24	1.56	101.8
33.	24	1.56	102.2
34.	27	1.49	97.2
35.	23	1.50	98
36.	23	1.48	97.1
37.	22	1.48	96.8
38.	23	1.51	98.7
39.	20	1.58	103
40.	22	1.58	103.3
41.	21	1.54	100.9
42.	32	1.40	91.2
43.	24	1.50	98.3
44.	25	1.47	96
45.	25	1.49	97.1

46.	24	1.48	96.6
47.	24	1.50	98
48.	24	1.52	99.5
49.	20	1.53	100
50.	21	1.54	100.7
51.	18	1.63	106.6
52.	22	1.56	101.7
53.	24	1.51	98.6
54.	22	1.53	99.7
55.	23	1.56	101.5
56.	23	1.54	100.4
57.	24	1.53	100.2
58.	22	1.55	101.2
59.	27	1.50	98.4
60.	27	1.44	93.9
61.	26	1.51	98.6
62.	25	1.51	98.7
63.	26	1.48	96.6
64.	26	1.48	96.8
65.	26	1.46	95.6
66.	26	1.44	94.2
67.	25	1.5	98
68.	24	1.55	101.4
69.	25	1.58	103.2
70.	21	1.55	101.4
71.	24	1.55	101.9
72.	24	1.47	96.4
73.	24	1.56	102.5
74.	23	1.6	105.1
75.	20	1.6	105.2
76.	19	1.58	103.6
77.	20	1.61	105.6
78.	20	1.62	106.4
79.	26	1.38	90.1
80.	26	1.41	92
81.	26	1.45	94.5
82.	25	1.57	102.5
83.	25	1.56	102.1
84.	27	1.52	99.4
85.	25	1.55	101.6
86.	26	1.57	102.7
87.	26	1.54	100.7
88.	26	1.58	103.1
89.	24	1.61	105
90.	27	1.5	98
91.	26	1.55	101
92.	26	1.4	91.3
93.	26	1.38	90.1
94.	26	1.44	94.1
95.	26	1.53	100.3
96.	26	1.54	100.7
97.	24	1.55	101.4
98.	25	1.49	97.5
99.	26	1.56	101.8
100.	25	1.46	95.6

APPENDIX 10.3

ATTERBERG LIMIT RESULTS

LIQUID LIMIT CALCULATION (CONE PENETROMETER METHOD)

London Clay

Test No.	1	2	3	4	5
Sample Type	LC	LC	LC	LC	LC
Cone penetration (mm)	15	16	16	24.7	19.1
Container No.	20	11	7	12	67
Mass of wet soil & container (g)	24.44	28.71	32.64	21.92	26.97
Mass of dried soil & container (g)	17.5	19.6	21.6	14.8	17.9
Mass of container (g)	4.94	4.71	5.37	5.28	4.8
Mass of moisture (g)	6.94	9.11	11.04	7.12	9.07
Mass of dried soil (g)	12.56	14.89	16.23	9.52	13.1
Moisture Content %	55.3	61.2	68	74.8	69.2
Liquid limit	61	66	73	68	71

Average London Clay ll = 68

Mercia Mudstone

Test No.	1	2	3	4	5
Sample Type	MM	MM	MM	MM	MM
Cone penetration (mm)	20.9	15	19.2	26.4	24.6
Container No.	31	2	41	5	31
Mass of wet soil & container (g)	29.45	29.18	34.64	37.98	36.98
Mass of dried soil & container (g)	23.8	23.8	27.8	29.5	28.4
Mass of container (g)	5.36	4.59	5.39	4.81	5.38
Mass of moisture (g)	5.56	5.38	6.84	8.48	8.58
Mass of dried soil (g)	18.44	19.21	22.41	24.69	23.02
Moisture Content (g)	30.6	28	30.5	34.5	37.3
Liquid Limit	30	31	31	33	35

Average ll = 32

PLASTIC LIMIT

Sample No	1	2	3	4
Sample Type	MM	MM	LC	LC
Mass of wet soil & container (g)	11.40	12.69	10.09	13.8
Container No.	9	7	18	5
Mass of container (g)	3.19	3.34	5.47	4.5
Mass of dry soil & container (g)	10.1	10.35	9.2	11.6
Mass wet soil (g)	8.21	9.35	4.62	9.3
Mass dry soil (g)	6.91	7.01	3.73	7.1
Moisture Content %	18.8	33.4	23.9	31
Plastic Limit (%)	26		28	

APPENDIX 10.4

MCV RESULTS

LONDON CLAY MOISTURE CONDITION VALUE RESULTS

Sample No.	LC a		LC b	
Soil Description	Dry London Clay 1.5kg		Wet London Clay *Some break out from base	
Total No. of blows	Penetration (mm)	Change in penetration (mm)	Penetration (mm)	Change in penetration (mm)
1	37	11.1	61.5	40.4
2	43	11.2	83	22.8
3	48.1	9.4	93.9	12.1
4	48.1	12.2	101.9	4.6
6	51.2	12.7	105.8	0.7
8	54.2	13.8	105.8	0.7
12	57.5	12	106 *	0.5
16	60.3	10.7	106.5	0
24	63.9	7.1	106.5	0
32	68	3	106.5	0
48	69.5	1.5	106.5	
64	71.0	0		
96	71.0	0		
128	71.0	0		
192				
256				
MCV	14.8		6	
Container No.	5M		12M	
Container mass (g)	317.8		313.8	
Mass of wet soil & tray (g)	773.4		774.4	
Mass dried soil (g)	407.9		335.9	
Mass wet soil (g)	463.4		460.4	
Moisture Content %	13.6		37.1	

Sample No.	LC c		LC d	
Soil Description	Moist London Clay		Dry London Clay	
Total No. of blows	Penetration (mm)	Change in penetration (mm)	Penetration (mm)	Change in penetration (mm)
1	29.1	28.5	78.9	10
2	37.4	43.5	84	10
3	48.9	38.02	86.5	5. 3
4	57.6	30.3	88.9	10 .1
6	71.8	16.1	91.9	9. 6
8	80.9	7	94	8. 2
12	86.92	0.98	91.8	10 .4
16	87.9	0	99	3. 2
24	87.9	0	101.5	0. 7
32	87.9		102.2	0
48			102.2	0
64			102.2	
96				
128				
192				
256				
MCV	9.7		10.5	
Container No.	18		6	
Container mass (g)	9.6		4.9	
Mass of wet soil & tray (g)	80.9		25.6	
Mass wet soil (g)	71.3		20.7	
Mass dried soil (g)	54.2		18.6	
Moisture content %	31.5		11.3	

Sample No.	LC e		LC f	
Soil Description	Moist London Clay		Dry London Clay	
Total No. of blows	Penetration (mm)	Change in penetration (mm)	Penetration (mm)	Change in penetration (mm)
1	32.3	48.7	42	18
2	55.4	28.3	50.8	18.3
3	69.7	14	57.1	19.3
4	81	2.7	60	19
6	83.7 SEEP	0	66.8	17.1
8	83.7	0	69	17.7
12	83.7	0	76.4	13.5
16			79	10.9
24			83.9	9
32			86.7	7.1
48			89.9	3.9
64			89.9	3.9
96			92.9	0.9
128			93.8	0
192			93.8	0
256			93.8	0
MCV	5.9		15.8	
Container No.	18		119B	
Container mass (g)	9.7		9.1	
Mass of wet soil & tray (g)	93.3		94.4	
Mass wet soil (g)	83.6		85.3	
Mass dried soil (g)	61.1		77.6	
Moisture Content %	36.8		9.9	

Sample No.	LC g	
Soil Description	Moist London Clay	
Total No. of blows	Penetration (mm)	Change in penetration (mm)
1	11	44
2	33.9	42.9
3	45.4	36
4	55	29
6	69.9	14.1
8	76.8	11.2
12	81.4	2.6
16	84	0
24	84	0
32	84 SEEP	0
48	84	0
64	84	0
96	84	0
128		
192		
256		
MCV	10.2	
Container No.	18	
Container mass (g)	9.6	
Mass of wet soil & tray (g)	112.8	
Mass wet soil (g)	103.2	
Mass dried soil (g)	77.9	
Moisture Content %	32.5	

MERCIA MUDSTONE MOISTURE CONDITION VALUE RESULTS

Sample No.	MM h		MM i	
Soil Description	Mercia Mudstone Dry stony material		Mercia Mudstone	
Total No. of blows	Penetration (mm)	Change in penetration (mm)	Penetration (mm)	Change in penetration (mm)
1	60.4	12.7	53 (10.7)	27.9
2	65	16.5	66.9 (93.1)	26
3	69.2	16.7	75 (85)	23.6
4	73.1	15.9	80.9 (79.1)	20.1
6	77.5	14.5	87.8 (72.2)	13.2
8	81.5	12.4	92.9 (67.1)	8.1
12	85.9	10.1	98.6 (61.4)	2.4
16	89	8.5	101 (59)	0
24	92	6.5	101 (59)	0
32	93.9	4.6	(59)	0
48	96	2.5	(59)	0
64	97.5	1		
96	98.5	0		
128	98.5	0		
192				
256				
MCV	14.6		10	
Container No.	19A		A5	
Container mass (g)	79.5		97.2	
Mass of wet soil & tray (g)	457.9		520.1	
Mass dry soil & container (g)	441.7		462.7	
Mass wet soil (g)	378.4		422.9	
Mass dried soil (g)	362.2		365.5	
Moisture Content %	4.5		15.7	

Sample No.	MM j		MM k	
Soil Description	Moist Mercia Mudstone Very stoney & sandy		Drier MM - some small clods	
Total No. of blows	Penetration (mm)	Change in penetration (mm)	Penetration (mm)	Change in penetration (mm)
1	99	18.3	69	17.8
2	117	1.5	74.1	22.5
3	115	3.5	81.2	19.3
4	117.3	1.2	86.8	13.7
6	118.5	0	93	7.5
8	118.5	0	96.6	3.9
12	118.5	0	100.5	0
16	118.5		100.5	0
24			100.5	0
32			100.5	
48				
64				
96				
128				
192				
256				
MCV	2.3		8.4	
Container No.	72C		1A	
Container mass (g)	4.5g		4.5g	
Mass of wet soil & tray (g)	76.2		44.6	
Mass wet soil (g)	71.7		40.1	
Mass dried soil (g)	61.8		35.2	
Moisture Content %	16		13.9	

Sample No.	MM l		MM m	
Soil Description	MM wet, v. sandy, stony			
Total No. of blows	Penetration (mm)	Change in penetration (mm)	Penetration (mm)	Change in penetration (mm)
1	88	8.6	77.9	14
2	95.9* seep	0.7	90	3.8
3	96	0.6	91	4.5
4	96.6	0	91.9	3.6
6	96.6	0	91.9	3.6
8	96.6	0	93.8	1.7
12			95.5* seep	0
16			95.5	0
24			95.5	0
32			95.5	
48				
64				
96				
128				
192				
256				
MCV	2		4.5	
Container No.	72C		72C	
Container mass (g)	4.6		4.6	
Mass of wet soil & tray (g)	92.1		92.4	
Mass wet soil (g)	87.5		87.8	
Mass dried soil (g)	73.8		73.27	
Moisture Content %	18.6		19.8	

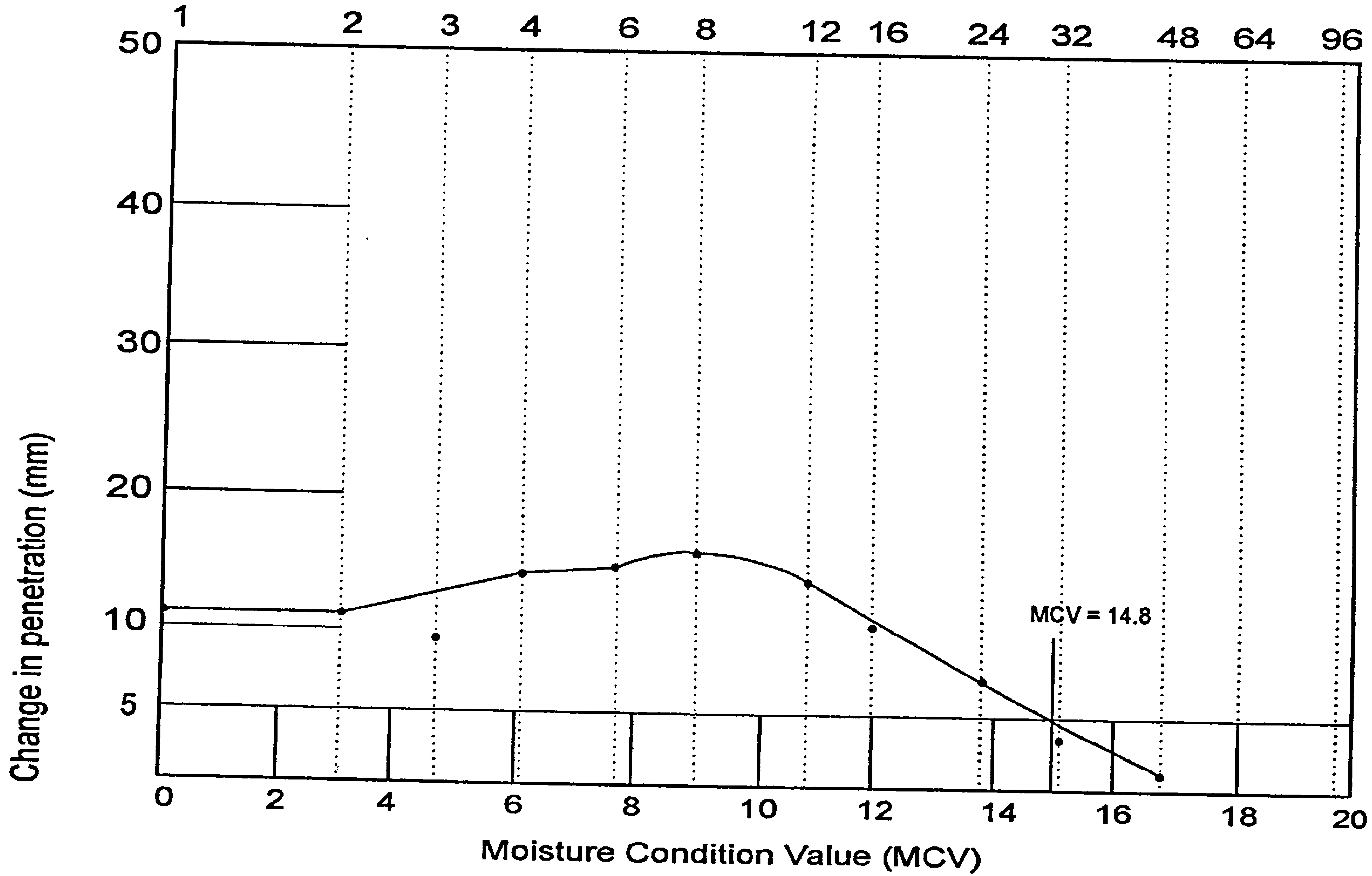


Figure 4.16 London Clay (Result a)

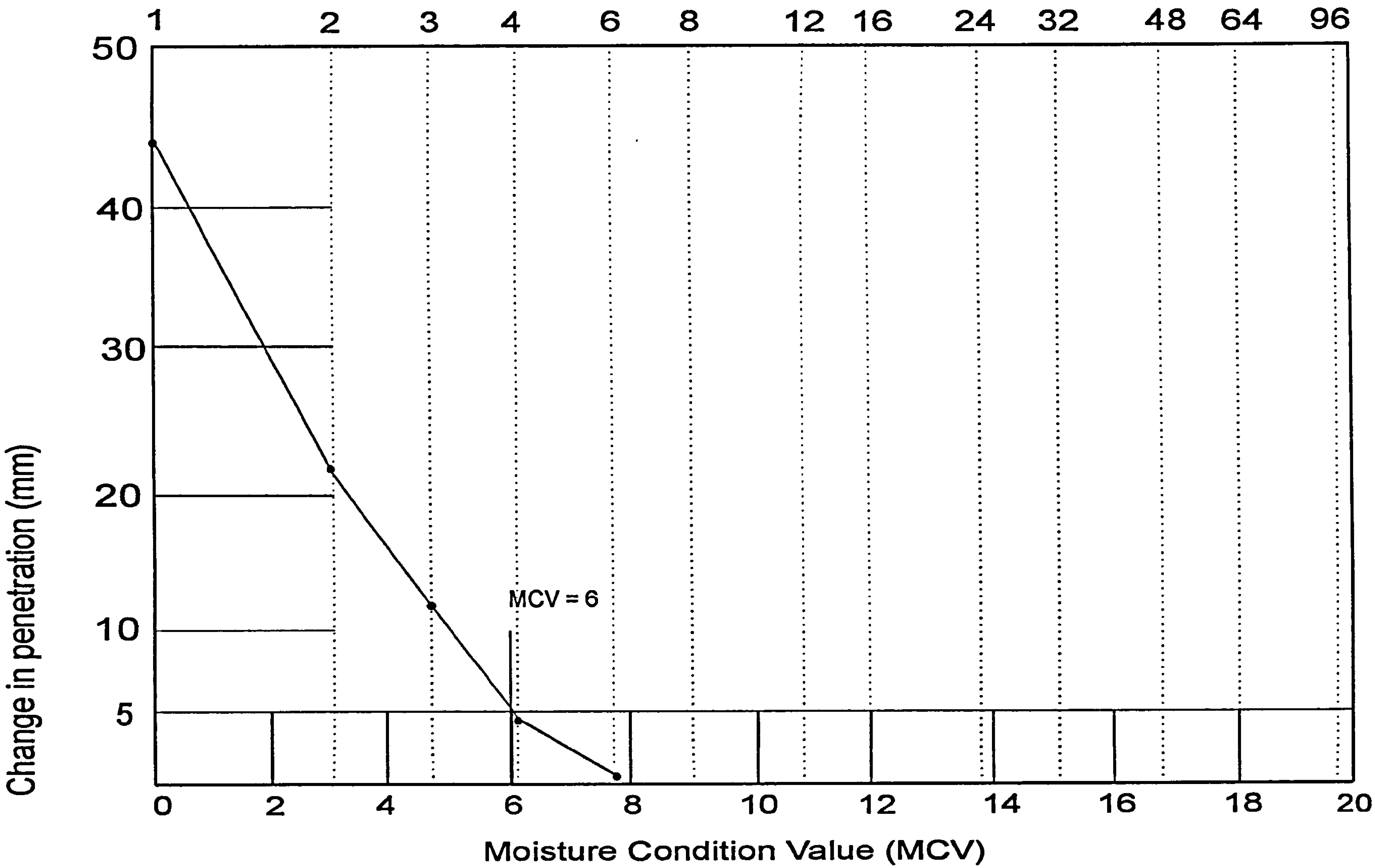


Figure 4.16 London Clay (Result b)

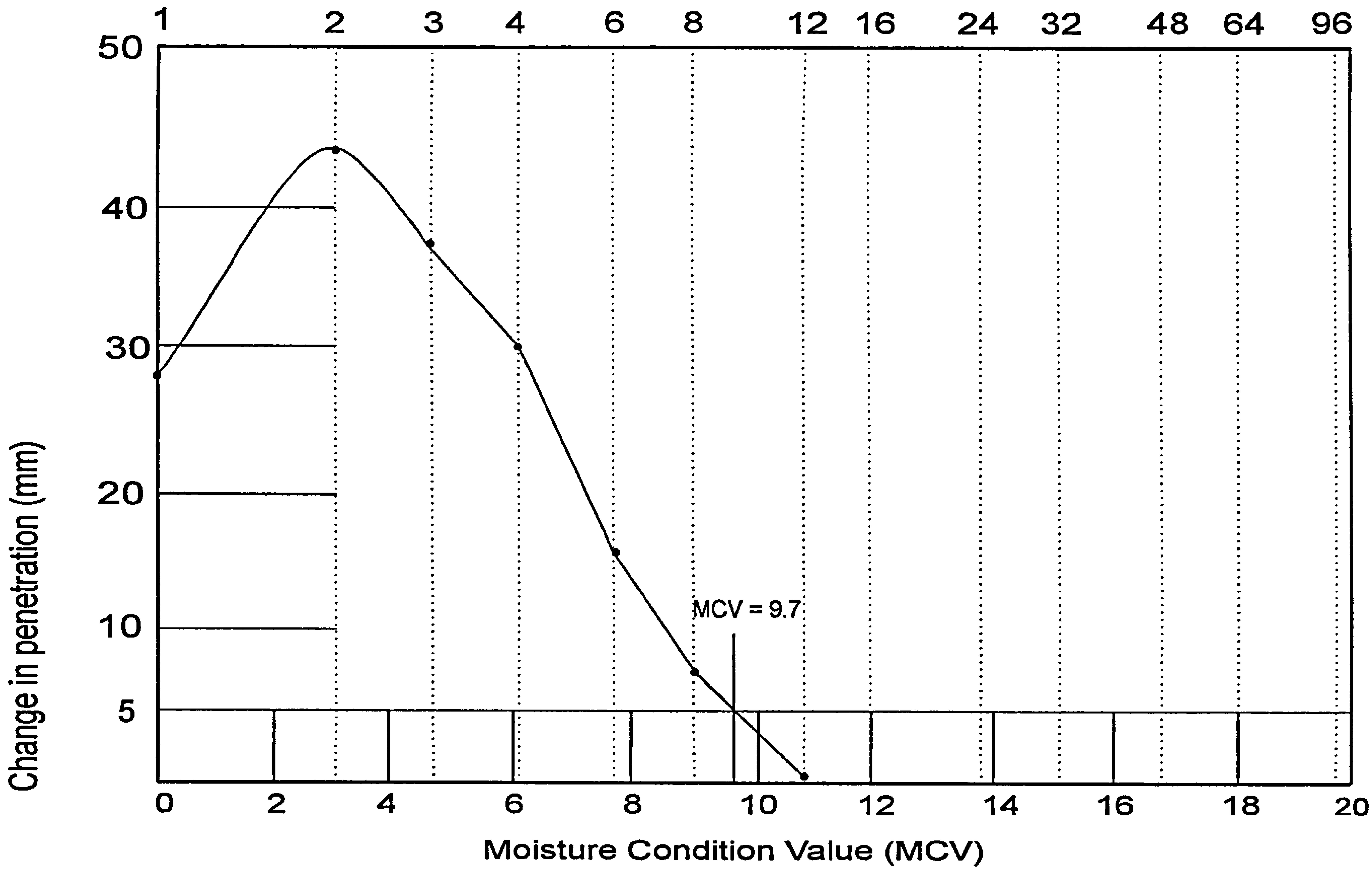
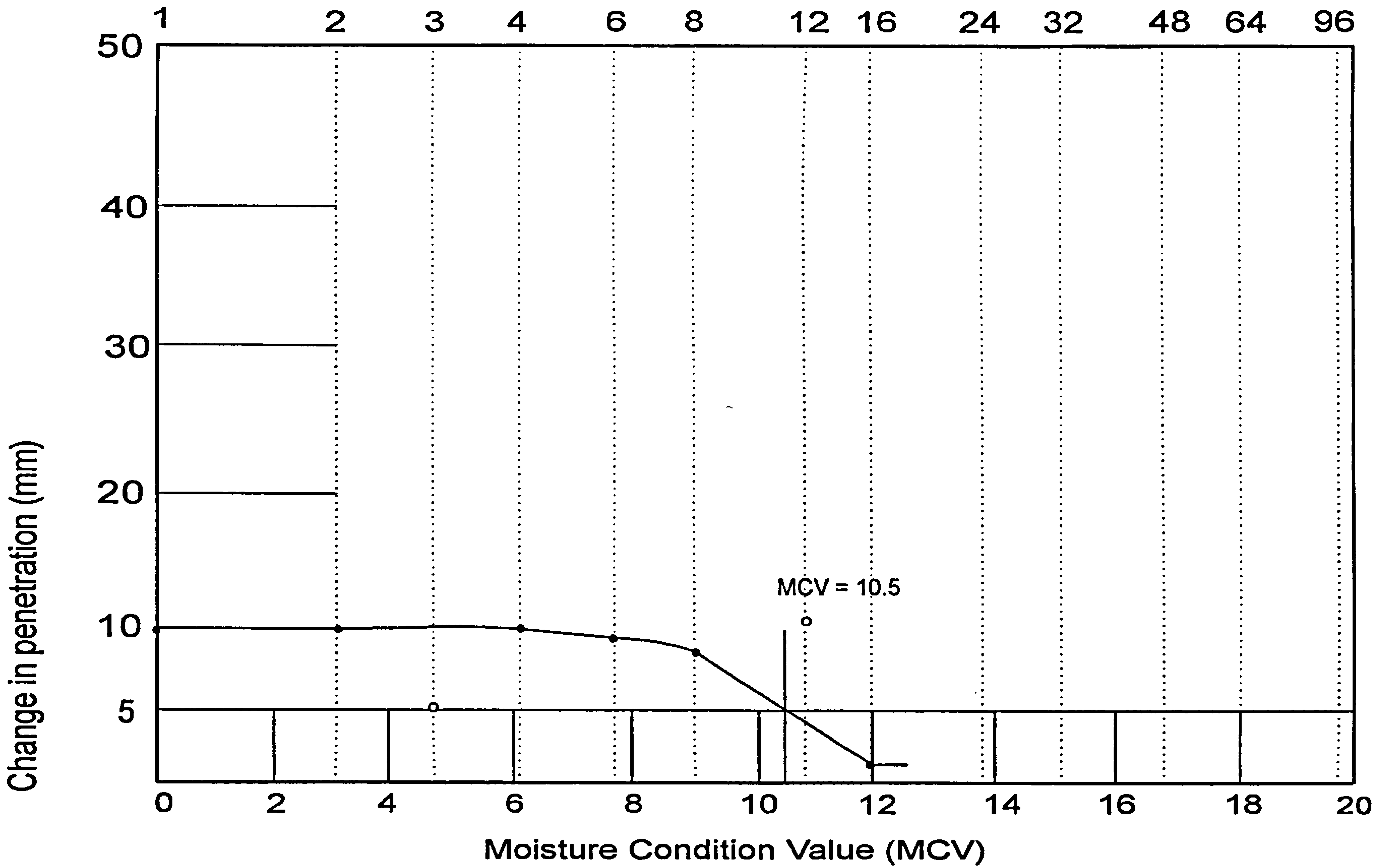


Figure 4.16 London Clay (Result c)



O represent anomalous results

Figure 4.16 London Clay (Result d)

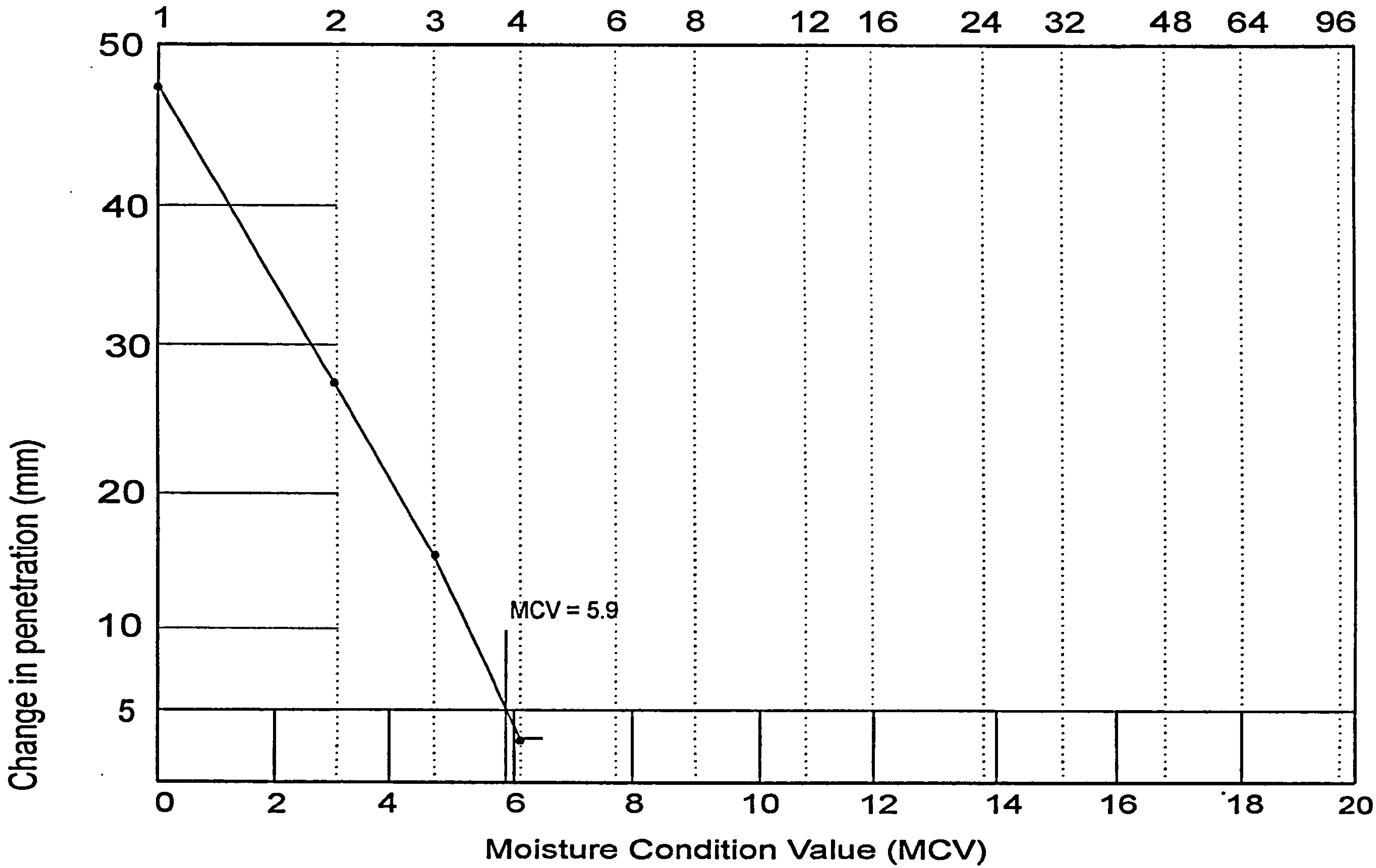


Figure 4.16 London Clay (Result e)

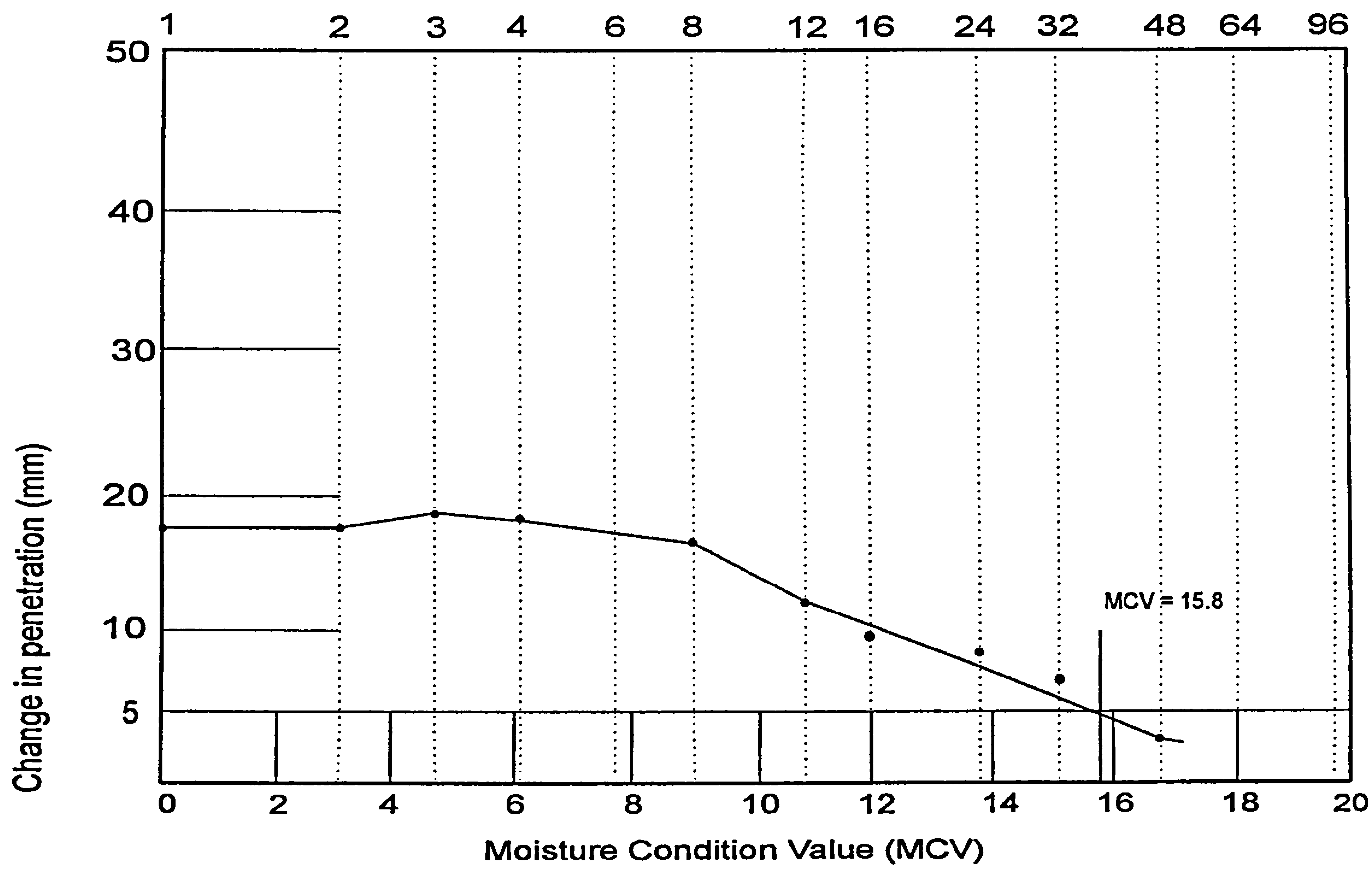


Figure 4.16 London Clay (Result f)

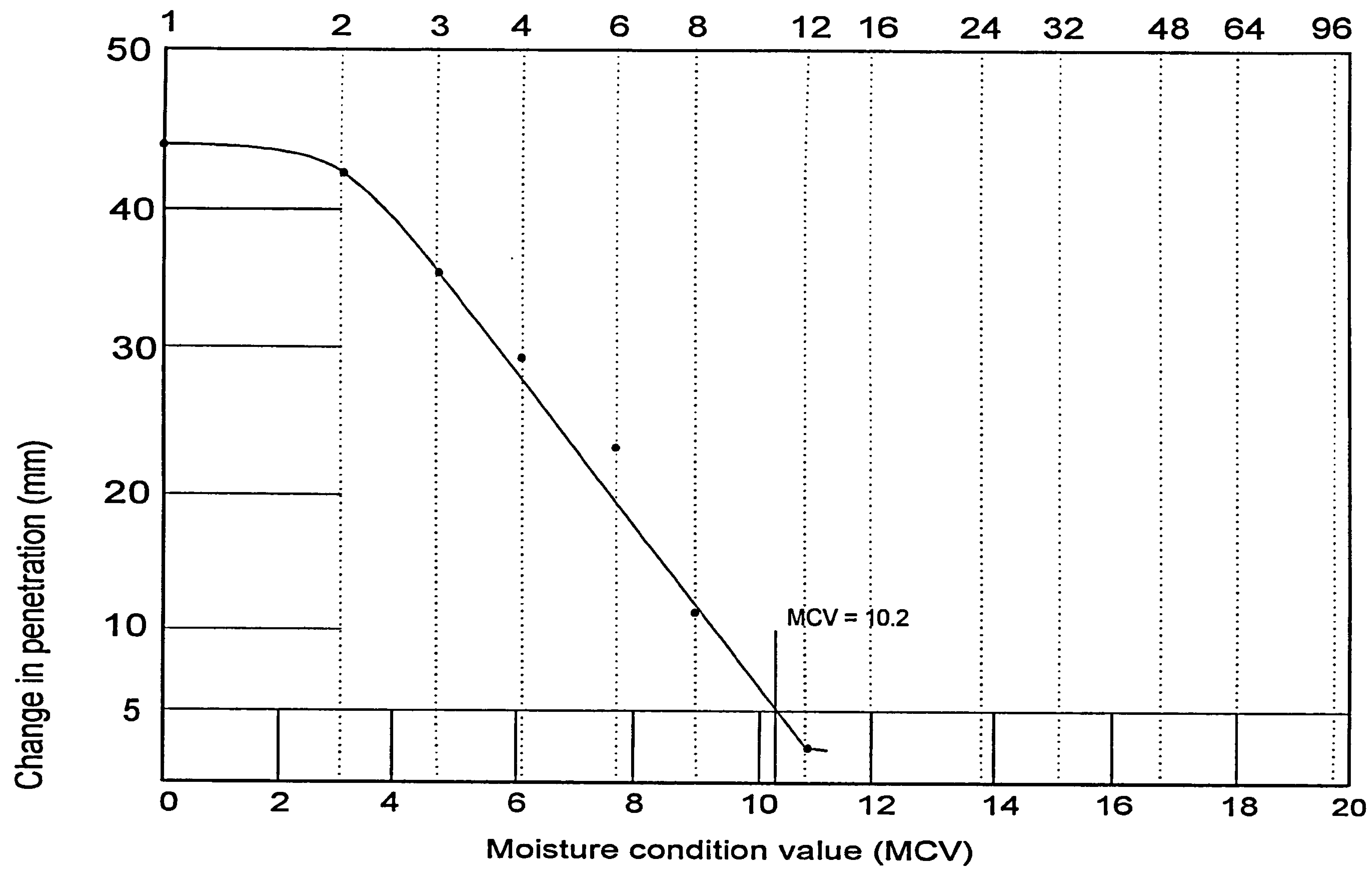


Figure 4.16 London Clay (Result g)

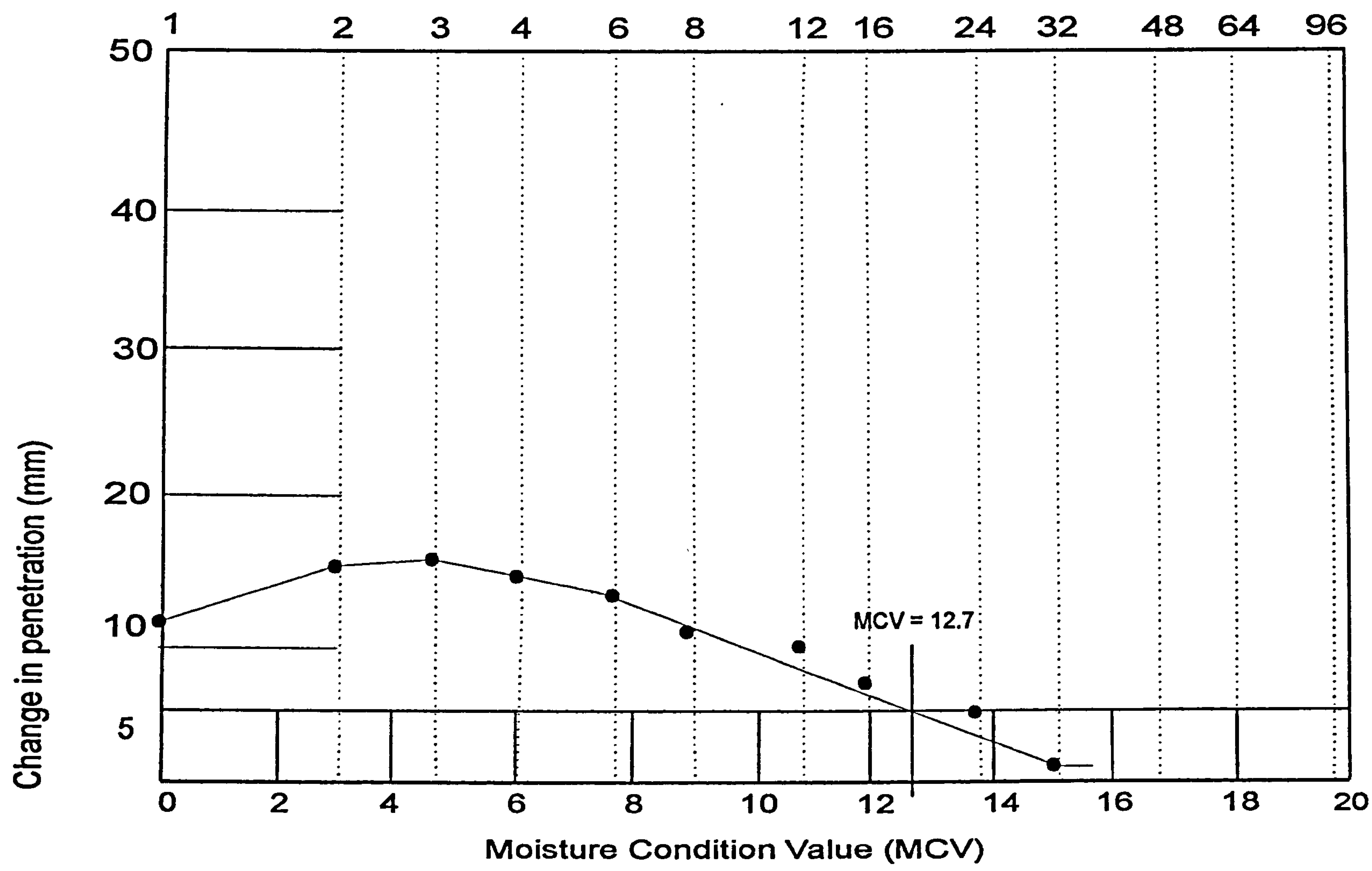


Figure 4.16 Mercia Mudstone (Result h)

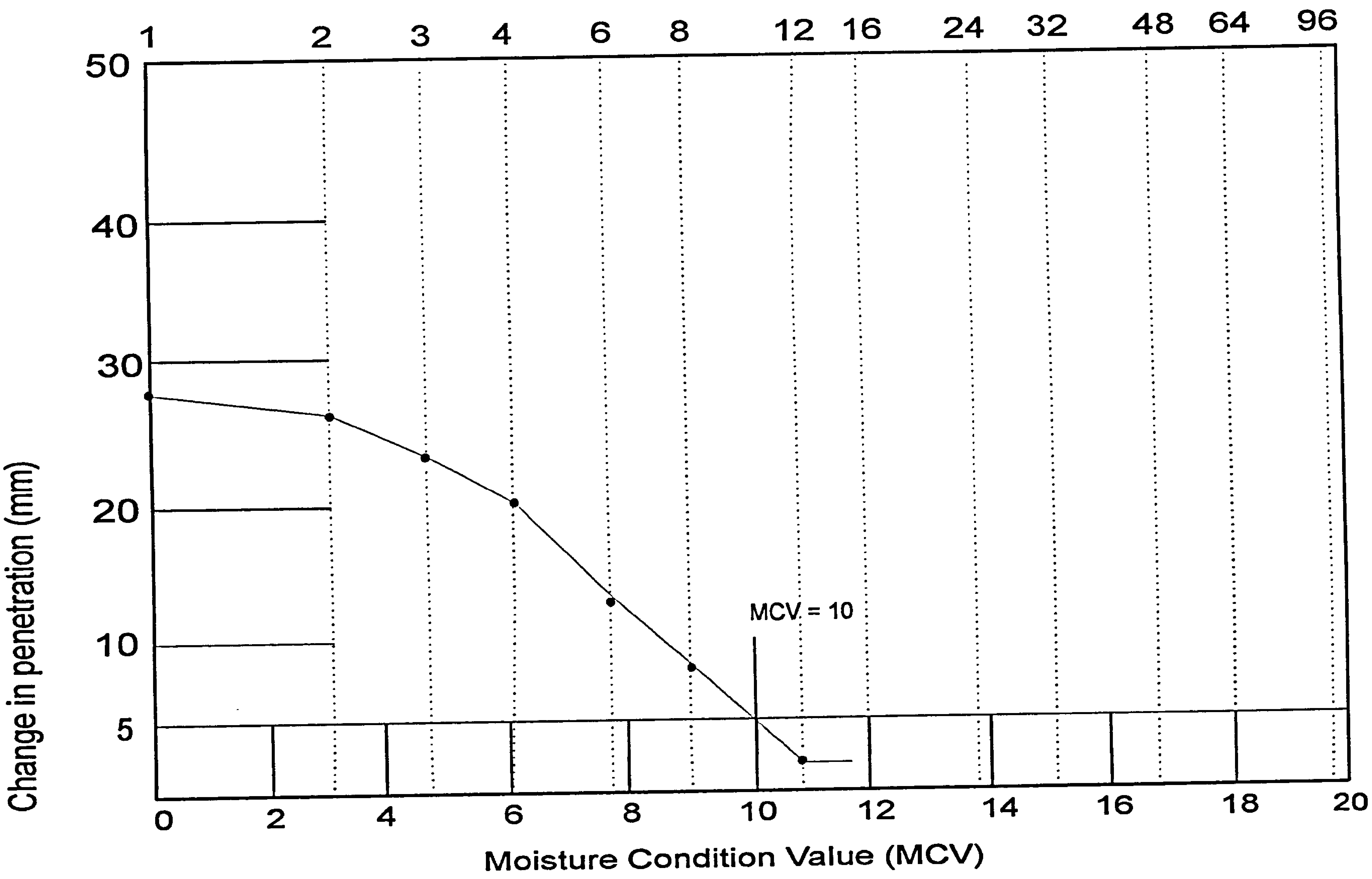


Figure 4.16 Mercia Mudstone (Result i)

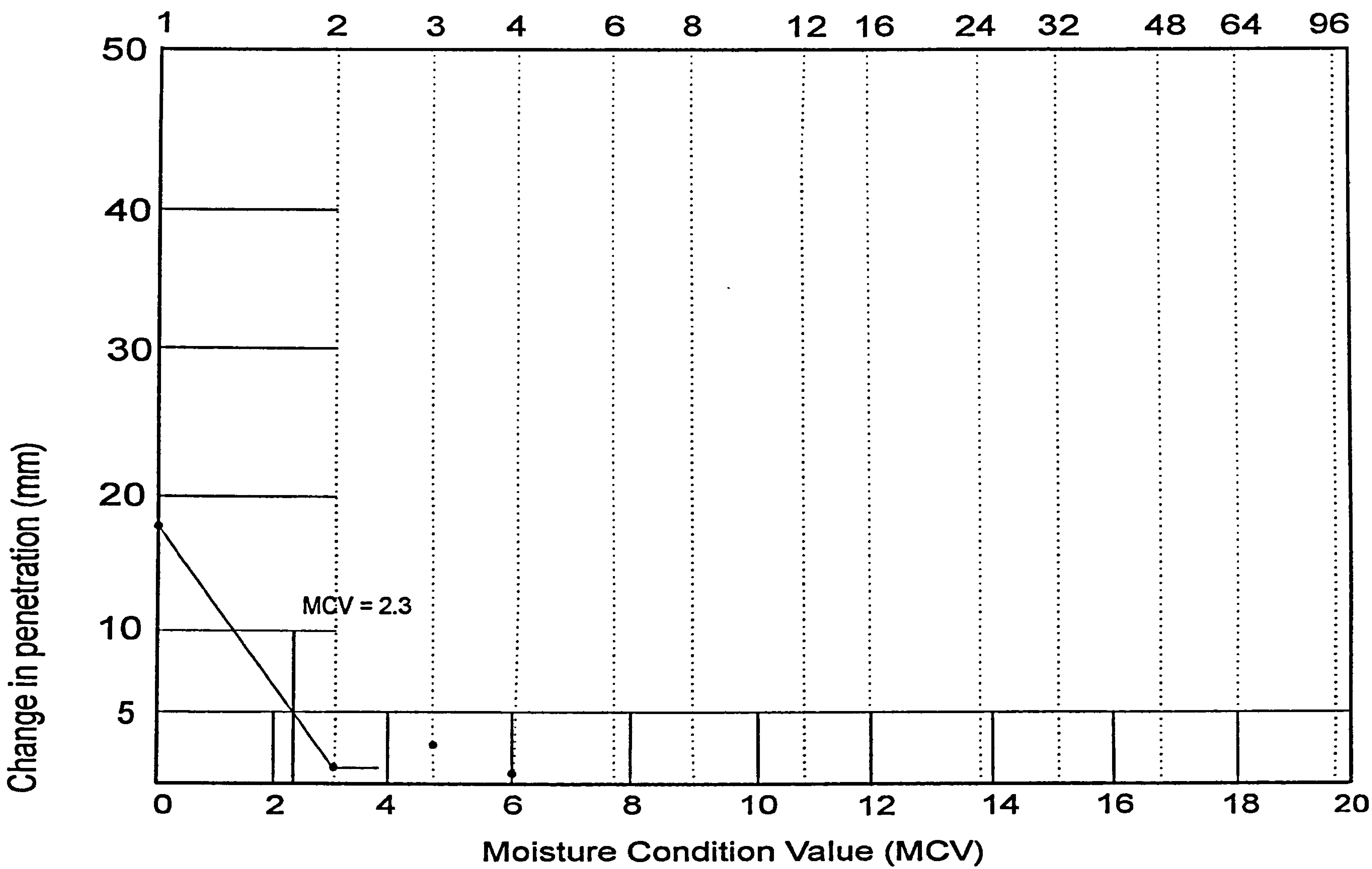


Figure 4.16 Mercia Mudstone (Result J)

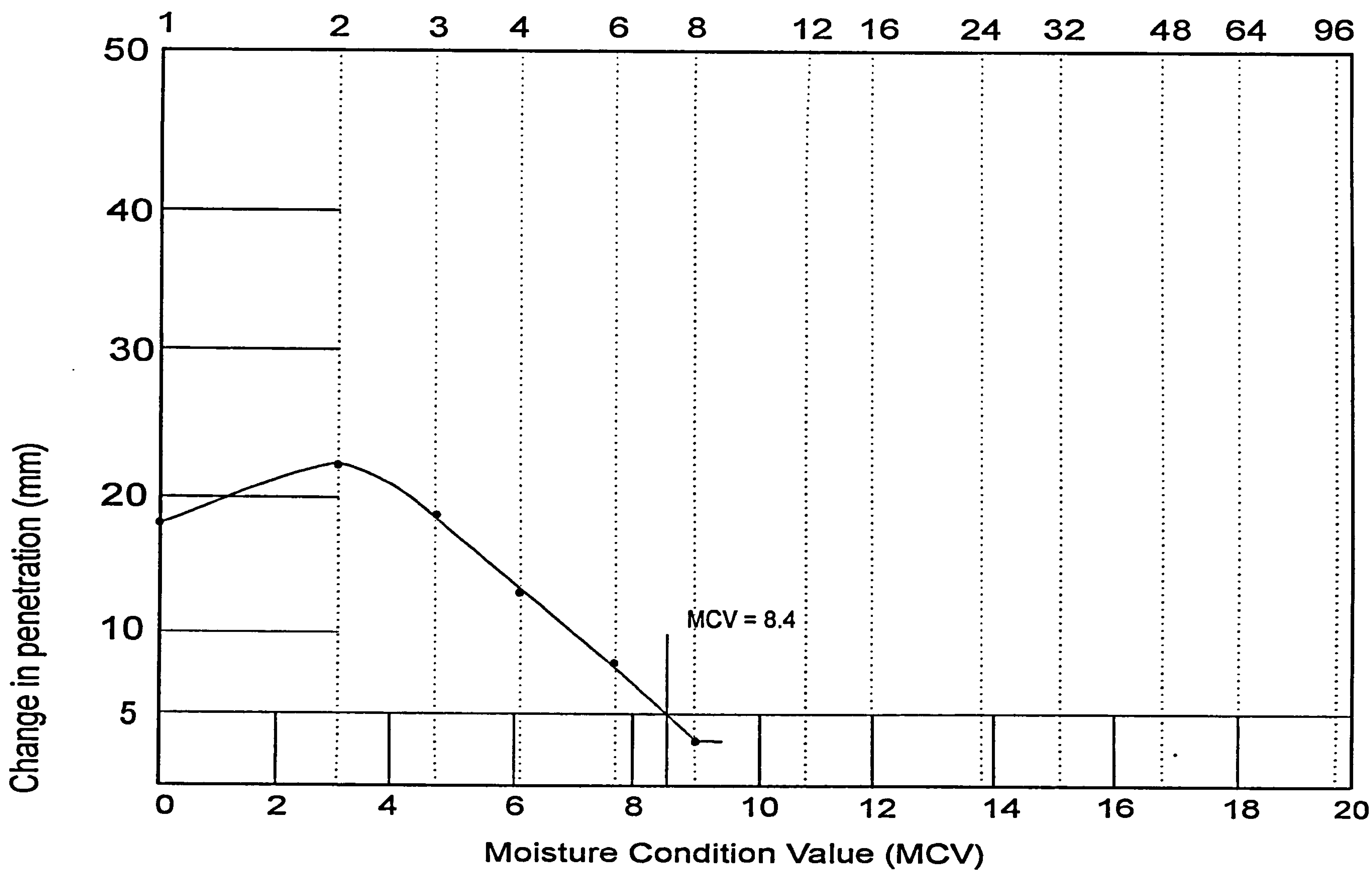


Figure 4.16 Mercia Mudstone (Result K)

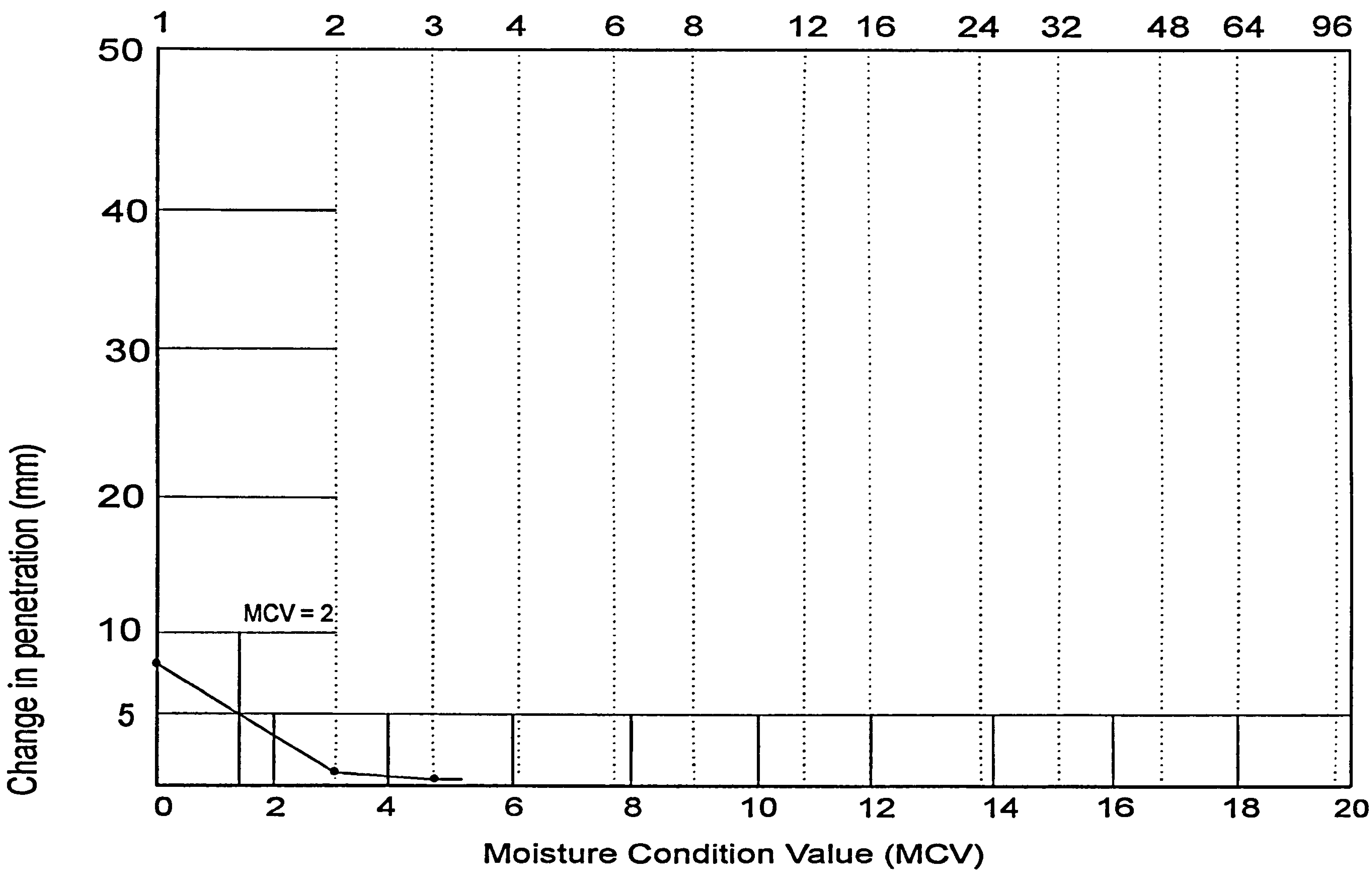


Figure 4.16 Mercia Mudstone (Result L)

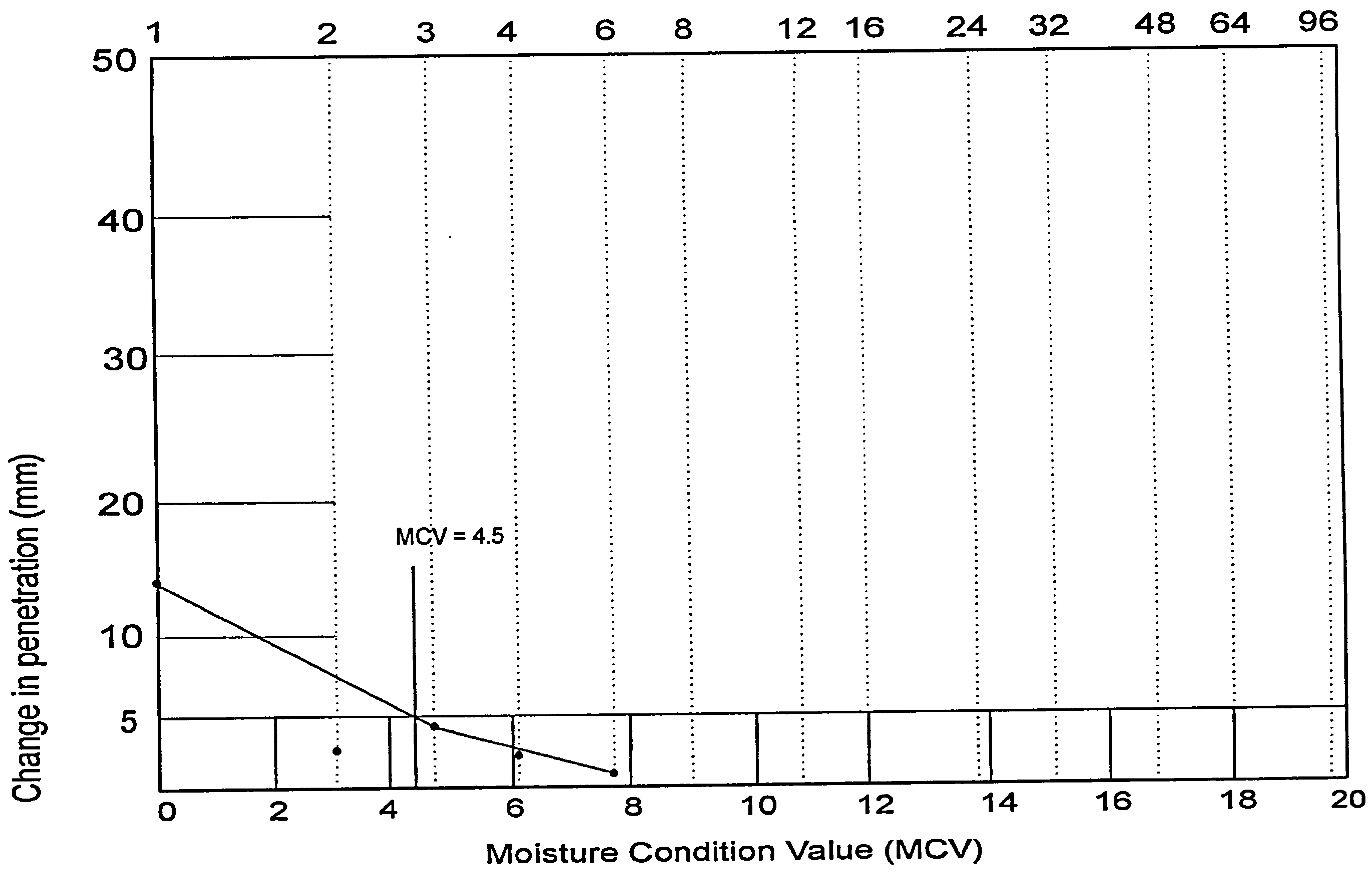


Figure 4.16 Mercia Mudstone (Result m)

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