"Evaluation Of The Soil Cover Reclamation Method For Chemically Contaminated Land"

Thesis submitted to CNAA as partial fulfillment of the requirements for the degree of Doctor of Philosophy

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January 1989

Abstract

This thesis set out to establish the validity of soil covers, in practical engineering terms, as a safe and economic method of reclaiming chemically contaminated land.

Initially, it looks at the problems and hazards created by contaminated land, and discusses the various reclamation techniques which are available.

The CRISP computer model is used to design soil covers for the 1990 garden festival sites, at Gateshead.
This model requires data relating to the suction - hydraulic conductivity relationship of each soil in any proposed soil cover.

Whilst such data can be estimated from a soils particle size distribution, such estimates can produce erroneous results. And, since tests showed that the computer model was very sensitive to the input data, parameters were determined experimentally when ever possible.

As there would be limited time available in a commercial design office to conduct such experiments, emphasis was placed on rapid and simple techniques.

The suction - hydraulic conductivity relationship for each soil was determined using the filter paper method, the hanging water column method and the hot air method.
The equipment and experimental proceedure of the latter method was improved such that accuracy and repeatability were obtained.

As empirical models such as CRISP are inevitably subject to over simplification, the models accuracy was assessed by comparing results obtained for contaminant rise against measured values obtained from soil column studies.

Despite the uniform packing of these soil columns, problems were encountered when trying to obtain a representative sample of soil. This was due to the large variation of grain size in the soil materials, and resulted in variable water content and sulphate concentrations being recorded in the soil column experiments.

Whilst it is acknowledged that the CRISP computer model over estimates the value for contaminant rise in the given soil cover materials, this over estimate is not consisered to be excessive, as, in a commercial environment, the amount of data pertaining to specific soil materials under design drought conditions would be limited. Thus this in built error adds an extra margin of safety to the soil cover design.

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1.1 Introduction

Changing technologies and the subsequent decline of the older "heavy" industries have resulted in many former industrial sites being left abandoned, derelict and often contaminated.

Contaminated land may be described as:

> (1) Land which because of its former uses now contains substances that give rise to the principal hazards likely to affect the proposed form of development and which
> (2) Requires an assessment to decide whether the chosen development may proceed safely or whether it requires some form of remedial action, which may include changing the layout or the form of development." (ref 1.1)

Such land is generally found in or around urban and industrial centres and is typically associated with the older "heavy" industries such as metal, chemical and energy production, however, land may become contaminated as a result of a variety of activities (table 1.1).

The contamination present on a site may be compounded by multiple use of a site for a variety of industrial processes, either at any one time, or, over a site's history.

Table 1.1 Activities which give rise to contaminated land

Activity	Example	Ref.	Main Contaminants
Coal mining/ smelting	Welbeck	(1.2)	Cd, As, FeS_2,
Metal extracting	Lower Swansea Valley	(1.3)	Cu, Zn, Ni, Pb
Coal gas production	Beckton Alps	(1.4)	Cyanides, phenols, Sulphates
Landfill/ refuse tips	Willowtree Lane	(1.5)	Methane, possibly heavy metals
Sewage works	Beaumont Leys	(1.6)	Zn, Cu, Ni, Pb, Cd, As, Cr
Docklands	London Docks	(1.7)	As, Cd, Cr, Cu, Pb, Ni, Hg, methane
Arsenal	Thamesmead	(1.8)	As, Cd, Cr, Cu, Pb, Ni, Hg, B
Pesticide manufacture	San Joaquin Valley, California	(1.9)	As, phenoxy acids, chlorinated phenols

For example, since the early 1700's the site of the Woolwich arsenal, Thamesmead, (ref 1.8) has been used for the following activities:

Heavy machine shop and forging works
Non ferrous metal foundries
Cadmium and other metal plating
Town gas manufacture
Laboratory testing of paints
Manufacture of acetylene
Testing of weapons and explosives
Destruction of explosives by burning
Destruction of incendiary devices
Storage of coal stocks
Dumping of waste products from the gas works
Dumping of industrial waste

Each of the above was founded on the waste of the preceding activity and, during its lifetime, added its own waste to the layers of those deposited by previous occupiers.

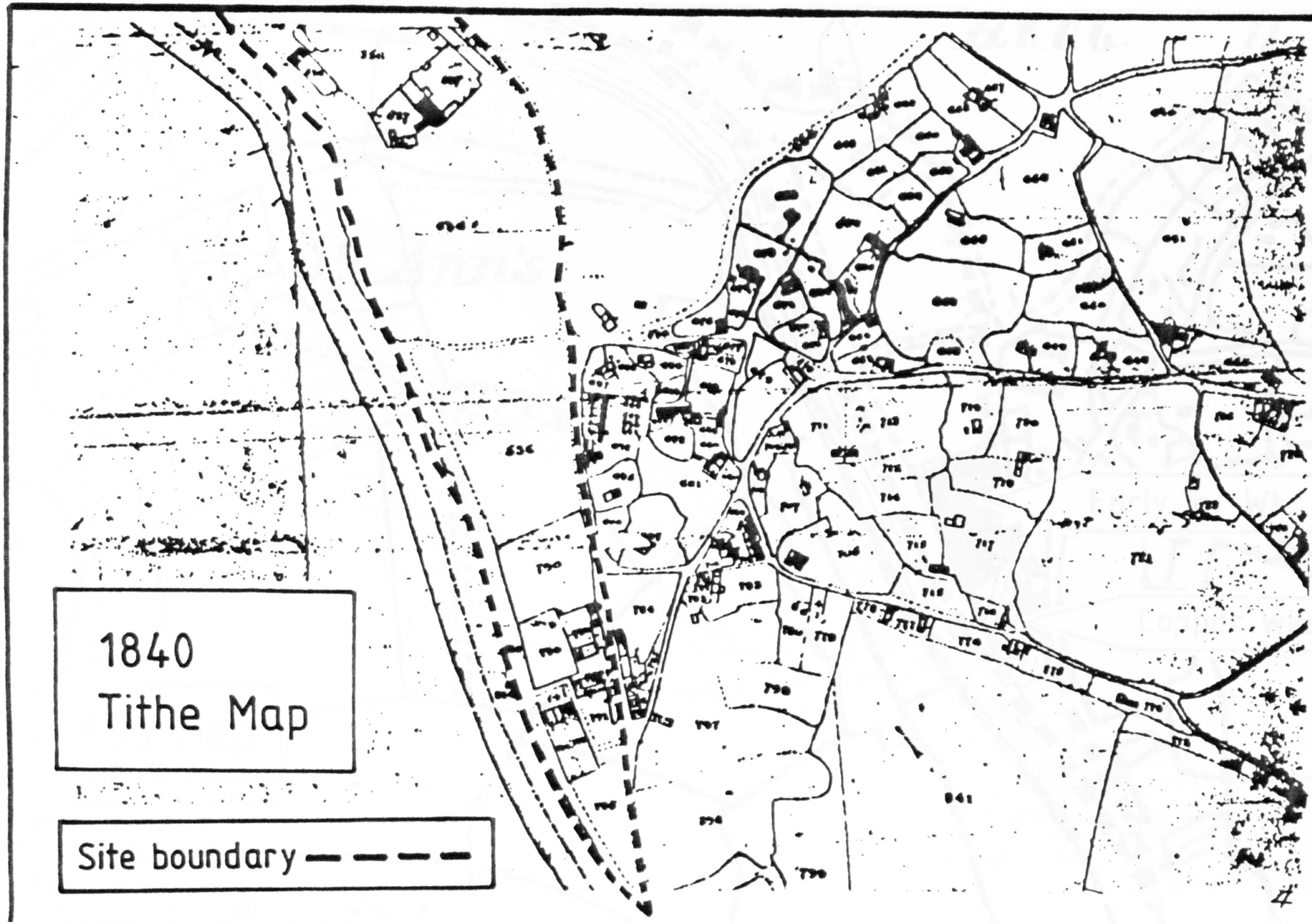
This point is further exemplified in figures 1.2 to 1.6, which show the development of a site in Bristol (figure 1.1) from 1769 (figure 1.2) to 1905 (figure 1.6). In 1769 a copper refinery existed at the southern end of the site, however the tithe map of 1840 (figure 1.3) shows no sign of any industrial development. Ten years later (figure 1.4) both a copper works and a tar works had been founded on the southern section of the site. The first industrial development evident at the northern end of the site appears in 1880, and consists of a chemical works and a brick and tile works, (figure 1.5), and by 1905 (figure 1.6) the majority of the site had been given over to chemical manufacture and tar distilling.

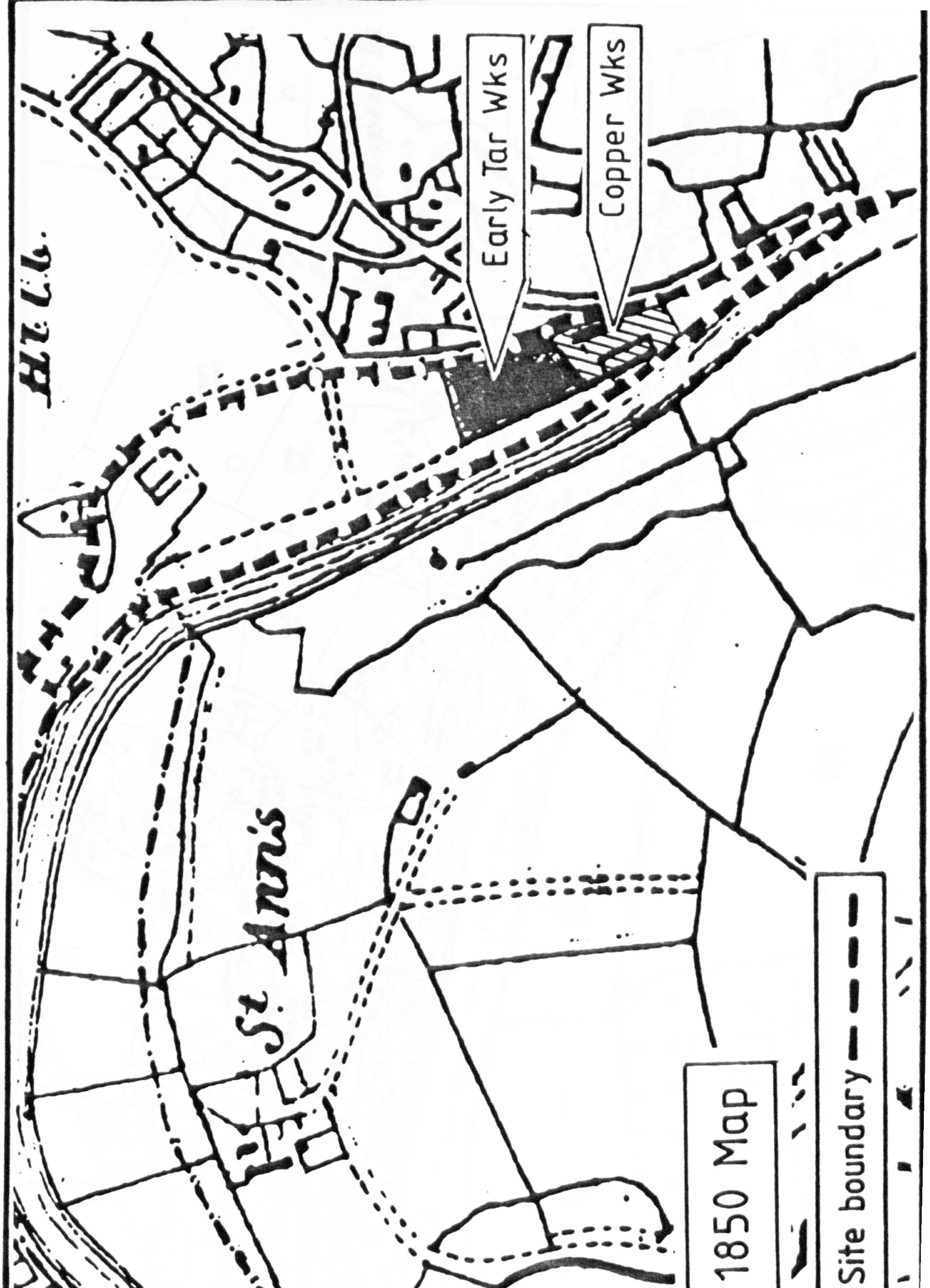
It is difficult to estimate the amount of contaminated land in the U.K. as there has not been a detailed survey of land in this category. A recent estimate by the Department of the Environment (DoE) suggests that there is approximately 12,500 hectares of contaminated land in England, and possibly 7,000 hectares in Scotland, which is currently available for reclamation (ref 1.10). A similar survey in Wales identified more than 700 potentially contaminated sites, representing an area in excess of 3,787 hectares (ref 1.11). As land which is probably contaminated, but still in active use, was excluded from the survey the above figures are an underestimate of the total amount of contaminated land. Obviously the problem is more widespread than is generally recognised.

Figure 1.1 Location map of Crews Hole Bristol

Figure 1.2 Site map 1769

Figure 1.3 Site map 1840




Hill
St Ann's
Early Tar Wks
Copper Wks
1850 Map
Site boundary

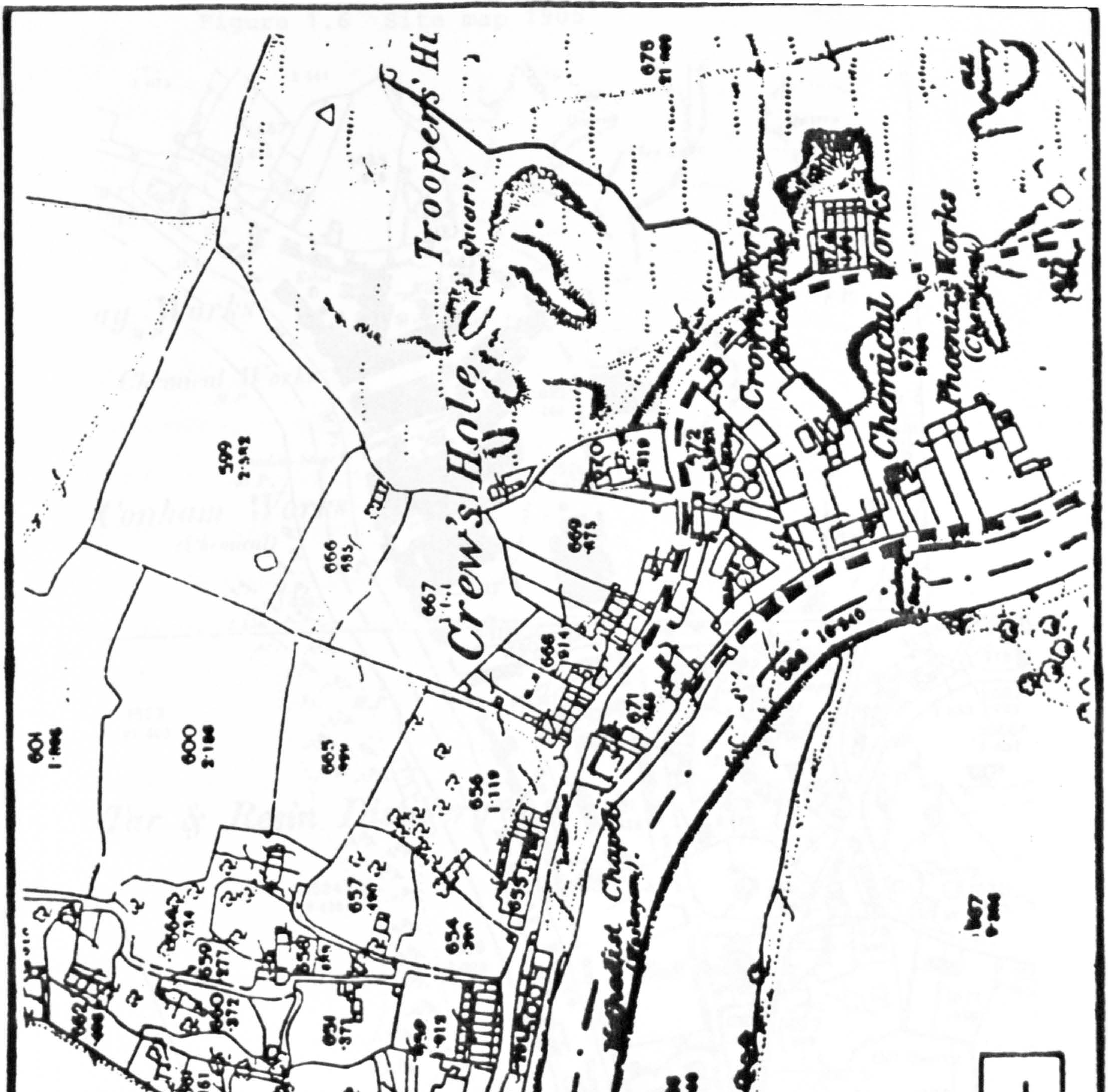
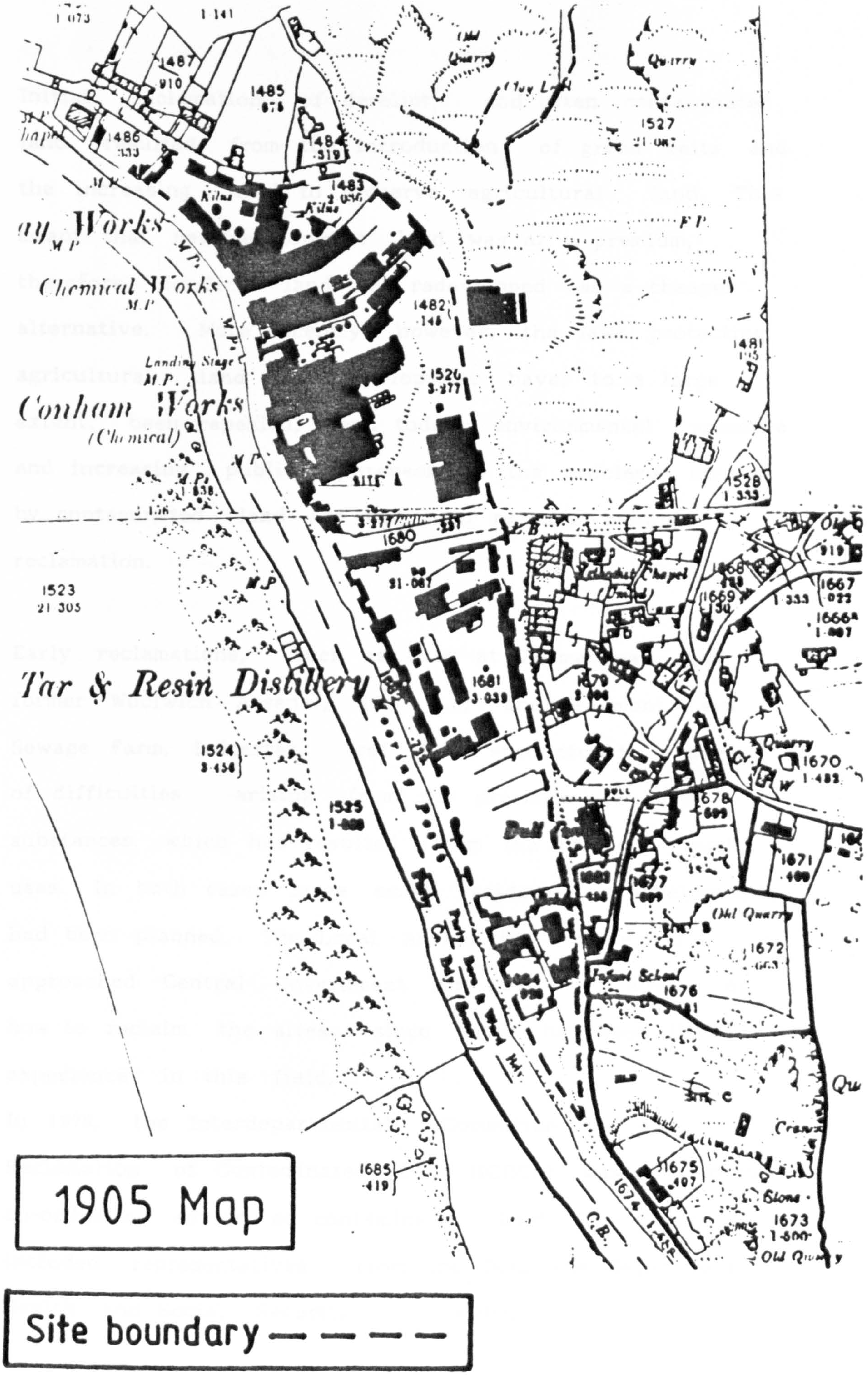

1880 Map
Site boundary
Crew's Hole
Troopers' Hill
Quarry
Old Quarry
Crown Works
Chemical Works
Phoenix Works (Chemical)
Methodist Chapel (Wesleyan)

Figure 1.6 Site map 1905



Initial reclamation of derelict, and often contaminated land, resulted from the introduction of green belts and the increasing need to preserve agricultural land. This meant that new development land was at a premium, therefore derelict land was redeveloped as a cheaper alternative. More recently however, the laws protecting agricultural land from development have, to a large extent, been repealed, and today, environmental pressure and increasing public awareness to the problems created by contaminated land are the main reasons behind reclamation.

Early reclamations, such as that at Thamesmead, the former Woolwich Arsenal, (ref 1.8) and Beaumont Leys Sewage Farm, Leicester, (ref 1.6) encountered a number of difficulties arising from the presence of toxic substances which had resulted from the previous land uses. In both cases large scale residential developments had been planned. The Local Authorities concerned approached Central Government for advice on advice on how to reclaim the sites, since there had been little experience in this field.

In 1976, the Interdepartmental Committee for the Reclamation of Contaminated Land (ICRCL) was set up to co-ordinate advice on contaminated land. The Committee included representatives from the DoE, the Department of Health and Social Security, the Welsh Office, the Health and Safety Executive and the Ministry of Agriculture, Fisheries and Food. The Committee had four main work areas (ref 1.12):

(1) To provide information to Local Authorities and private developers dealing with contaminated land

(2) To publish information which could guide developers. As a result a number of guide line papers were published (refs 1.13 to 1.19)

(3) To initiate research into areas of contaminated land where little was known or understood. This research included the following:

The behaviour of contaminants under certain types of remedial treatment in relation to metal uptake by plants (refs 1.20 and 1.21)

Engineering methods of reducing metal levels in the soil (ref 1.22)

Problems of contaminant migration (refs 1.23 and 1.24)

Performance of past reclamations (ref 1.25)

A number of other related topics such as combustibility of fill materials, problems created by methane and a review of in-situ treatment options for use on contaminated land were also studied

(4) To bring the subject of contaminated land into open debate.

Perhaps the most important product of the Committee was the definition of "trigger concentrations" for certain contaminants (table 1.2). These are the maximum permissable levels below which a site is considered safe to develop. Sites containing higher levels of contamination should be investigated further to determine whether or not remedial action or some form of reclamation is required, or whether the land's allowable land use has to be restricted to a relatively non-sensitive development.

The ICRCL was involved in the organisation of the Society of Chemical Industry Conference (1979) on the Reclamation of Contaminated Land (ref 1.27), the first of such specialist conferences in Europe.

In November 1981 NATO/CCMS (Committee on the Challenges of Modern Society) began a pilot study on contaminated land. Seven countries were represented on the Committee (Canada, Denmark, Federal Republic of Germany, France,

Table 1.2 Tentative "trigger concentrations" for contaminants associated with former coal carbonisation sites (ref 1.14)

Contaminants	Planned Uses	Trigger Concentrations (1)
Coal Tar (2)	Domestic gardens, amenity areas	200
	Public open space	500
	Industrial (no landscaping)	5,000
Phenols	Domestic gardens and all other uses with mains water services	5
	All other uses	100
Free Cyanide	Domestic gardens, amenity areas, open space	50
	Industrial (no landscaping)	500
Complex Cyanides	Any use where plants are to be grown	50
Thiocyanate	All uses	50
Sulphur	All uses	1,000
Sulphide	All uses	250
Sulphate (3)	Residential, industrial and commercial developments with no landscaping	1,000
	All other uses including domestic gardens, open space and landscaped areas	200

Notes (1) all values are expressed as mg/kg air-dried soil

(2) these values do not take into account the possible hazard to skin contact

(3) See also BRE Digest 250:1981 for requirements for protection of concrete against sulphate attack (ref 1.26)

Netherlands, U.K. and U.S.A.). Each was assigned one or more study areas. The aim was to draw on each country's knowledge and experience of the problems created by contaminated land and the different reclamation techniques used by each country. The following fields were examined:

In-situ treatment of contaminated sites
On-site processing of contaminated soils
Covering and barrier systems
Control and treatment of ground water
Rapid on-site methods of chemical analysis
Long term effectiveness of remedial measures
Toxic and flammable gasses

Exchange of information between study groups was co-ordinated by the U.K. as the host nation. The Committee's findings and recommendations were published in 1985 (ref 1.28).

1.2 The Hazards of Contaminated Land

A number of immediate or potential hazards can arise from the re-use of chemically contaminated land. In a series of guideline papers (refs 1.13 to 1.19) the ICRCL has identified the following:

(i) The effect on vegetation

As plants take up moisture from the soil they also absorb nutrients which are in solution. On contaminated land the nutrients in the soil water may be in excess of the levels required for healthy plant growth. In such cases some substances (especially heavy metals) are toxic to plants or may retard plant growth, cause foliage to become discoloured, and ultimately cause the plant to die. A recent example of this occurred at a site in Tyneside, (ref 1.29) where the presence of sulphates, phenols and in some cases free cyanides at the soil surface caused large patches of the grass cover over a former gasworks site to die off completely.

Whilst such effects are undesirable and unsightly they are more of a nuisance than a hazard in the true sense of the word. More dangerous are those cases where plant species which are able to tolerate elevated levels of absorbed contamination in their foliage and fruit. Lettuce, amongst the normal domestic crops, is especially able to do this (ref 1.30). Obviously when such vegetation is consumed by man or animals a direct hazard is introduced to the food chain. An example of this situation occurred at Beaumont Leys sewage farm, Leicester. Sewage sludge from the farm was applied to parts of the surrounding agricultural land, however, this was later found to contain high levels of metals, especially lead, cadmium, nickel, zinc and copper which had been adsorbed by the soil. The discovery of these high levels of metals led to a complete re-cast of the local authorities development plans for the area (ref 1.31)

Originally the authority had planned to build houses with private gardens, and to incorporate recreational, shopping and industrial areas. Upon investigation it was found that the areas used for sludge spreading (more than 80 ha.) were so contaminated with cadmium and lead that domestic housing was out of the question. The area was therefore zoned for lower-risk activities i.e. industrial areas, parks and a shopping centre. On the remainder of the site contaminant levels were found to be more acceptable. Research on the site showed that there was no risk of cadmium or lead poisoning even if the area were used for domestic housing with private gardens, though it was agreed that all top soil with a cadmium concentration greater than 7mg/kg would be removed and the remainder mixed with fresh top soil to reduce concentrations to acceptable levels (ref 1.6), eventually it was found that this approach was unnecessary as the contamination was only present in the surface layer of the soil. This was therefore removed and the site declared safe to develop.

(ii) The direct effects on people.

Obviously direct ingestion of contaminants is hazardous. Whilst this is not generally a problem with most people, there is a group (especially young children) who do suffer from pica (ingesting non-food materials) and are therefore at risk even when only quite small amounts of contaminated soils are ingested.

More widespread are the risks associated with handling or inhaling contaminants. Acid contaminants (eg. phenols) can severely burn and blister the skin, whilst prolonged exposure times can result in digestive disorders, affect the central nervous system and may be carcinogenic. Inhalation of tars or asbestos can cause cancer, especially where exposure times are prolonged. The inhalation of some gases i.e. hydrogen sulphide, carbon monoxide, or hydrogen cyanide can be fatal.

(iii) Chemical attack on building materials.

A range of contaminants are known to attack building materials. For example, sulphates attack and weaken concrete foundations and structures (ref 1.26), oils and tars corrode metals and attack a range of polymeric materials and phenols migrate through the walls of uPVC pipes and may therefore contaminate water supplies.

As such attacks would normally occur below ground they are difficult to detect until some failure has occurred, this could prove disastrous, (i.e. if the collapse of a block of flats resulted in substantial loss of life). A particular difficulty in such cases is that contaminant attack on building materials is a relatively slow process, thus adverse effects may not become apparent for tens of years after completion of the development.

Perhaps the earliest recorded case of chemical attack on building materials occurred on a housing development at Lekkerkerk, Holland (ref 1.32). The housing development had been constructed over a series of drainage ditches which had been infilled using domestic and industrial refuse. The housing programme was completed in 1975, however, by 1978 abnormally high numbers of burst pipes had been recorded. Upon investigation it became obvious that not only had buried pipes been weakened by acid attack, but also, the water supply had been contaminated by unacceptable levels of phenolic substances and, more importantly, liquids and gases (eg. toluene and xylene) had collected in the creep spaces beneath housing units and presented explosion risks.

The cost of repairing the damage and removing the source of the problem (the fill material) was in excess of $65 million.

Long term research to identify the nature of contaminants and the rate of contaminant attack on widely used building materials has been commissioned by the Construction Industry Research and Information Association (ref 1.33)

1.2.2 Summary

Contaminated land has only been recognised for relatively few years and the research so far has been limited. Thus whilst we know that some particular contaminants are hazardous and have trigger levels (table 1.2) defined for these by the ICRCL, (ref 1.14) it has to be openly admitted that the hazard ratings for a whole range of chemical substances is as yet not clearly understood. This is especially understandable when one considers that the direct hazards to people posed by particular contaminants cannot be proved by experimentation on human subjects, and that the problem of long term exposure to very low (in a chemical analysis sense) concentrations of chemicals may well take scores of years to quantify.

Thus chemically contaminated land has to be accepted as potentially hazardous, a fact recognised by the latest DoE/Welsh Office joint circular (ref 1.34) on the subject. This circular indeed emphasises the problem by including the following phrases:

> That the hazards "may be a direct threat to health and safety"
> and that "a balance has to be struck between the risks and liabilities and the need to bring the land into beneficial use"

This emphasises that whilst the re-use of old industrial derelict sites is a national policy and priority, care has to be taken to ensure that such re-use does not entail hazards to future generations.

The obvious conclusion is that all methods of reclaiming such land have to be rigorously evaluated to

(a) Ensure that they include definable safety measures

and (b) remain safe for the likely period of the site's re-use.

1.3 Available Reclamation Methods

1.3.1 Introduction

There are a variety of reclamation methods available to developers. Essentially they involve excavation, or treatment, or encapsulation or a combination of any of these. In the U.K. one variety of the encapsulation method, the soil cover, is the most favoured technique because of its relative cheapness and ease of installation. However it does leave the contamination <u>in-situ,</u> albeit beneath a "clean" soil material. The Dutch authorities prefer treatment methods which either destroy contaminants or fix them in the ground in a harmless state. Such treatment methods can however be time consuming and expensive and may be declining in popularity in Holland because of national economic factors (1.35).

To a large extent the type of reclamation method chosen will depend on :

(i) The contaminants present
(ii) The scale of contamination
(iii) Availability of funds
(iv) The proposed end use of the site
(v) The local conditions

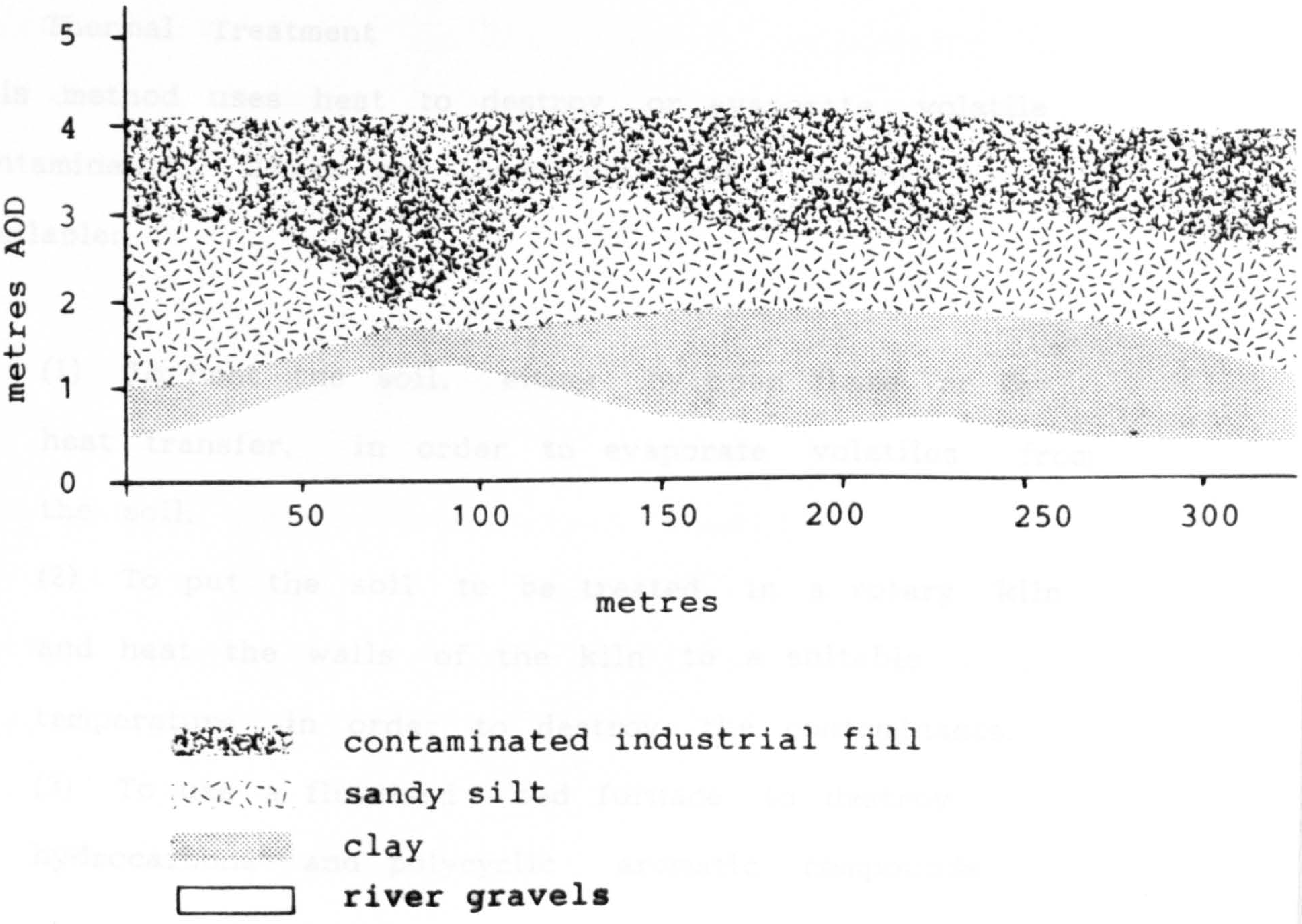
1.3.2 Excavation

Perhaps the most obvious solution to contaminated land is to excavate the offensive materials and deposit them in a more suitable place, such as the hazardous waste tip at Pitsea, Kent. The practicalities of this method however often preclude its use. Where near surface ground water tables exist a site would have to be drained prior to excavation. A similar situation existed at Redheugh gas works site, Gateshead (Ref 1.36), where the river gravels (figure 1.7) contain ground water under such a high artesian pressure head that removal of the contaminated industrial fill (and the load it imposes) would allow the artesian water to break through the thinner zones of the clay stratum and flood the site. Thus excavation was not a feasible option in this case.

Frequently there is no sharp edge to the contamination, it is therefore difficult to assess where excavation should be terminated. This problem may be compounded if mobile contaminants have moved off site to adjacent land or beneath existing buildings.

Assuming that it is practical to excavate a site it is then necessary to find a suitable disposal site, and a cheap fill material to bring the site back to the required level. The cost of moving the excavated material and the new fill material may be prohibitively high, for example, infilling a 16 ha. site to a depth of one meter would require 160,000 cubic meters of material and 20,000 to 25,000 vehicle movements between the source of fill and the site (ref 1.8) Assuming the same amount of material had to be removed from the site then a total of 40,000 to 50,000 vehicle movements would be necessary, causing noise, dust and odour pollution to the surrounding area. Excavation of materials may also result in enhanced levels of contamination i.e. upon excavation a contaminant may be oxidised as it is brought into contact with the atmosphere, resulting in an increase in contaminant levels.

Figure 1.7 East - West section through the Redheugh Site



1.3.3 Treatment Methods

The main aim of the available treatment methods is to neutralise a contaminant, or render it harmless, or to 'fix' it in the soil. Generally, treatment methods require excavation of the material prior to treatment, thus many of the problems related to excavation would be incurred. Some methods may, however, be used in-situ, but are difficult to employ.

The available treatment methods can be divided into thermal treatment, chemical treatment, microbial degradation, fixation and solidification and leaching.

(i) Thermal Treatment

This method uses heat to destroy or evaporate volatile contaminants. There are three principal variants available:

(1) To heat the soil, either by open flame or by heat transfer, in order to evaporate volatiles from the soil.

(2) To put the soil to be treated in a rotary kiln and heat the walls of the kiln to a suitable temperature in order to destroy the contaminants.

(3) To use a fluidised bed furnace to destroy hydrocarbons and polycyclic aromatic compounds.

Caution must be exercised in the use of all the thermal treatment methods because some contaminants when burned produce toxic gases (i.e. chlorinated hydrocarbons produce chlorinated dibenzodins). Where such contaminants exist it is essential that the gas emitted from the furnace is collected for treatment.

Obviously the soil must be excavated prior to treatment and then taken to the treatment plant, (unless a mobile treatment plant is available on the site) thus incurring excavation and transportation costs and the problems associated with them. The cleaned sterile soil is then returned to the site, where fertilizer must be added if the soil is to be used as a growing medium.
The method is limited in the range of contaminants it can destroy, however it has been shown to be successful at destroying cyanides, poly-nuclear aromatics and mineral oil. Experience in Holland has shown that the thermal methods are less effective with clayey or silty materials than with granular sands (ref 1.37)

Although the costs of the various thermal methods are difficult to obtain, it is reasonable to assume that thermal methods are much more expensive than would be acceptable in the U.K.

(ii) Chemical Treatment

A variety of chemical treatments exist. Basically they aim to alter the contaminant to a more stable or acceptable state by one of the following methods: oxidation, reduction, neutralisation, hydrolysis or electrolysis. For example pyrite is common on colliery waste tips and is capable of producing extreme acidity even after liming. However if oxidised to ferric hydroxide its potential to create acid conditions is greatly reduced. Cyanide, one of the by-products of town gas production, may be hydrolysed to carbon dioxide and ammonia (ref 1.38) and once in this state the ammonia is leached from the soil leaving only the carbon dioxide.

One of the main drawbacks with chemical treatment is that former industrial sites are seldom contaminated with only one contaminant, for example, the contaminants present on the Redheugh Site, Gateshead are shown in figure 1.8 and table 1.3.

Thus the addition of a product to render one pollutant harmless may have adverse effects on another.

Figure 1.8 Contamination present in area 1 of the Redheugh Site (ref 1.39)

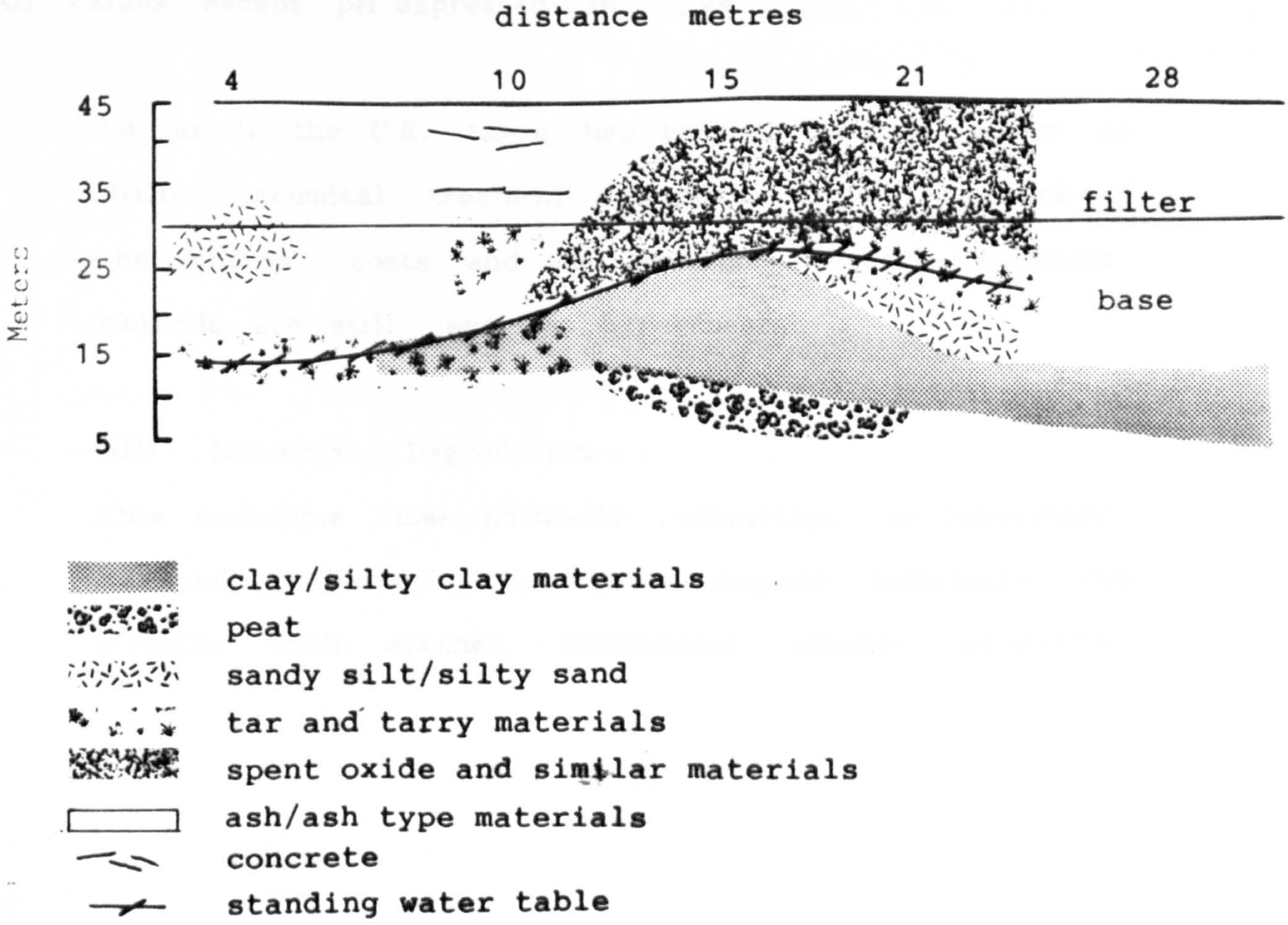


Table 1.3 Summary of the contaminants found in area 1 of the Redheugh gas works site (ref 1.39)

Parameter	Range	Mean	No. Of Samples
pH >7	7.1 - 11.4	7.73	34
pH <7	2.2 - 7.0	6.24	30
Total Cyanide	<2.5 - 7900	520.50	64
Free And Simple Cyanide	<2.5 - 220	18.40	64
Toluene Extract	500 - 320,000	21,125.80	64
Coal Tar Derivatives	<500 - 120,000	10,191.20	47
Total Phenols	<2.5 - 48	3.91	64
Acid Soluble Sulphate (SO_4)	350 - 78,000	14,984.90	64
Sulphide (h_2S)	<1.4 - 980	30.44	64
Arsenic	7.2 - 110	25.72	64
Lead	20 - 6,900	355.32	64
Zinc	32 - 2,000	421.88	64

All values except pH expressed in mg/kg

So far in the U.K. there has been no serious effort to utilise chemical treatment methods, largely because of the inherent costs and also because chemical treatment methods are still seen as experimental.

(iii) Microbial Degradation

This technique uses naturally occurring, or laboratory 'tailored', bacteria to degrade organic pollutants (i.e. straight chain alkanes, chlorinated alkanes, aromatics

and chlorinated aromatics) in the soil.
The natural bacterial decomposition process may be enhanced by improving the soil environment in order to promote degradation, i.e. by maintaining favourable soil temperatures and altering the oxygen level of the soil. Alternatively, the bacteria can be removed from the soil, cultivated in the laboratory and then reintroduced to the soil in much greater numbers. This second technique has been used by BioTreatment on a former gasworks site in Blackburn (ref 1.40) Soil was excavated from the site and aerobic bacteria added in vast numbers. The soil was kept in a polythene wind tunnel at approximately 20 degrees centigrade and fed with air to prevent anaerobic conditions developing. The first available data (table 1.4) claims the method was a success (ref 1.41).

In the Netherlands much more work has been done on developing microbial degradation of contaminants. The current technique is to excavate the soil and spread it on a drained sand bed. Fertilizer is added where necessary. Harrowing and sludge spreading are carried out at intervals. Decontamination of Rijswijk, an abandoned polyurethane factory, contaminated with heavy oils (up to levels of 6,000 mg/kg) began in July 1984 and by September 1985 conditions were satisfactory with reductions to 500 to 600 mg/kg being recorded (ref 1.42).

The advantages of this method are that it decontaminates the site without relocating the problem, it involves a low energy consumption, and it does not require costly removal of the soil. However its disadvantages are that it can only be used on organic pollutants, it takes about two years to reduce contaminants to acceptable levels and it is necessary to maintain favourable conditions for microbial growth during the treatment period.

Obviously for organic pollutants this is an exciting reclamation method which allows the total clean-up of a site, however it does require further research and development in order to obtain peak efficiency.

Table 1.4 Concentration of pollutants in contaminated areas of the Blackburn gas works site before and after treatment

Contaminant	Target Conc	Concentrations Before Treatment		Concentrations After Treatment	
		Est. Max	Est. Mean	Max	Mean
Phenols	5	9,000	205	69	3.2
PAHs	10,000	295,450	22,050	710	148.0
Free Cyanide	50	1,100	82	40	6.0
Complex Cyanide	2,500	20,000	714	65	9.5
Lead	2,000	5,500	696	1,200	231.0

All values expressed as mg/kg

(iv) Fixation and Solidification

Contaminants may be fixed in the soil matrix or solidified to reduce leachability by the following processes:

(1) addition of hydrophobic chemicals to isolate the contaminants from the soil water, thus preventing them from going into solution.

(2) Addition of chemicals to lock up contaminants and make them less soluble and therefore less available to plants.

(3) Control of soil pH and redox potential. If the soil environment is kept alkaline (above pH7) the amount of hydrogen ions in the soil will be reduced thus encouraging the retention of more soluble ions such as magnesium and calcium.

This method is most suited to metallic contaminants. Obviously the contaminants remain <u>in-situ</u> and may be released in future years to pose a new threat to the development. Once the treatment has been applied it is difficult to ensure that all contaminants have been immobilized. Indeed the United States Environmental Protection Agency noted that when they evaluated different fixation methods on various sludges most heavy metals failed to become insoluble (ref 1.43).

(v). Leaching

In this process, a liquid extracting agent is mixed with the soil causing soluble contaminants to be leached out in the extracting agent (ref 1.44) The leachate is then collected in drainage pipes for treatment or disposal. The method appears to be relatively simple, however, it is necessary first to determine the contamination spectrum and then to obtain an extracting agent suitable for the contaminants present. Again this would normally be successful only where one contaminant is present. It may also only be used on soluble contaminants. Prior to treatment it would be necessary to install suitable drainage to collect the leachate and so prevent it contaminating adjacent areas or nearby rivers and streams.

The method is probably most useful where a small amount of a single contaminant is present, and has not been utilised in the U.K. to date.

1.3.4 Encapsulation and Barrier Systems

This basically involves partial or total isolation of the contaminated area from the surrounding environment. There are a variety of materials available for this use including sheet steel piles, plastic membranes, grouting and soil materials. As no system can be completely "leak-free", reduced interaction between the contaminant and the surrounding environment is all that practically can be achieved.

Macro-encapsulation is the most extreme form of barrier system. It entails isolating the whole of the contaminated area from the surrounding area (figure 1.9) This method is favoured in the Federal Republic of Germany, (ref 1.45), where walls of bentonite cement have been used to seal the contaminated area from the surrounding area.
Other barrier systems may just restrict contaminant movement, for example, vertical walls of sheet piles or clay may be used to shield the contaminants from the prevailing flow of water (figure 1.10). Here sub-surface water is prevented from reaching the contaminants, therefore reducing the amount of contaminant in solution. Horizontal barriers may be placed over the contaminants (figure 1.11) to restrict percolating ground water from entering the contaminated material and thus reducing leachability. This particular method is favoured by the U.K. and its design, using soil materials as the barrier material, form the basic material of this research.

It is essential to choose the barrier system carefully. The material should be sufficiently robust to resist attack from the confined contamination for at least the duration of the planned development. It is also necessary to consider the effects of the barrier system on the hydrogeological regime of the area and in some instances it may be necessary to pump water from within the contaminated area to prevent any overflow of contaminated ground water.

The position of all the barrier materials should be carefully recorded in order to prevent accidental damage by any excavation, maintenance or service works which may have to be carried out in later years.

The main difficulty with barrier systems is that there is generally no sharp edge to the contamination, especially where mobile contaminants are present, so defining the area to be contained can be difficult. Also, because the contaminants are left in-situ, they are a potential hazard to future developments. However the relative cheapness of barrier systems compared to other reclamation techniques means that they will continue to be used for the foreseeable future.

Figure 1.9 Macro encapsulation

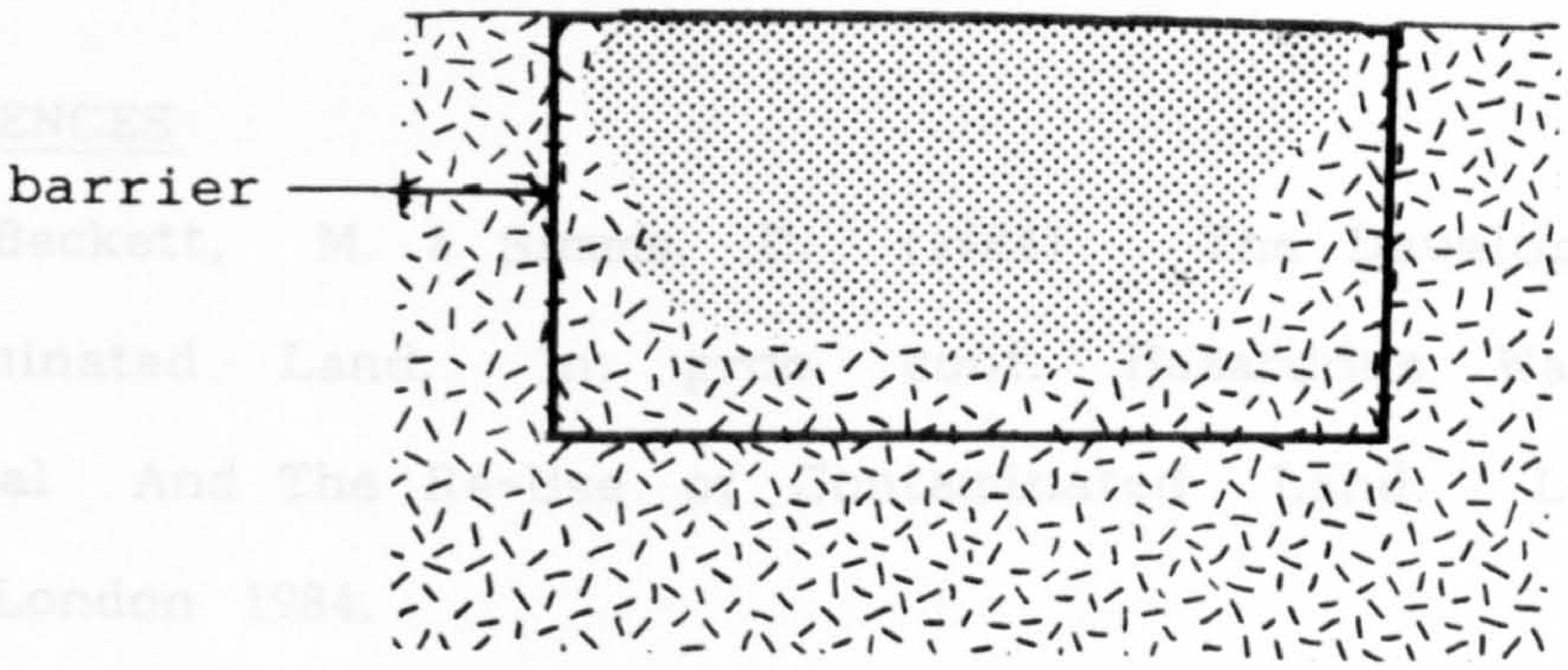


Figure 1.10 Vertical barrier system

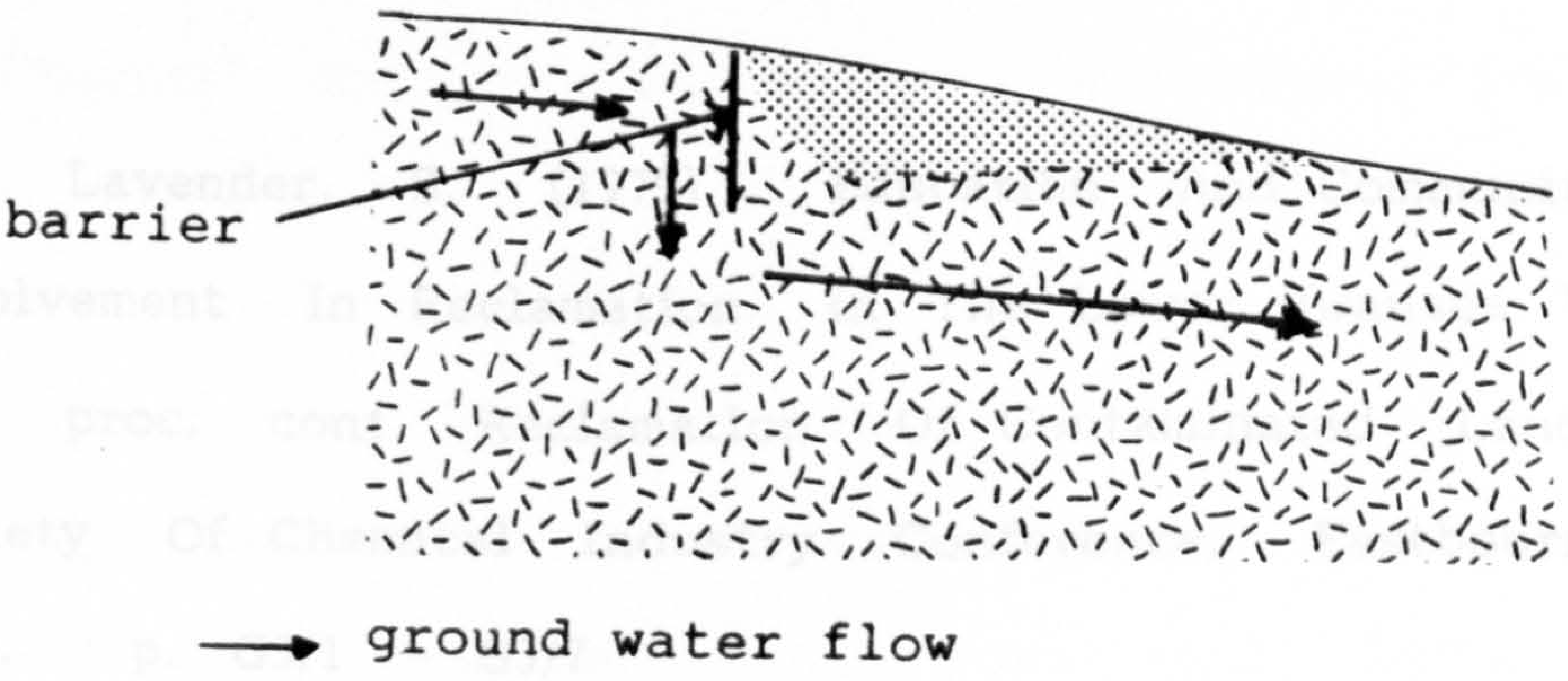
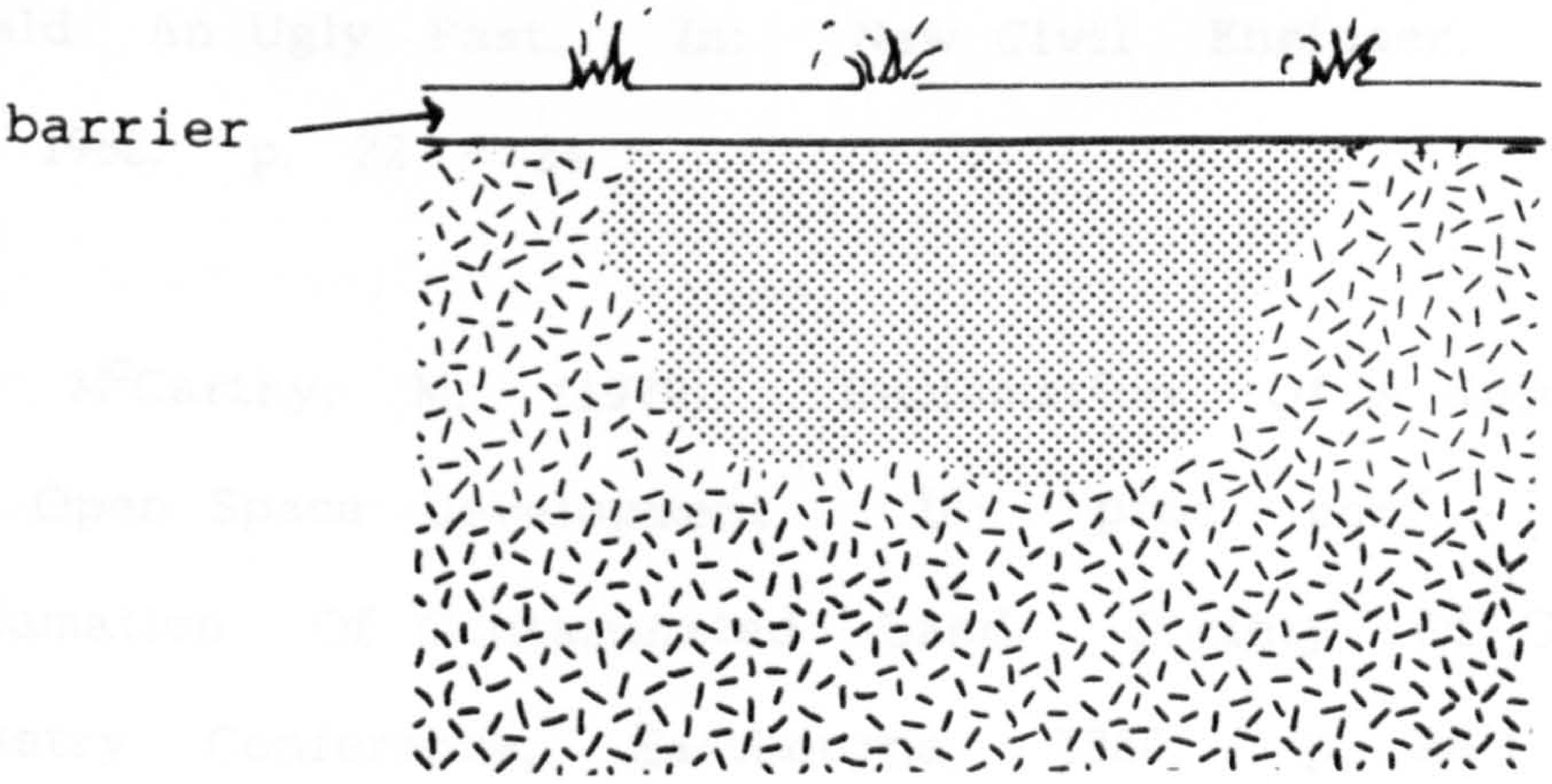


Figure 1.11 Horizontal barrier system



▨ contaminated soil

⁂ clean soil

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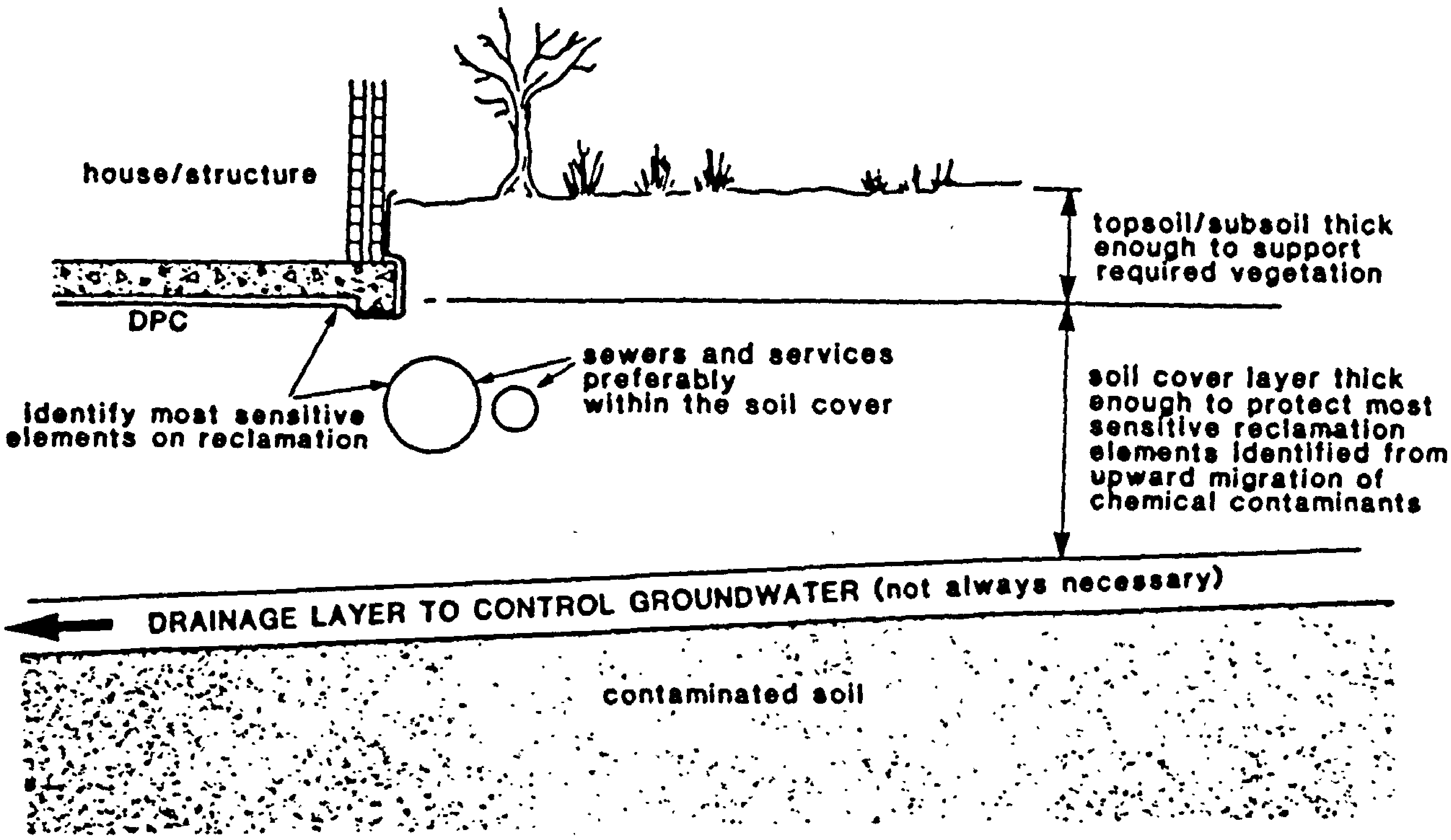
Chapter Two: The Soil Cover Method

2.1 Functions Of A Soil Cover

The soil cover method is the most popular reclamation technique practised in the U.K. It employs one or more layers of clean "soil" material to isolate the area of contamination from future site activities (figure 2.1).

Figure 2.1 Basic requirements of a soil cover



The soil cover might, depending upon individual site conditions, have to satisfy some or all of the following factors to:-

(i) provide a permanently safe barrier between the "at-risk" targets and the underlying contaminants

(ii) prevent or control gas movement on a site

(iii) prevent or control the movement of contaminated water on a site

(iv) fulfil an engineering role in order to permit successful redevelopment of a site

(v) resist erosion and subsidence

(vi) be quantifiably safe for at least the planned duration of the development (i.e. 100 years for domestic housing, or 20 to 25 years for industrial uses).

The last requirement raises the question of how thick does a cover have to be in order to be 'safe'? Obviously the thicker the cover the higher the reclamation costs. It is therefore essential that the thickness of a soil cover can be quantifiably assessed prior to installation in order to provide complete protection to 'at-risk' targets for at least the life of the development at a minimum cost.

There are four principal pathways via which contaminants may breach a soil cover, (ref 2.1), they are:-

(i) accidental exposure of contaminated material by domestic gardening, or laying or maintaining service pipes, cables, etc.

(ii) absorption of contaminants by deep rooting vegetation and concentration of those contaminants in foliage and fruit

(iii) the lifting of soluble contaminants to the ground surface by rising ground water, i.e. flooding

(iv) capillary rise of contaminated ground water during hot dry periods, such as the summer of 1976

Path (i) is relatively easy to secure. The soil cover should be sufficiently thick to allow the installation of all services. Where this is not possible over-sized trenches should be excavated in the contaminated material and backfilled with clean "soil" material. The services should be laid within this clean material.

Path (ii) can be controlled by the provision of sufficient depth of top soil to provide an adequate rooting medium for plants, this should also be the host material for soil fauna. (Frequently the nature of the soil cover material makes it inhospitable to soil fauna).

The third pathway is a little more difficult to control. During the wetter months of the year the ground water table may rise into the cover material bringing soluble contaminants with it. Cairney (ref 2.1) suggests that simple tile drainage, laid on an herringbone pattern, above the contaminated layer will intercept percolating ground water preventing it from reaching the contaminated layer and reducing the risk of flooding.

The final pathway (iv) is less easily resolved. During most of the year, in Europe, the predominant direction of soil water movement is down through the soil profile. During any hot, dry weather this soil water flow may be reversed. As water is evaporated from the soil surface a net imbalance occurs in the soil water profile, causing water to be drawn up the profile, by capillary action, from deeper, wetter horizons. If this water is drawn from the contaminated zone it may carry soluble contaminants with it. Indeed this was the case at a reclaimed gasworks site in Tyneside (ref 2.2). The 14 acre site was reclaimed during 1975 with a thin cover (<0.1 to 0.28 m) of clay soil laid above the usual phenol, sulphate and cyanide rich wastes which typify gasworks sites. By 1987 large patches of vegetation were dying. Upon investigation it was found that the soil in these areas was very acidic (approximately pH3) and contained high concentrations of chemical contaminants (Table 2.1). It would appear that plumes of contaminated material from the gasworks site had risen up through the thin soil cover over the past decade.
The practical consequences of this situation were:

the top meter of material had to be excavated and taken to a hazardous waste tip

the ground water table had to be lowered to allow

0.5 metre of gravel cover to be laid and, 0.5 metre of sub-soil and top soil had to be laid above the gravel to support the playing fields' grass cover.

This was an expensive exercise which could perhaps have been avoided had the cover been quantifiably assessed prior to installation.

Table 2.1 Examples of four ground level samples analysed from the school playing field situated on a former gas works site, Tyneside

Parameter	Sample No. 07	Sample No. 60	Sample No. 64	Sample No. 85
pH	1.64	8.18	7.19	1.67
Sulphate (SO_4)	33296	5832	36636	33190
Phenol	<0.10	23.80	4.20	4.00
Toluene Extract % w/w	-	3.10	-	-
Total CN	2650	175	4080	17250
Free CN	39.00	2.80	200.00	44.00
Ferro/Ferricyanide	1085	-	857	10530

All values except pH in mg/kg unless otherwise stated

This demonstrates the need to be able to assess a cover's performance, in terms of the amount of soluble contaminants likely to arrive at a site surface during a given period of drying, prior to the cover being laid.

The rate at which water, and therefore soluble contaminants, can be transmitted through a soil profile is determined by a number of factors including:

the soil's physical properties, especially suction and hydraulic conductivity

the intensity of drying at the surface

the number of layers in the soil cover

and the depth of the water table below the ground surface

Capillary rise through the soil profile can be expressed by a modified D'Arcy equation (eq 2.1):

$$V = K(h) \left(\frac{dh}{dz} - 1 \right) \qquad \text{eq 2.1}$$

Where: V = the flux (cm/day) through each cm^2 of soil surface

$K(h)$= the hydraulic conductivity of the soil at a given moisture content (cm/day)

h = the suction developed at that moisture content (cm of water head), where suction is the ability to lift water against gravity from deeper and wetter layers in a soil profile)

z = the height above the water table (cm)

As the drying profile of the soil is dynamic, manual calculation of the flux using equation 2.1 is both complex and time consuming and therefore necessitates the use of a computer model (section 2.2), however, some general trends are readily demonstrated by considering the anticipated values for the variables K, h and z. As can be seen in table 2.2, the value of K and h is dependant upon the soil type and the state of dryness.

Table 2.2 Change in soil properties with water content

Saturation value of soil %	Coarse gravelly sand		Fine beach sand		Estuarine clay	
	K cm/day	h cm/H_2O	K cm/day	h cm/H_2O	K cm/day	h cm/H_2O
100	2100	0	310	0	0.65	0
80	174	6.5	117	31	0.46	210
60	6.5	10	7.4	50	0.02	430
40	10^{-5}	65	0.04	79	0.01	1137
20	10^{-8}	84	10^{-6}	310	4.3×10^{-3}	12375

K = conductivity
h = suction

In saturated soils K is greater in coarse materials than in clays, consequently the flux through a saturated sand would be greater than through a saturated clay. However, in coarse soil materials, such as sands and gravels, as the soil begins to dry the macro pores empty and become air-locked restricting water flow and decreasing the conductivity. In fine grained soils, such as clays and silts, there is a fine network of micropores which drain only with great difficulty and tend not to become air-locked, thus retaining the soil's conductivity, therefore, a clay soil when dried will have a greater ability to transmit water than will an equally dried sand (table 2.2, ref 2.3)

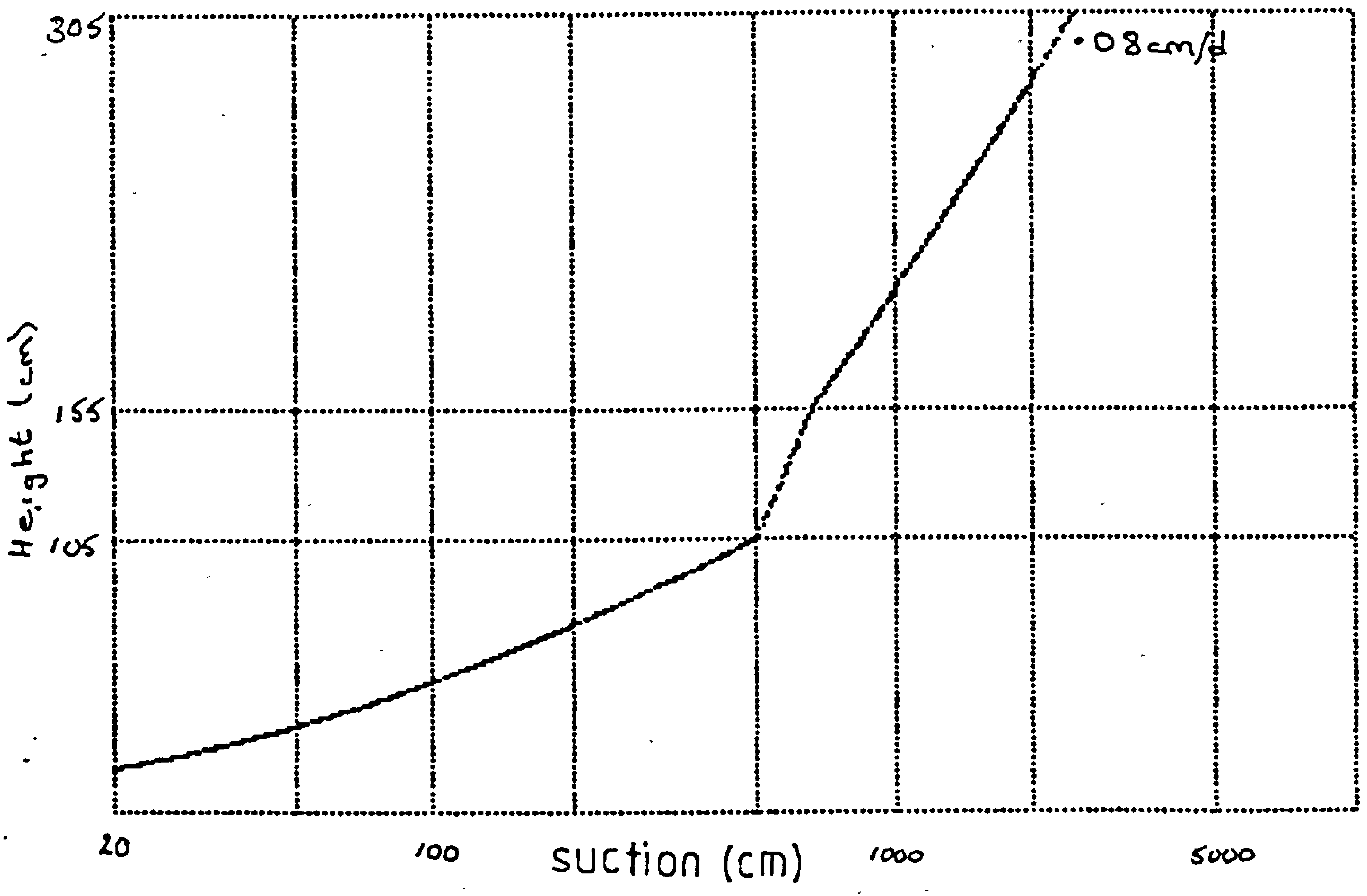
This suggests that using a coarse granular material would permit a safe cover of lesser thickness (and therefore cost) than would be possible with a clay material.

Also as any soil dries out its suction value, h, increases (table 2.2). Obviously, the greater the drying the greater the suction generated in the soils' pores and therefore the greater the height to which soil water may be lifted from deeper wetter horizons in the profile. Table 2.2 shows that clayey materials can generate much greater suctions (for a particular degree of drying) than can granular materials. This emphasises the general advantage of granular materials over clayey materials in a soil cover.

The state of a soil's dryness in a design drought can be determined by obtaining precipitation figures for a specific drought severity from Meteorological Office records, in conjunction with MAFF soil moisture deficit details for the soil type under investigation. This latter information is not always available as such data is only available in areas where regional trial plot studies have been conducted, and even where there is a convenient trial plot close to the site which is to be reclaimed, the soil type being monitored can be quite different to the soil of interest. Similar work in Holland has, however, revealed that the worst prolonged surface suction recorded is approximately 1000cms of suction. A trial plot near the Gateshead site similarly showed that a once in a century drought for the North of England can be shown to give a surface dryness in a clayey soil equal to 1000 cm's of water head sustained at the soil surface for 100 days. This surface suction value permits the designer to calculate the volume of water (and therefore soluble contaminants) able to rise through the soil under the worst suction conditions likely to occur.

If soil water has to rise through more than one soil material in order to reach the ground surface its progress up the soil profile will be determined by the parameters of each soil material in turn. In figure 2.2 the change in rate of flow of a flux (0.006 cm/day) as it passes through three different soil materials is demonstrated. Frequently, soil covers are designed with a coarse granular material at the base and one or more sandy layers above. Obviously the less conductive the basal layer the greater the suction required to bring soil water through it and to the surface. Where more than one material is used to produce a soil cover it is important that the grading of subsequent materials is chosen with care to prevent filtering of fine materials into the coarse layer as this would clog the pores and result in increased conductivity.

Figure 2.2 Change in the rate of flow of a flux as it passes through a series of different soil materials



The greater the depth (z) of the cover the greater is the depth to the water table. From equation 2.1 it can be seen that the depth 'z' is crucial in calculating the height of capillary rise, as the greater the depth the smaller the amount of water able to reach the soil surface (see Chapter 3). This in effect, provides scientific proof of the rule of thumb - the thicker the cover the better. Also it should emphasise the need to control the ground water level at as low a level as is possible.

When designing a soil cover it is necessary to consider all the controlling factors which influence the height to which soil water may rise under given drought conditions and to develop the most suitable and economic cover possible. Obviously this would be very complex if each possible covers' performance was assessed manually, however, there are a number of computer models available which allow more rapid assessment of a covers suitability and performance.

2.2 Available Models

A variety of models are available to assist the calculation of capillary rise of soil water (table 2.3). Upon investigation it was decided that the Bloemen computer model, CRISP, (ref 2.4) was the most suitable because it uses relatively simple laboratory experiments (Chapters 5 and 6) to obtain the input data (see section 2.2.3), requires no complex mathematical calculations and gives the information required in an easily understandable form.

A modification of the CRISP model has been developed to suit the specific requirements of this research (ref 2.7). It is capable of predicting capillary rise through up to ten soil layers and can output the results in both graphical and tabulated form.

The CRISP computer model is based on the D'Arcy equation for unsaturated flow (eq 2.1). Bloemen (1980, ref 2.4) describes how this can be transformed such that the height of capillary rise, z, of any flux, v, under a

Table 2.3 Models available to predict capillary rise in soil profiles

Model	Description	Input
CRISP (Bloemen) (ref 2.4)	Based on the integration of the D'Arcy equation and using K - h functions, the programme calculates the height of capillary rise of soil water, in single and multi layered soil profiles.	Number of layers in the profile Thickness of each layer Depth of the water table below the soil surface Ke, hw, and ns (see section2.3.2) for each layer
UPFLUX (Alexander) (ref 2.5)	Calculates the maximum depth of the water table, for a given soil profile, that will supply a given maximum flux to a predetermined height.	Number of layers in the profile Thickness of each layer K - h pairs for each layer (starting with h=0
Hartmann and de Boodt (ref 2.6)	Based on a study in Easter Flanders the capillary conductivity from a shallow ground water table is calculated according to D'Arcy's Law, using a lysimeter	Depth of the water table below the soil surface Capillary conductivity soil moisture tension

known suction, h, can be calculated (eq 2.2) for an average value of hydraulic conductivity of k(h). Because of the dynamic variation of K and h at every increment above the ground water table, calculation of the height of capillary rise requires step by step numerical integration according to equation 2.2:

$$z_2 = z_1 + \frac{k \, \frac{h_1 + h_2}{2} \, (h_2 - h_1)}{v + k(\bar{h})} \qquad \text{(cm)} \quad \text{eq 2.2}$$

when h>hw

The computer model is considered to be an essential time saving device for solving equation 2.2, as such integrations are complex and time consuming when performed manually.

Using the computer model requires its operator to input the following:

The required flux values

The depth of the ground water below the soil surface

The effective conductivity value (Ke) of the lowest layer

The water - entry suction (hw) of this layer

The scanning curve ratio (ns) of this layer

Details of further layers (up to 10) are entered in the same manner

The operator then enters the required suction values for which capillary rise is to be determined (see page 49) and the number of integration steps that will be performed between the given suction values (see chapter 3)

Where: "Ke", is the effective conductivity of a soil after rewetting.

"hw", is the suction at which Ke is attained on the wetting curve

and "Ns", is the slope of the average scanning curve of the hysteresis loop obtained during the wetting and drying cycle of the soil (see figure 2.3)

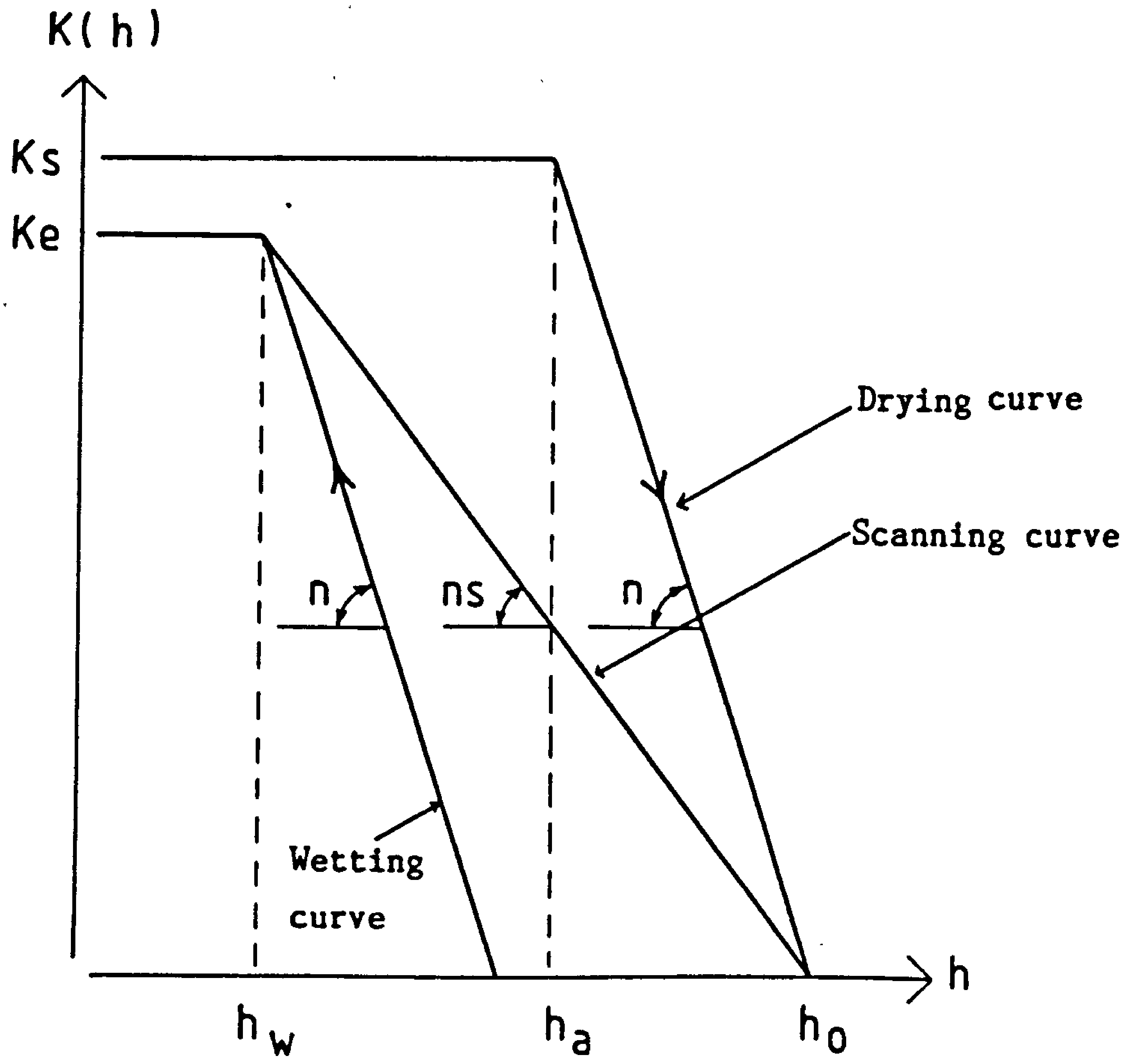
The parameters Ke, hw and ns are related by the Brooks and Corey equation, as modified to account for hysteresis:

$$K(h) = Ke \left(\frac{hw}{h} \right)^{ns} \quad \text{for } h > hw \quad \text{eq } 2.3$$

which calculates the conductivity value corresponding to any suction value.

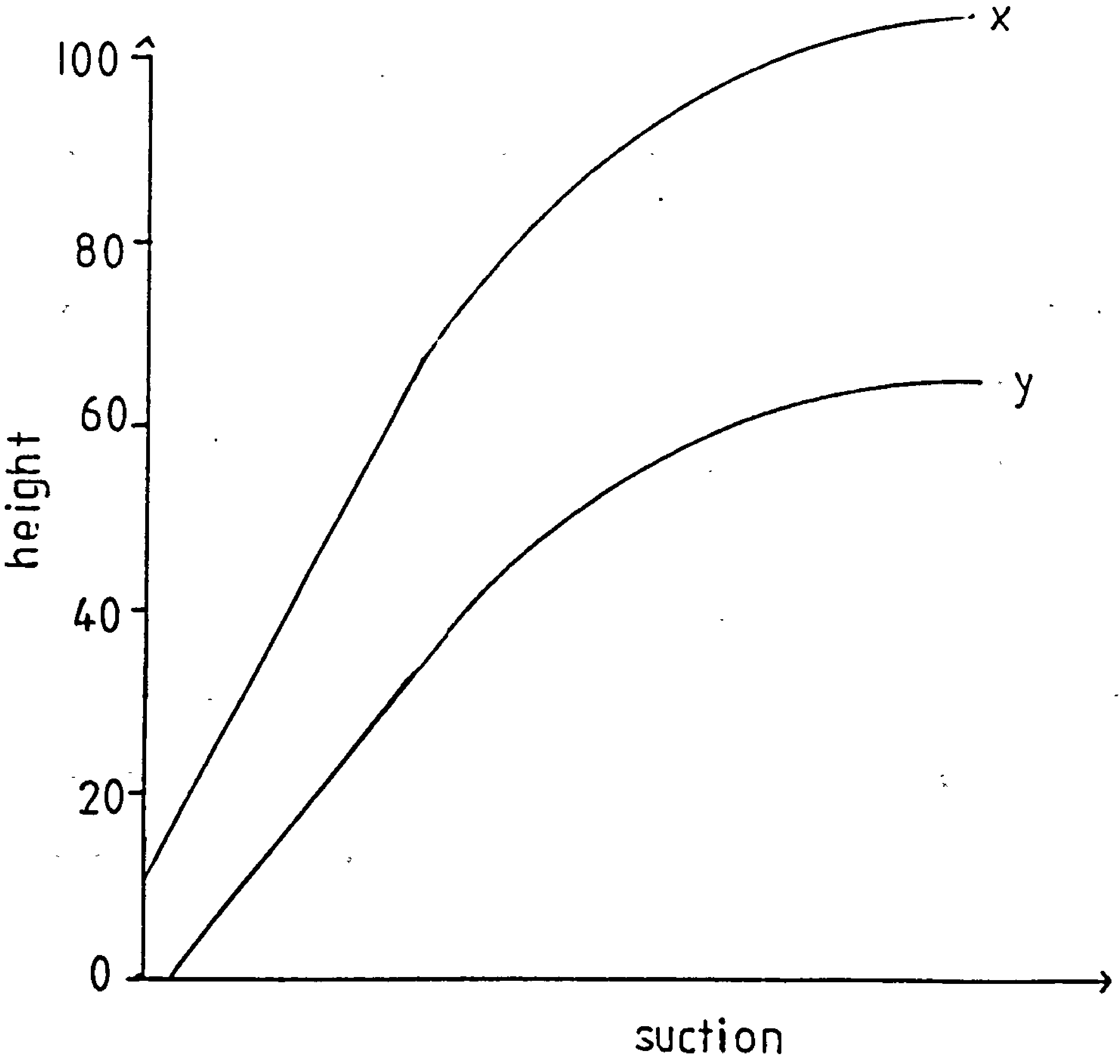
Substitution of this value in the D'Arcy equation (eq 2.1) and subsequent integration results in the derivation of equation 2.2.

Figure 2.3 Hysteresis loop showing the relationship between parameters required for the computer model



2.3. Obtaining the parameters for the computer

The range of fluxes required is largely determined after a trial run of the model using a wide variety of flux values, which allows the flux range corresponding to the height of interest above the ground water table to be identified. For example, if one wishes to identify the flux reaching 80 cm in the example below one can see that flux 'x' will reach 100 cm and flux 'y' will reach 60 cm, obviously fluxes within the range 'x' to 'y' will give the information required and therefore all fluxes outside of this range can be disregarded.



The depth of the ground water table below the soil surface is determined from actual site investigations, however, the operator must remember to add the thickness of the proposed soil cover to the recorded depth, i.e. if the water table is 0.45 m below the existing soil surface and a cover of 1 m is proposed for the site the new ground water depth would be 1.45 m.

The value of 'Ke', (the effective conductivity), is taken as half of the saturated conductivity value, following the work of Brooks and Corey (1964, ref 2.9), which has aparently not been challenged by later workers. The saturated conductivity, "Ks" value of a soil can be measured in the laboratory using a standard falling head permeability test. This was the approach used in this research.
The value of 'hw' is the suction value at which 'Ke' is attained (see figure 2.3). Obviously if one obtains a wetting curve for the soil then this value can be read off the graph directly. However, in practice measurement of the sorption curve over the entire range from air dry to fully saturated is time consuming and expensive both in terms of laboratory time and the equipment required, as a number of laboratory tests are necessary to obtain the full range of data, and accuracy towards the extremes of wetting and drying can be variable. For this reason a number of authors (ref 2.10 to 2.14) have looked at the possibility of obtaining various soil

parameters from more easily obtainable soil data such as particle size.

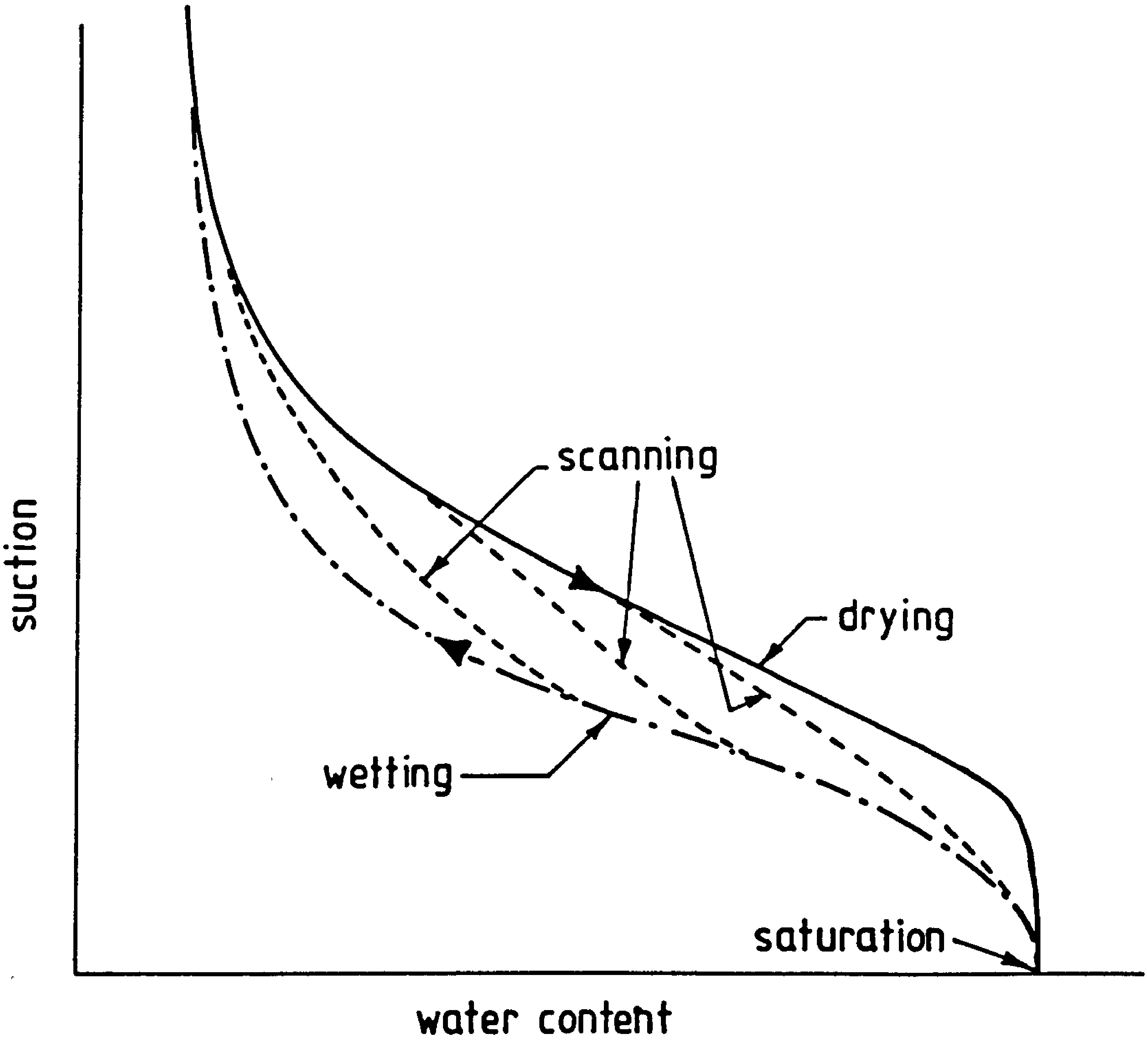
An example of this is the work of Bloemen, (1980, ref 2.14) who explored the possibility of obtaining the unsaturated hydraulic conductivity function of a soil from the grain size distribution and organic matter content of the soil. Calculations were based on the Brooks and Corey formula because of its attractive simplicity.

$$K(h) = Ks \left(\frac{ha}{h}\right)^{n} \qquad \text{cm/d} \qquad \text{eq 2.3}$$

Where: K(h) is the conductivity at any suction 'h'
Ks is the saturated conductivity (cm/d)
ha is the air entry pressure head
n is a measure of pore size distribution

Solving equation 2.4 will not generally yield results which are applicable to field situations because few soils will actually dry from a fully saturated state, or vice versa. The suction water content relationship for the soil will therefore be represented by a scanning curve (figure 2.4), however which curve is actually applicable will depend on the recent history of wetting and drying in the soil profile. As this is a very tentative basis on which to base calculations of K and capillary rise Bloemen (ref 2.14) suggests that the average scanning curve should provide a satisfactory result (equation 2.3)

Figure 2.4 Hysteresis loop and scanning curves



Calculation of hw and ns from particle size data has been discussed by Bloemen (ref 2.14).

The value of hw can be determined from the relationship:

$$C = \frac{hw}{ha} \qquad \text{eq 2.5}$$

Where: C is a coefficient whose value is chosen from the range 0.34 (clayey soils) to 0.22 (sandy soils) according to soil texture (ref 2.8).

hw is the water entry suction head

ha is the air entry suction head, the value of which is determined from the equation:

$$ha = 2914 \; Md^{-0.96} \; f^{0.79} \qquad \text{eq 2.5}$$

(Alternatively it can be determined experimentally, see chapter six)

Where: Md is the median grain size

f the grain size distribution index (confer ref 2.14)

hw is therefore the product of C x ha

The value of 'ns' is determined according to the equation:

$$ns = \log 2 \left(\frac{ha}{ho}\right)^{nd} / \log \left(\frac{hw}{ho}\right) \quad \text{eq. 2.7}$$

Where: ha is the air entry suction head

nd is derived graphically from the gradient of the drying curve for suction against hydraulic conductivity

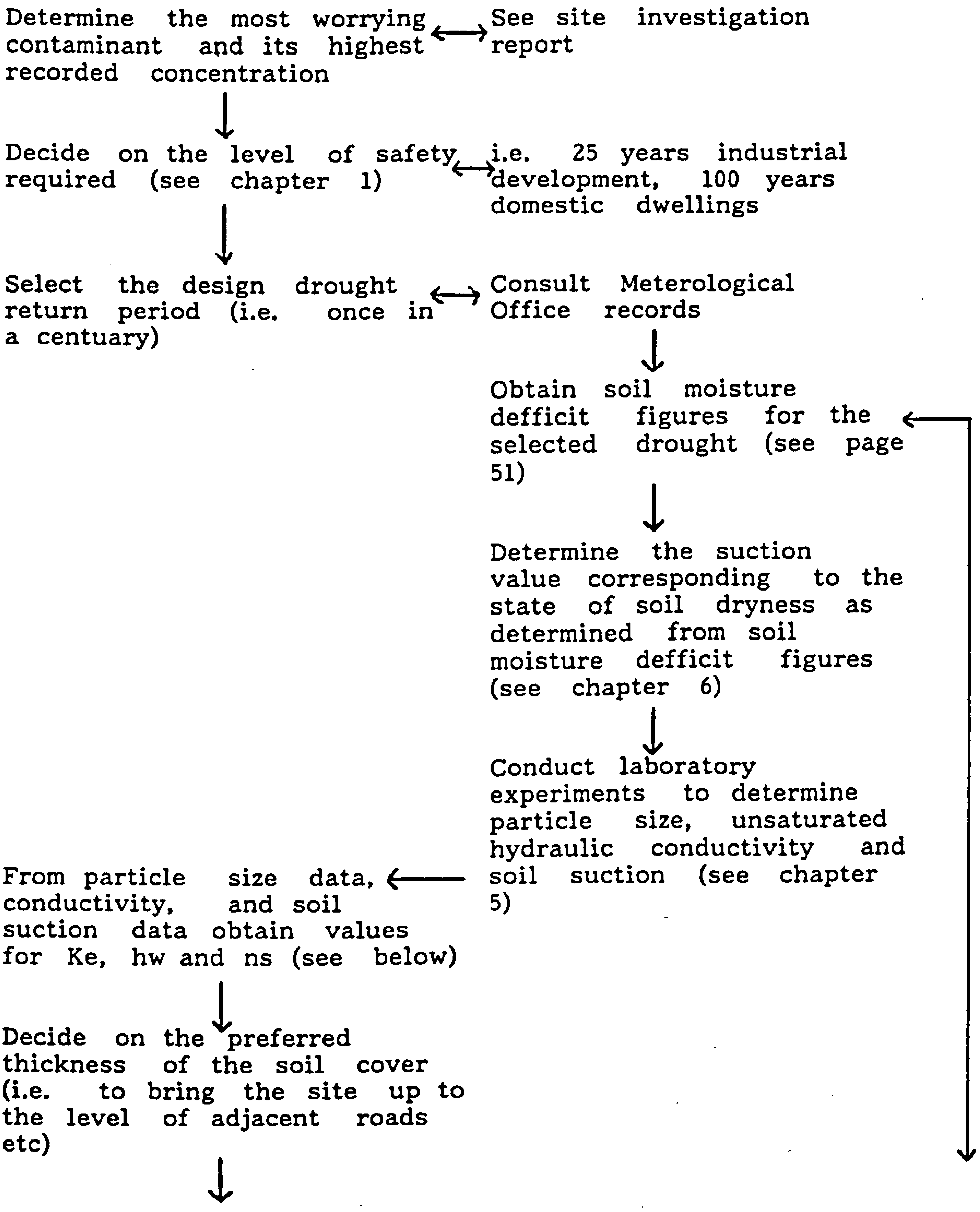
hw is the water entry suction head

and ho is the soil moisture suction head where the scanning curve and the drying curve approach. This value is chosen according to soil texture, from the range: 10^6 in the heaviest clays or loams to 10^3 in the coarsest sands (ref 2.14)

Again ns can be determined experimentally if both a wetting and drying curve are obtained for the soil (see chapter six), however, in this research it was not possible to determine ns experimentally, use was therefore made of the above equation.

2.4 Using The Computer Model

A simple flow chart will help to outline the main steps required to use the computer model:



Determine the most worrying contaminant and its highest recorded concentration

See site investigation report

Decide on the level of safety required (see chapter 1)

i.e. 25 years industrial development, 100 years domestic dwellings

Select the design drought return period (i.e. once in a centuary)

Consult Meterological Office records

Obtain soil moisture defficit figures for the selected drought (see page 51)

Determine the suction value corresponding to the state of soil dryness as determined from soil moisture defficit figures (see chapter 6)

Conduct laboratory experiments to determine particle size, unsaturated hydraulic conductivity and soil suction (see chapter 5)

From particle size data, conductivity, and soil suction data obtain values for Ke, hw and ns (see below)

Decide on the preferred thickness of the soil cover (i.e. to bring the site up to the level of adjacent roads etc)

...cont

↓

Determine the depth of the water below this new soil surface

↓

Run the computer model for the suction value likely to occur during the chosen drought ↔ See soil moisture defficit figures

↓

From the computer output determine the flux which reaches the height of interest in the soil cover, ie root zone, foundations (figure 2.5)

↓

Determine the value dv/dz at this height (see below)

↓

Calculate the amount of contamination able to reach the soil surface using equation 2.7

2.3. Designing A Soil Cover

An example of the use of this model in a particular soil cover design (the Norwood coke works reclamation, Gateshead) will help to emphasise the data which is required and the questions which need to be asked.

The Norwood site, a former coal storage depot, in the Newcastle area extends over some 47 acres. It is to be developed initially as part of the 1990 National Garden Festival and ultimately used for domestic housing. The site was originally surfaced with coal waste (and so posed a combustion hazard) and associated shale fragments and was also contaminated with the phenols, sulphates, cyanides and sulphides that typify all old coal carbonisation sites (table 2.4).

The combustion hazards entailed by the large coal content of the site's upper layers were removed economically by washing the top 2 metres of the site material, recovering and selling the coal so collected.

The washing process helped to reduce contaminant levels on the site (table 2.4) by oxidising the phenols and removing the tarry products from the coal waste. The removal of the coal material obviously reduced the sulphate concentration, but also resulted in decreasing the acidity of the site, as pyrite (i.e. FeS_2), which is common in spoil materials, when oxidised produces sulphuric acid and thus maintains soil acidity

Of the remaining contaminants, sulphates gave the greatest cause for concern, as values as high as 2,000 mg/kg had been detected, (early 1986). This is twice the trigger concentrations for developments where there is to be no landscaping and ten times the trigger concentrations determined for all other uses (table 1.2).

Table 2.4 Summary of the contaminants found on the Norwood site

	Before Washing	After Washing	
Parameter	Soil Sample	H_2O Sample	H_2O Sample
pH	2.0 - 8.5	4.4 - 7.6	>7.2
Sulphates	100 - 24100	1350 - 23900	<2000
Phenols	<2 - 17.0	0 - 0.08	NIL
Toluene extract	3000 - 97400	<20 - 25	NIL
Total Cyanide	<1 - 27.5	-	-
Ammonia	<1 - 28.3	-	-

All values except pH expressed in mg/kg

The water level on the site was everywhere more than 1.05 meters below the ground surface.

The site topography is such that a soil cover of up to two meters could easily be accommodated. Three local sub soil/boulder clay materials were potentially available cheaply and in sufficiently large quantities for use as a soil cover, together with a supply of pulverised fuel ash (PFA), which could be used as a fire blanket if this was found to be necessary. No granular soil materials were economically available, so the soil cover had to utilise clayey materials despite the lesser efficiency of these.

The site developers suggested that the first 0.5 meter of cover should be a PFA fire blanket over which up to 1.5 meters of any one of the three available sub soil/boulder clay materials should be laid.

Liverpool Polytechnic was approached to evaluate the performance of each of the three materials as a soil cover (both with and without the PFA fire blanket), by quantifying the amount of contamination likely to arrive at the new site surface during a design drought. Samples of each of the materials, including PFA, were received for testing along with three samples of the site's surface as it would be after the coal content had been removed by a washing process.

Data for each of the materials received for use in the soil covers (table 2.5) were entered into the computer to predict the height of capillary rise of soil water under drought conditions. There were eighteen possible combinations, (as note had to be taken of the variable product produced as discard after the coal washing process) the results for each proposed cover can be seen in tables 2.6 to 2.23 and figures 2.5 to 2.22. Material No 2 produced the largest values for contaminant rise of the sites surface materials and would therefore give the most extreme results for contaminant rise, so its properties were used as representative of the surface material in order to design for the worst possible case.

Table 2.5 Physical characteristics of the soil cover materials

	Material	Sat H_2O content %	Dry density	SG.	Ks.	Ke.	ns.	hw.
	Insitu clay	29	1.53	2.63	0.051	0.026	1.31	9.8
	Imported clay	31	1.40	2.61	0.886	0.443	1.02	24.6
	Eighton clay	21	1.70	2.65	7.720	3.860	1.03	2.9
	PFA	45	1.10	2.20	13.070	7.53	1.62	21.0
Discard	Material No 1	19	1.25	1.80	26 060	13.030	1.40	0.6
	Material No 2	17	1.50	2.20	9.220	4.610	1.00	0.7
	Material No 3	18	1.40	2.15	1.73	0.86	1.03	0.6

Table 2.6 Capillary rise through Material No 1 overlaid by Insitu Clay

```
Layer Height  ns      ke      hw      hw'
  1     0.0  1.40  13.030   0.60    0.60
  2   105.0  1.31   0.026   9.80    0.09

Ground-water depth is 255 cm


 100 integration steps/suction level

==============================================================================
                Flux (cm/day)
                0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
==============================================================================
Suction (cm)        Height (cm)
          20     14.6  15.4  16.2  17.2  18.5  19.3  19.5  19.7  19.8  19.9
          50     24.2  26.4  29.3  33.2  39.2  44.7  45.9  47.1  48.5  49.4
         100     31.1  34.7  39.7  47.4  61.1  77.6  81.8  86.7  92.7  96.9
         200     36.8  41.8  48.9  60.5  84.2 108.1 110.9 115.5 127.5 148.1
         500     42.6  48.9  58.4  74.4 105.9 117.8 123.6 134.0 162.3 221.3
        1000     45.8  52.9  63.7  82.3 108.2 123.6 131.3 145.5 184.6 255.0
        2000     48.2  55.9  67.7  88.4 110.1 128.3 137.6 154.9 203.2 255.0
        5000     50.5  58.9  71.6  94.2 112.1 133.1 144.1 164.6 222.6 255.0
       10000     51.8  60.5  73.7  97.4 113.2 136.0 147.9 170.3 234.1 255.0
```

Figure 2.5 Capillary rise through Material No 1 overlaid by Insitu Clay

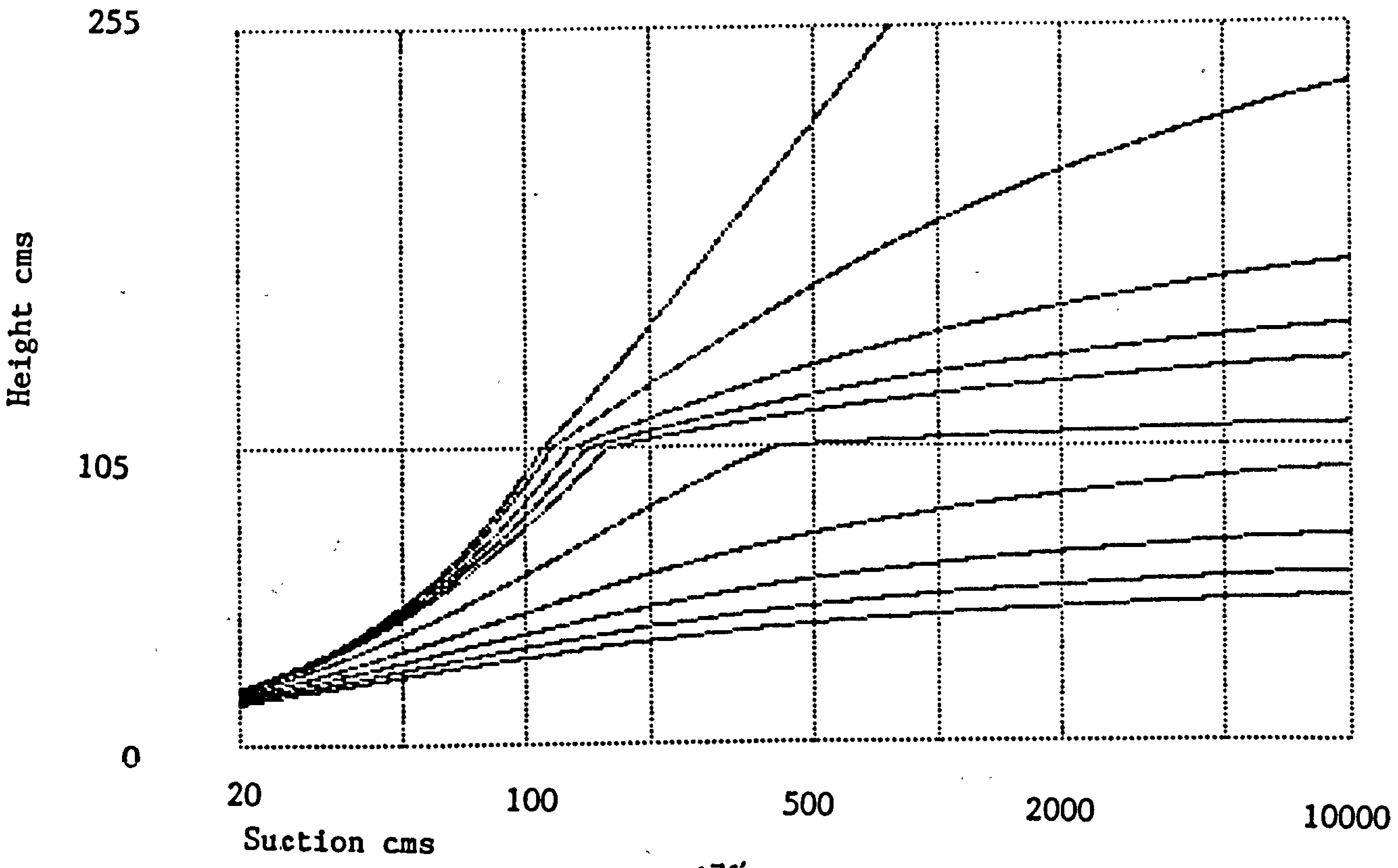


Table 2.7 Capillary rise through Material No 2 overlaid by Insitu Clay

```
Layer Height   ns       ke      hw      hw'
  1     0.0   1.00    4.610    0.70    0.70
  2   105.0   1.31    0.026    9.80    0.19

Ground-water depth is 255 cm


 100 integration steps/suction level

==========================================================================
            Flux (cm/day)
            0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
==========================================================================
Suction (cm)      Height (cm)
        20   15.6  16.2  17.0  17.9  18.9  19.5  19.6  19.8  19.9  20.0
        50   30.2  32.5  35.3  38.9  43.6  47.1  47.8  48.5  49.2  49.7
       100   45.5  50.3  56.5  65.0  77.8  89.3  91.7  94.3  97.0  98.8
       200   63.7  72.0  83.4 100.6 106.6 111.4 113.9 118.9 129.7 149.8
       500   90.4 104.7 105.7 107.4 110.5 121.0 126.5 137.5 164.4 222.9
      1000  105.2 105.6 106.5 108.5 112.8 126.8 134.2 148.9 186.8 255.0
      2000  105.6 106.1 107.1 109.5 114.7 131.5 140.5 158.3 205.4 255.0
      5000  106.0 106.6 107.8 110.5 116.7 136.4 147.0 168.1 224.8 255.0
     10000  106.2 106.9 108.1 111.0 117.8 139.3 150.8 173.8 236.2 255.0
Final layer:    2     2     2     2     2     2     2     2     2     2
```

Figure 2.6 Capillary rise through Material No 2 overlaid by Insitu Clay

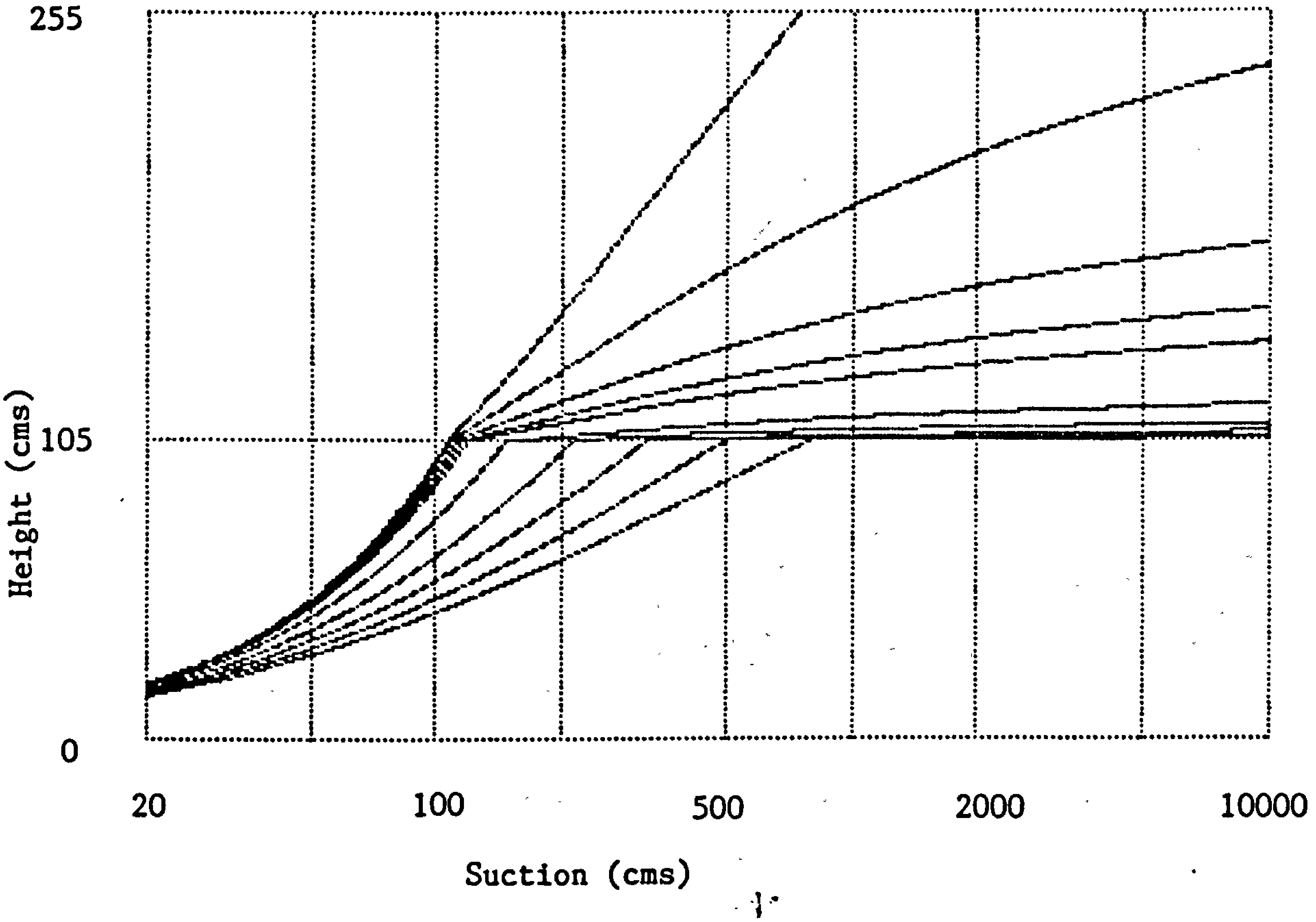


Table 2.8 Capillary rise through Material No 3 overlaid by Insitu Clay

Layer	Height	ns	ke	hw	hw'
1	0.0	1.03	0.860	0.60	0.60
2	105.0	1.31	0.026	9.80	0.68

Ground-water depth is 255 cm

100 integration steps/suction level

	Flux (cm/day)									
	0.100	0.080	0.060	0.040	0.020	0.008	0.006	0.004	0.002	0.001
Suction (cm)	Height (cm)									
20	7.8	8.7	10.0	11.7	14.5	17.2	17.8	18.5	19.2	19.7
50	11.5	13.2	15.6	19.4	26.6	36.0	38.5	41.5	45.2	47.9
100	14.4	16.8	20.2	26.1	38.4	57.6	63.6	71.6	82.7	92.0
200	17.3	20.4	25.0	33.1	51.5	84.9	96.9	108.1	121.3	144.4
500	21.2	25.2	31.4	42.6	69.8	109.8	115.5	126.7	156.1	217.6
1000	24.1	28.8	36.2	49.7	83.8	115.6	123.2	138.2	178.5	255.0
2000	26.9	32.3	40.9	56.7	97.8	120.3	129.5	147.5	197.0	255.0
5000	30.6	36.9	47.0	65.8	106.3	125.1	136.0	157.3	216.4	255.0
10000	33.3	40.3	51.5	72.6	107.4	128.0	139.8	163.0	227.9	255.0

Figure 2.7 Capillary rise through Material No 3 overlaid by Insitu Clay

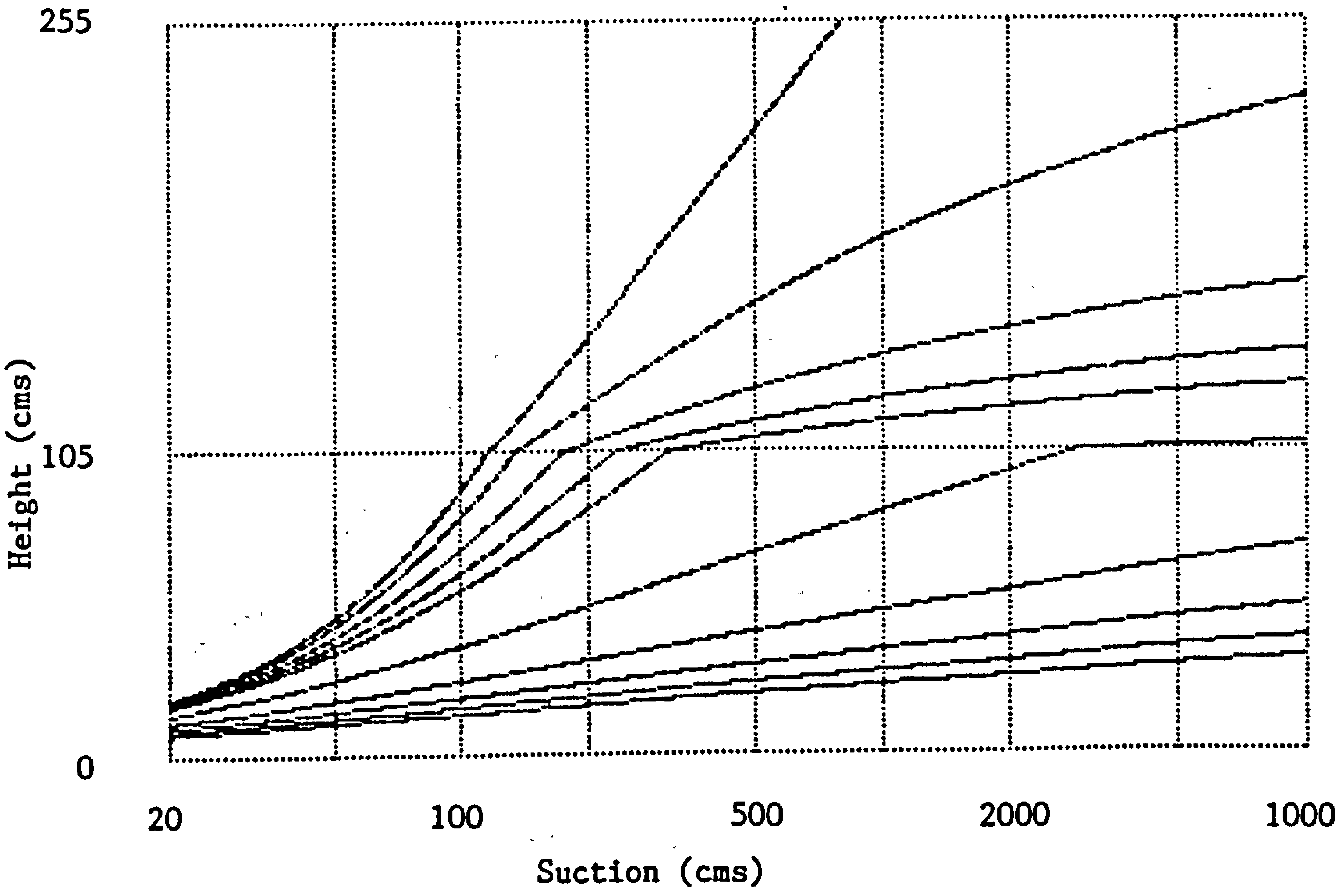


Table 2.9 Capillary rise through Material No 1 overlaid by Imported Clay

```
Layer Height   ns      ke       hw      hw'
  1     0.0   1.40  13.030    0.60    0.60
  2   105.0   1.31   0.026    9.80    0.09

Ground-water depth is 255 cm

 100 integration steps/suction level
==========================================================================
               Flux (cm/day)
               0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
==========================================================================
Suction (cm)        Height (cm)
       20       14.6  15.4  16.2  17.2  18.5  19.3  19.5  19.7  19.8  19.9
       50       24.2  26.4  29.3  33.2  39.2  44.7  45.9  47.1  48.5  49.4
      100       31.1  34.7  39.7  47.4  61.1  77.6  81.8  86.7  92.7  96.9
      200       36.8  41.8  48.9  60.5  84.2 108.1 110.9 115.5 127.5 148.1
      500       42.6  48.9  58.4  74.4 105.9 117.8 123.6 134.0 162.3 221.3
     1000       45.8  52.9  63.7  82.3 108.2 123.6 131.3 145.5 184.6 255.0
     2000       48.2  55.9  67.7  88.4 110.1 128.3 137.6 154.9 203.2 255.0
     5000       50.5  58.9  71.6  94.2 112.1 133.1 144.1 164.6 222.6 255.0
    10000       51.8  60.5  73.7  97.4 113.2 136.0 147.9 170.3 234.1 255.0
```

Figure 2.8 Capillary rise through Material No 1 overlaid by Imported Clay

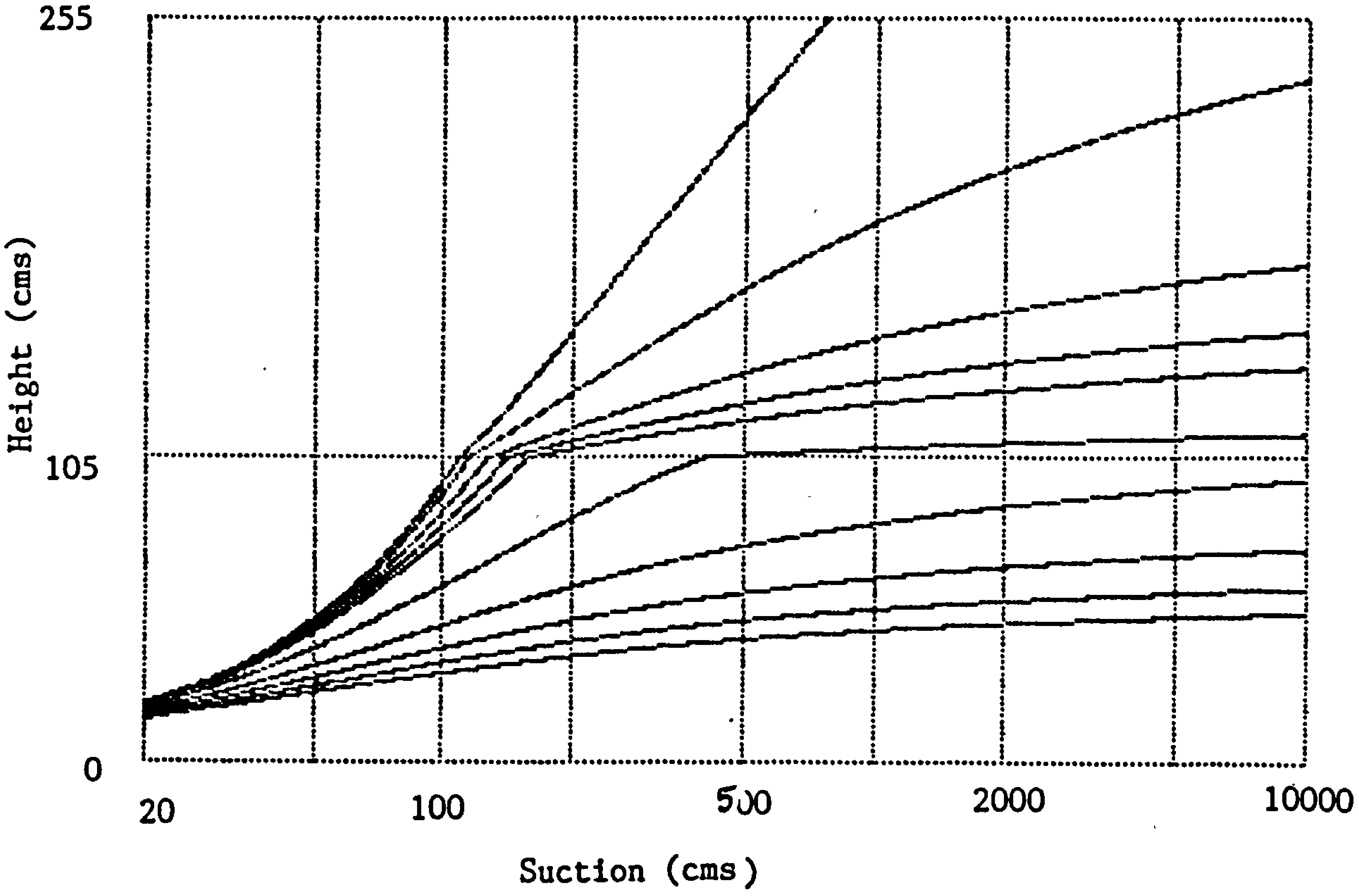


Table 2.10 Capillary rise through Material No 2 overlaid by Imported Clay

```
Layer Height   ns       ke       hw       hw'
  1     0.0   1.00    4.610    0.70     0.70
  2   105.0   1.02    0.443   24.60     2.48

Ground-water depth is 255 cm

 100 integration steps/suction level

========================================================================
              Flux (cm/day)
              0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
========================================================================
Suction (cm)       Height (cm)
          20    15.6  16.2  17.0  17.9  18.9  19.5  19.6  19.8  19.9  20.0
          50    30.2  32.5  35.3  38.9  43.6  47.1  47.8  48.5  49.2  49.7
         100    45.5  50.3  56.5  65.0  77.8  89.3  91.7  94.3  97.0  98.8
         200    63.7  72.0  83.4 100.6 144.1 176.4 182.1 187.9 193.9 197.5
         500    90.4 104.7 156.6 225.7 255.0 255.0 255.0 255.0 255.0 255.0
        1000   124.8 178.7 251.3 255.0 255.0 255.0 255.0 255.0 255.0 255.0
        2000   189.8 255.0 255.0 255.0 255.0 255.0 255.0 255.0 255.0 255.0
        5000   255.0 255.0 255.0 255.0 255.0 255.0 255.0 255.0 255.0 255.0
       10000   255.0 255.0 255.0 255.0 255.0 255.0 255.0 255.0 255.0 255.0
```

Figure 2.9 Capillary rise through Material No 2 overlaid by Imported Clay

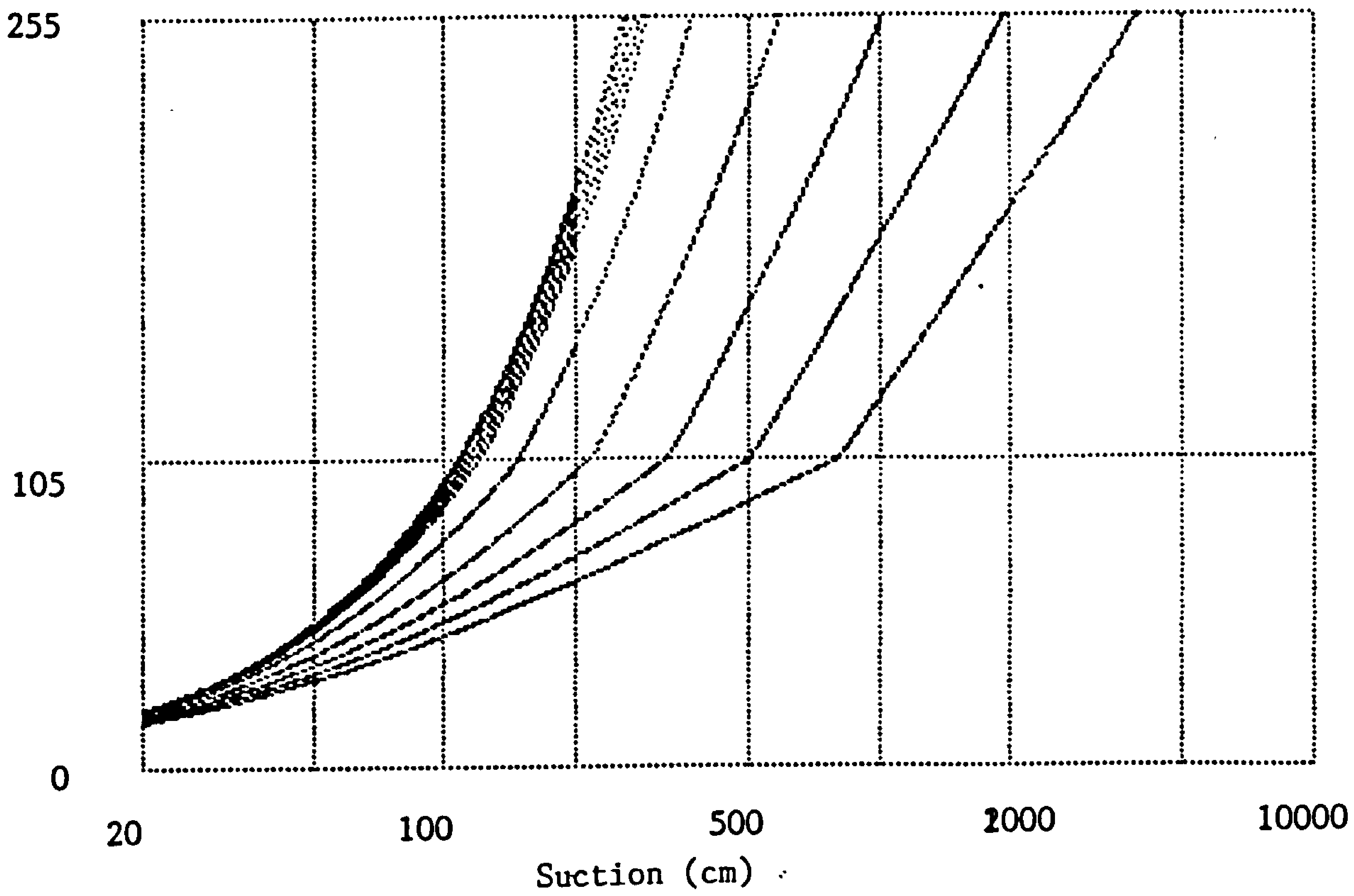


Table 2.11 Capillary rise through Material No 3 overlaid by Imported Clay

```
Layer Height   ns      ke      hw      hw'
  1     0.0   1.03   0.860    0.60    0.60
  2   105.0   1.02   0.443   24.60   12.84

Ground-water depth is 255 cm


 100 integration steps/suction level

==========================================================================
                 Flux (cm/day)
                 0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
==========================================================================
Suction (cm)         Height (cm)
          20      7.8   8.7  10.0  11.7  14.5  17.2  17.8  18.5  19.2  19.7
          50     11.5  13.2  15.6  19.4  26.6  36.0  38.5  41.5  45.2  47.9
         100     14.4  16.8  20.2  26.1  38.4  57.6  63.6  71.6  82.7  92.0
         200     17.3  20.4  25.0  33.1  51.5  84.9  96.9 128.5 168.6 188.4
         500     21.2  25.2  31.4  42.6  69.8 244.3 255.0 255.0 255.0 255.0
        1000     24.1  28.8  36.2  49.7  83.8 255.0 255.0 255.0 255.0 255.0
        2000     26.9  32.3  40.9  56.7  97.8 255.0 255.0 255.0 255.0 255.0
        5000     30.6  36.9  47.0  65.8 255.0 255.0 255.0 255.0 255.0 255.0
       10000     33.3  40.3  51.5  72.6 255.0 255.0 255.0 255.0 255.0 255.0
```

Figure 2.10 Capillary rise through Material No 3 overlaid by Imported Clay

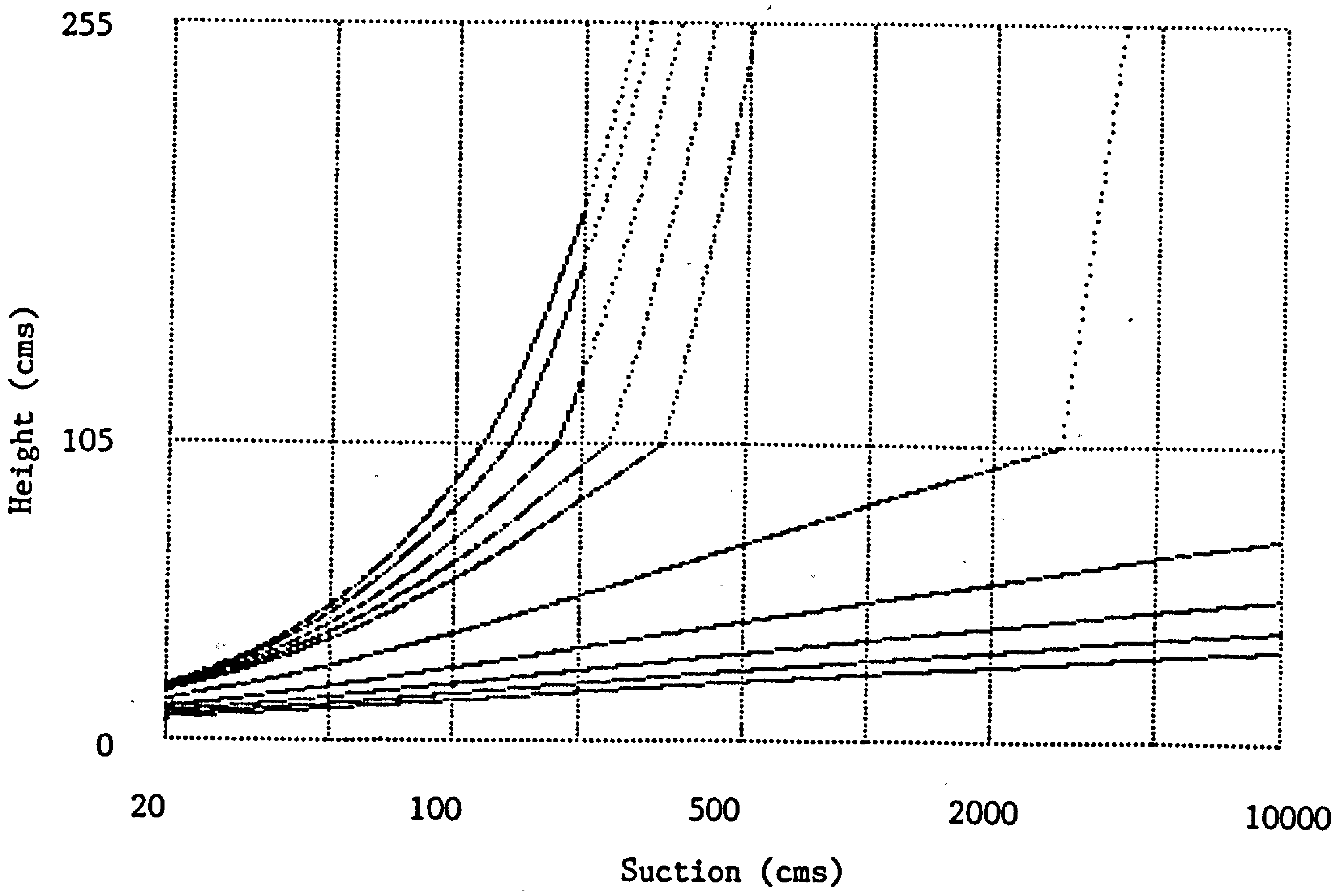


Table 2.12 Capillary rise through Material No 1 overlaid by Eighton Clay

```
Layer Height  ns       ke      hw      hw'
  1    0.0   1.40  13.030    0.60    0.60
  2  105.0   1.03   3.860    2.90    0.89

Ground-water depth is 205 cm


 100 integration steps/suction level

=====================================================================
                Flux (cm/day)
                0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
=====================================================================
Suction (cm)        Height (cm)
         20      14.6  15.4  16.2  17.2  18.5  19.3  19.5  19.7  19.8  19.9
         50      24.2  26.4  29.3  33.2  39.2  44.7  45.9  47.1  48.5  49.4
        100      31.1  34.7  39.7  47.4  61.1  77.6  81.8  86.7  92.7  96.9
        200      36.8  41.8  48.9  60.5  84.2 141.2 158.0 173.5 187.2 195.0
        500      42.6  48.9  58.4  74.4 154.6 205.0 205.0 205.0 205.0 205.0
       1000      45.8  52.9  63.7  82.3 205.0 205.0 205.0 205.0 205.0 205.0
       2000      48.2  55.9  67.7  88.4 205.0 205.0 205.0 205.0 205.0 205.0
       5000      50.5  58.9  71.6  94.2 205.0 205.0 205.0 205.0 205.0 205.0
      10000      51.8  60.5  73.7  97.4 205.0 205.0 205.0 205.0 205.0 205.0
```

Figure 2.11 Capillary rise through Material No 1 overlaid by Eighton Clay

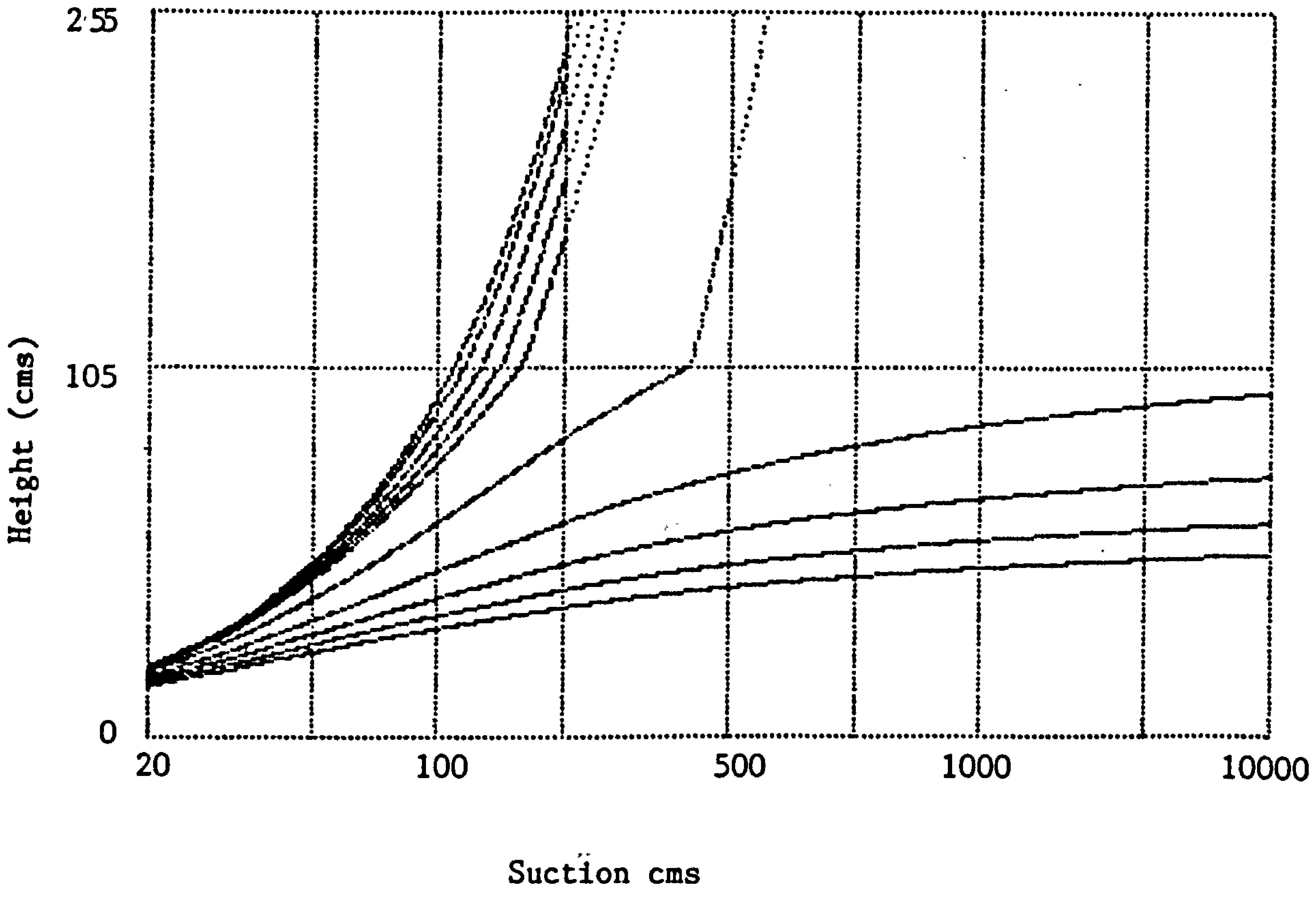


Table 2.13 Capillary rise through Material No 2 overlaid by Eighton Clay

Layer	Height	ns	ke	hw	hw'
1	0.0	1.00	4.610	0.70	0.70
2	105.0	1.03	3.860	2.90	2.44

Ground-water depth is 255 cm

100 integration steps/suction level

	Flux (cm/day)									
	0.100	0.080	0.060	0.040	0.020	0.008	0.006	0.004	0.002	0.001
Suction (cm)	Height (cm)									
20	15.6	16.2	17.0	17.9	18.9	19.5	19.6	19.8	19.9	20.0
50	30.2	32.5	35.3	38.9	43.6	47.1	47.8	48.5	49.2	49.7
100	45.5	50.3	56.5	65.0	77.8	89.3	91.7	94.3	97.0	98.8
200	63.7	72.0	83.4	100.6	143.5	175.9	181.7	187.6	193.7	197.5
500	90.4	104.7	154.3	221.4	255.0	255.0	255.0	255.0	255.0	255.0
1000	123.6	174.3	243.6	255.0	255.0	255.0	255.0	255.0	255.0	255.0
2000	184.0	248.7	255.0	255.0	255.0	255.0	255.0	255.0	255.0	255.0
5000	255.0	255.0	255.0	255.0	255.0	255.0	255.0	255.0	255.0	255.0
10000	255.0	255.0	255.0	255.0	255.0	255.0	255.0	255.0	255.0	255.0

Figure 2.12 Capillary rise through Material No 2 overlaid by Eighton Clay

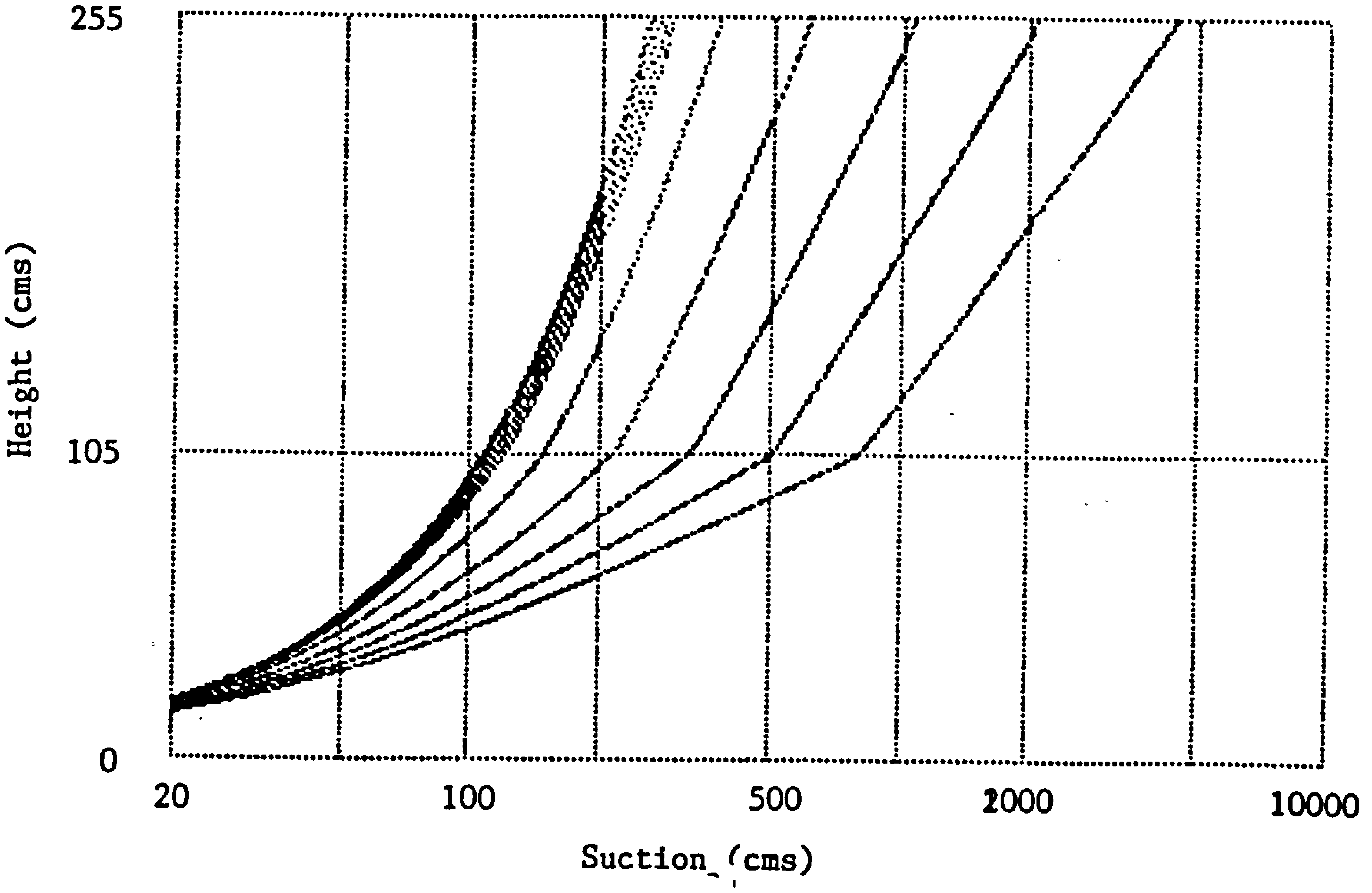


Table 2.14 Capillary rise through Material No 3 overlaid by Eighton Clay

```
Layer Height  ns      ke      hw     hw'
  1     0.0   1.03   0.860   0.60   0.60
  2   105.0   1.03   3.860   2.90  12.46

Ground-water depth is 255 cm

 100 integration steps/suction level

==========================================================================
               Flux (cm/day)
               0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
==========================================================================
Suction (cm)        Height (cm)
        20      7.8   8.7  10.0  11.7  14.5  17.2  17.8  18.5  19.2  19.7
        50     11.5  13.2  15.6  19.4  26.6  36.0  38.5  41.5  45.2  47.9
       100     14.4  16.8  20.2  26.1  38.4  57.6  63.6  71.6  82.7  92.0
       200     17.3  20.4  25.0  33.1  51.5  84.9  96.9 128.4 168.5 188.4
       500     21.2  25.2  31.4  42.6  69.8 242.1 255.0 255.0 255.0 255.0
      1000     24.1  28.8  36.2  49.7  83.8 255.0 255.0 255.0 255.0 255.0
      2000     26.9  32.3  40.9  56.7  97.8 255.0 255.0 255.0 255.0 255.0
      5000     30.6  36.9  47.0  65.8 255.0 255.0 255.0 255.0 255.0 255.0
     10000     33.3  40.3  51.5  72.6 255.0 255.0 255.0 255.0 255.0 255.0
```

Figure 2.13 Capillary rise through Material No 3 overlaid by Eighton Clay

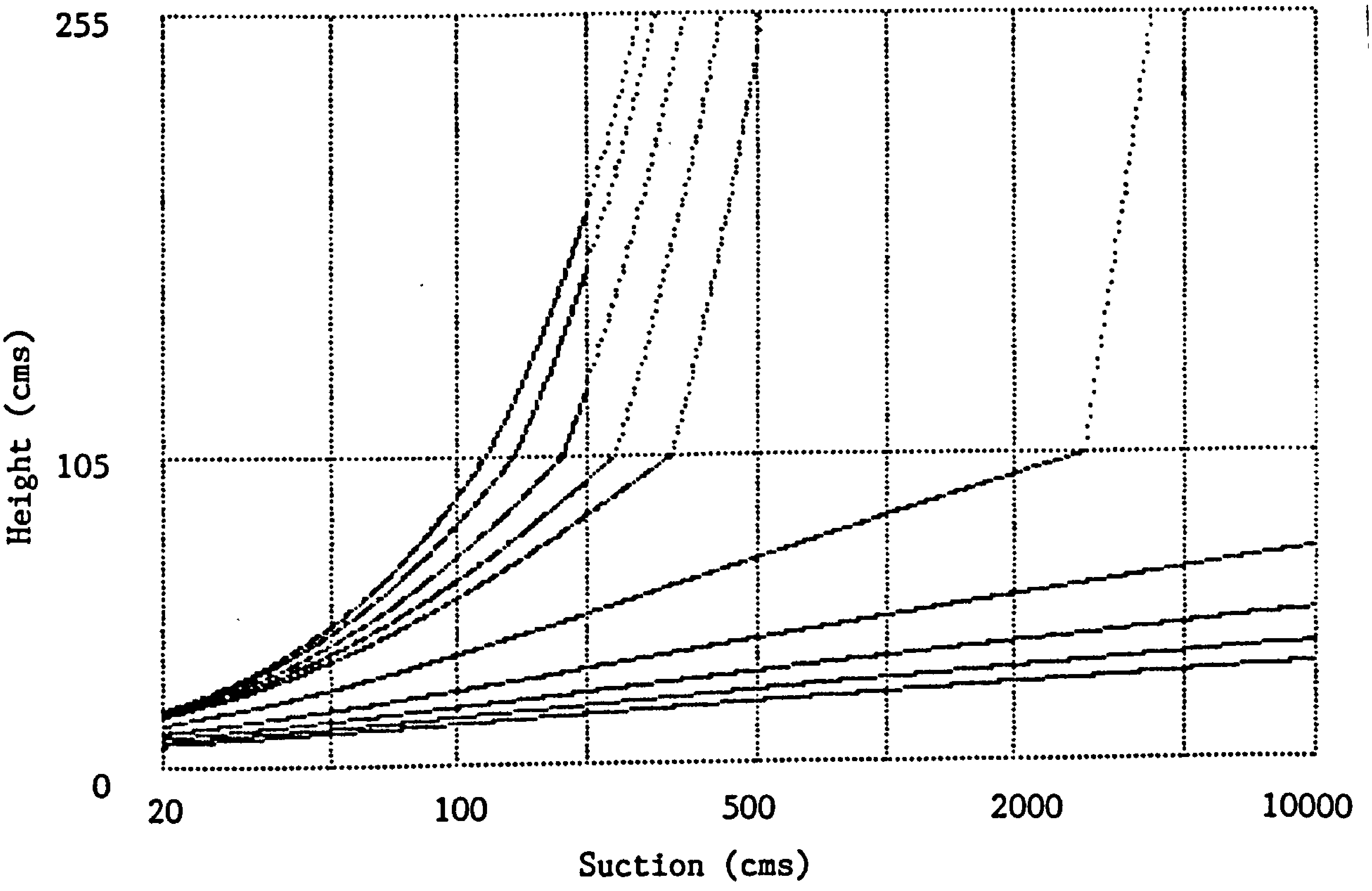


Table 2.15 Capillary rise through Material No 1 overlaid by PFA and Imported Clay

```
Layer Height  ns      ke      hw     hw'~
  1     0.0   1.40  13.030   0.60   0.60
  2   105.0   1.62   7.530  21.00  14.97
  3   155.0   1.02   0.443  24.60   0.89

Ground-water depth is 305 cm

 100 integration steps/suction level

=================================================================================
                 Flux (cm/day)
                 0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
=================================================================================
Suction (cm)          Height (cm)
       20         14.6  15.4  16.2  17.2  18.5  19.3  19.5  19.7  19.8  19.9
       50         24.2  26.4  29.3  33.2  39.2  44.7  45.9  47.1  48.5  49.4
      100         31.1  34.7  39.7  47.4  61.1  77.6  81.8  86.7  92.7  96.9
      200         36.8  41.8  48.9  60.5  84.2 145.0 161.6 175.9 188.3 195.5
      500         42.6  48.9  58.4  74.4 169.5 305.0 305.0 305.0 305.0 305.0
     1000         45.8  52.9  63.7  82.3 305.0 305.0 305.0 305.0 305.0 305.0
     2000         48.2  55.9  67.7  88.4 305.0 305.0 305.0 305.0 305.0 305.0
     5000         50.5  58.9  71.6  94.2 305.0 305.0 305.0 305.0 305.0 305.0
    10000         51.8  60.5  73.7  97.4 305.0 305.0 305.0 305.0 305.0 305.0
```

Figure 2.14 Capillary rise through Material No 1 overlaid by PFA and Imported Clay

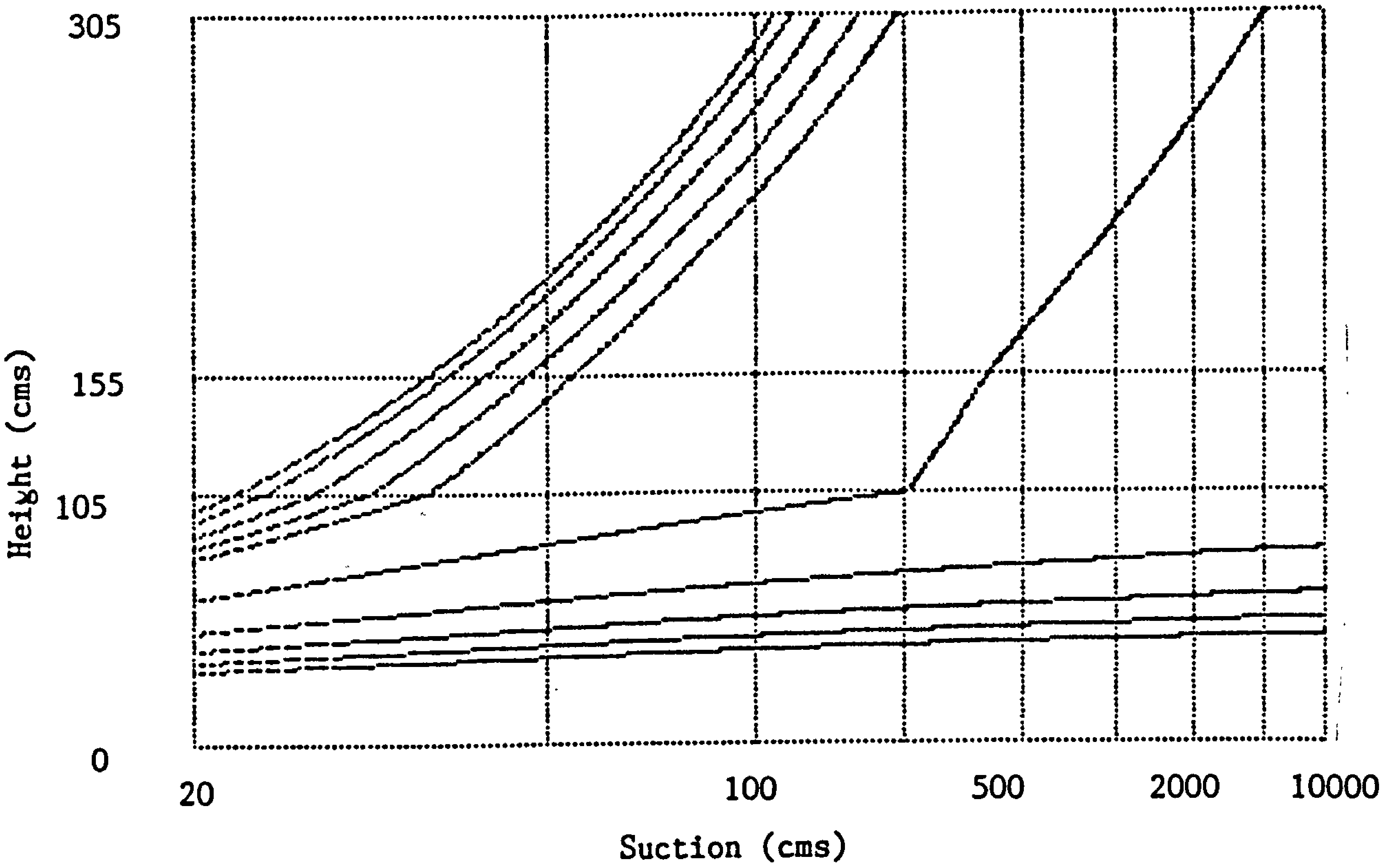


Table 2.16 Capillary rise through Material No 2 overlaid by PFA and Imported Clay

```
Layer Height  ns      ke      hw      hw'
  1     0.0   1.00   4.610   0.70    0.70
  2   105.0   1.62   7.530  21.00   28.43
  3   155.0   1.02   0.443  24.60    2.48

Ground-water depth is 305 cm


 100 integration steps/suction level

=========================================================================
                 Flux (cm/day)
                 0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
=========================================================================
Suction (cm)         Height (cm)
          100     45.5  50.3  56.5  65.0  77.8  89.3  91.7  94.3  97.0  98.8
          200     63.7  72.0  83.4 100.6 153.1 180.3 185.0 189.8 194.8 197.9
          300     75.2  86.0 101.3 164.4 221.3 264.2 272.4 281.0 290.3 296.0
          400     83.7  96.4 146.1 206.9 281.0 305.0 305.0 305.0 305.0 305.0
          500     90.4 104.7 177.6 243.4 305.0 305.0 305.0 305.0 305.0 305.0
          600     96.0 135.5 201.3 275.2 305.0 305.0 305.0 305.0 305.0 305.0
          700    100.7 159.6 222.0 303.4 305.0 305.0 305.0 305.0 305.0 305.0
          800    104.9 174.1 240.5 305.0 305.0 305.0 305.0 305.0 305.0 305.0
          900    120.2 187.1 257.1 305.0 305.0 305.0 305.0 305.0 305.0 305.0
```

Figure 2.15 Capillary rise through Material No 2 overlaid by PFA and Imported Clay

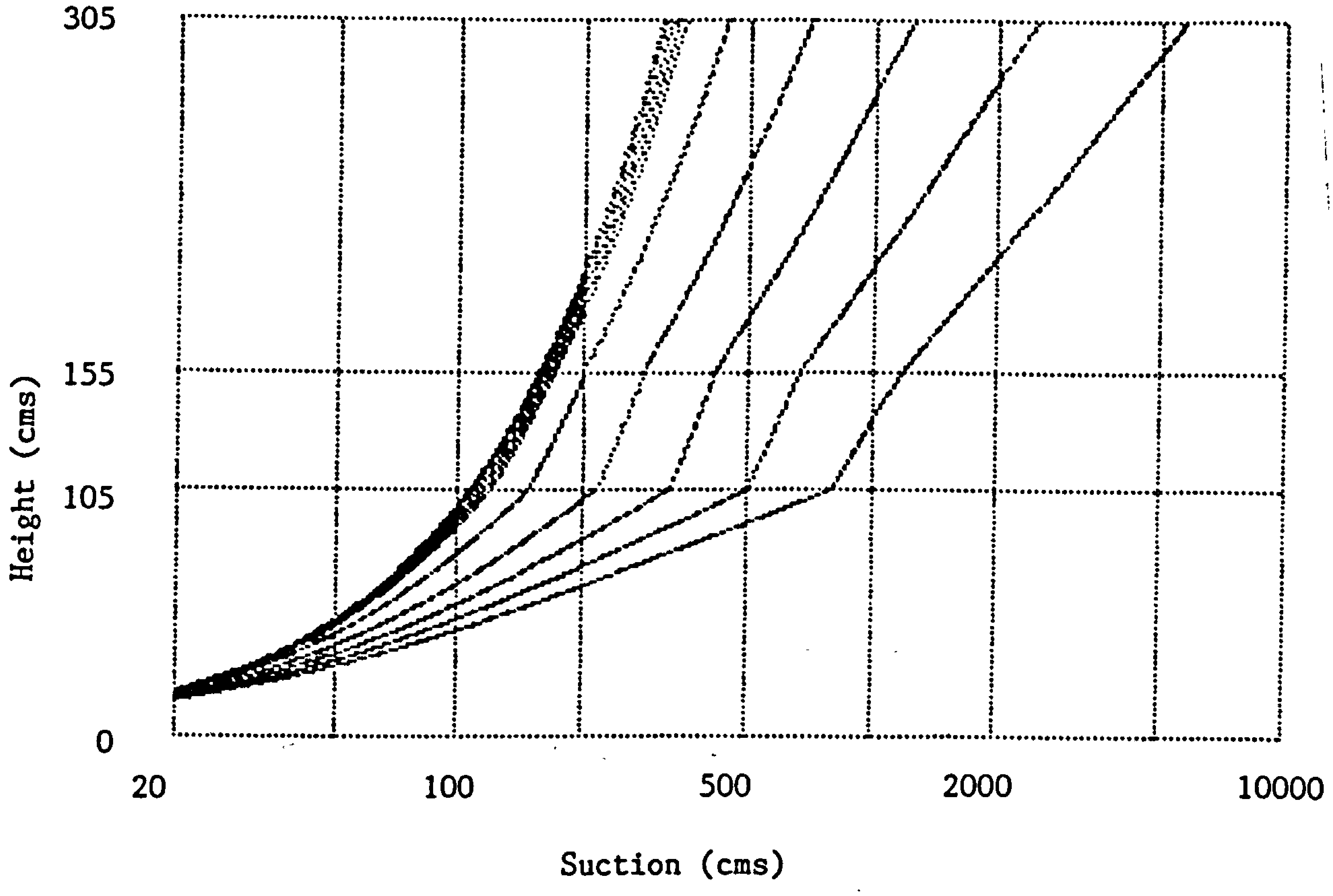


Table 2.17 Capillary rise through Material No 3 overlaid by PFA and Imported Clay

```
Layer Height  ns      ke      hw     hw'
  1    0.0   1.03   0.860   0.60   0.60
  2  105.0   1.62   7.530  21.00  80.15
  3  155.0   1.02   0.443  24.60  12.84

Ground-water depth is 305 cm


 100 integration steps/suction level

=========================================================================
             Flux (cm/day)
             0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
=========================================================================
Suction (cm)        Height (cm)
      20        7.8   8.7  10.0  11.7  14.5  17.2  17.8  18.5  19.2  19.7
      50       11.5  13.2  15.6  19.4  26.6  36.0  38.5  41.5  45.2  47.9
     100       14.4  16.8  20.2  26.1  38.4  57.6  63.6  71.6  82.7  92.0
     200       17.3  20.4  25.0  33.1  51.5  84.9  96.9 129.7 169.7 188.8
     500       21.2  25.2  31.4  42.6  69.8 251.2 305.0 305.0 305.0 305.0
    1000       24.1  28.8  36.2  49.7  83.8 305.0 305.0 305.0 305.0 305.0
    2000       26.9  32.3  40.9  56.7  97.8 305.0 305.0 305.0 305.0 305.0
    5000       30.6  36.9  47.0  65.8 305.0 305.0 305.0 305.0 305.0 305.0
   10000       33.3  40.3  51.5  72.6 305.0 305.0 305.0 305.0 305.0 305.0
```

Figure 2.16 Capillary rise through Material No 3 overlaid by PFA and Imported Clay

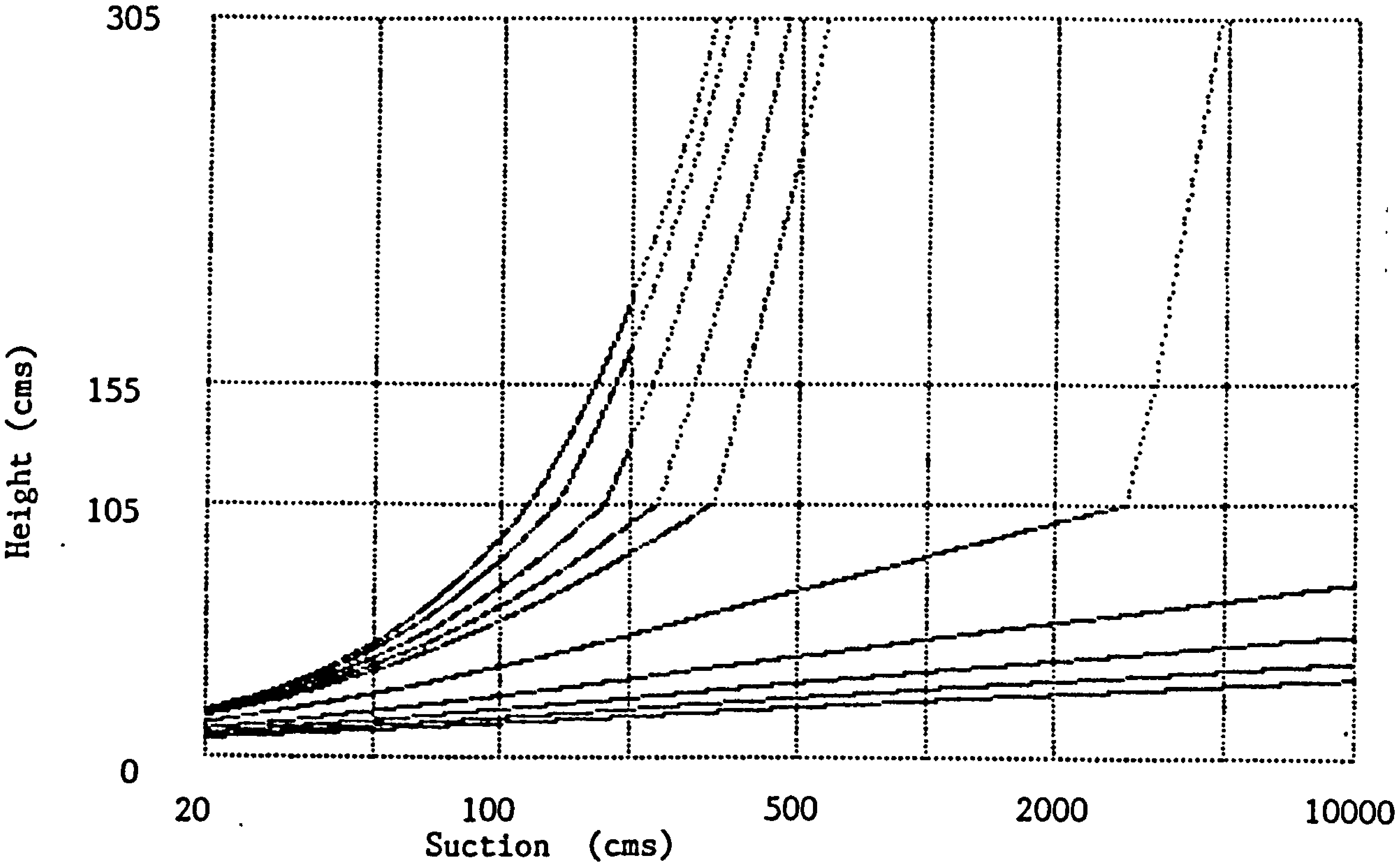


Table 2.18 Capillary rise through Material No 1 overlaid by PFA and Insitu Clay

```
Layer Height   ns      ke      hw     hw'
  1     0.0   1.40  13.030   0.60   0.60
  2   105.0   1.62   7.530  21.00  14.97
  3   155.0   1.31   0.026   9.80   0.09

Ground-water depth is 305 cm

 100 integration steps/suction level

==================================================================================
               Flux (cm/day)
               0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
==================================================================================
Suction (cm)        Height (cm)
        20      14.6  15.4  16.2  17.2  18.5  19.3  19.5  19.7  19.8  19.9
        50      24.2  26.4  29.3  33.2  39.2  44.7  45.9  47.1  48.5  49.4
       100      31.1  34.7  39.7  47.4  61.1  77.6  81.8  86.7  92.7  96.9
       200      36.8  41.8  48.9  60.5  84.2 145.0 155.9 158.0 162.9 172.3
       500      42.6  48.9  58.4  74.4 155.8 165.5 168.6 176.6 197.7 245.4
      1000      45.8  52.9  63.7  82.3 158.2 171.3 176.3 188.0 220.1 297.6
      2000      48.2  55.9  67.7  88.4 160.1 176.0 182.5 197.4 238.6 305.0
      5000      50.5  58.9  71.6  94.2 162.0 180.8 189.0 207.1 258.0 305.0
     10000      51.8  60.5  73.7  97.4 163.2 183.7 192.9 212.9 269.5 305.0
```

Figure 2.17 Capillary rise through Material No 1 overlaid by PFA and Insitu Clay

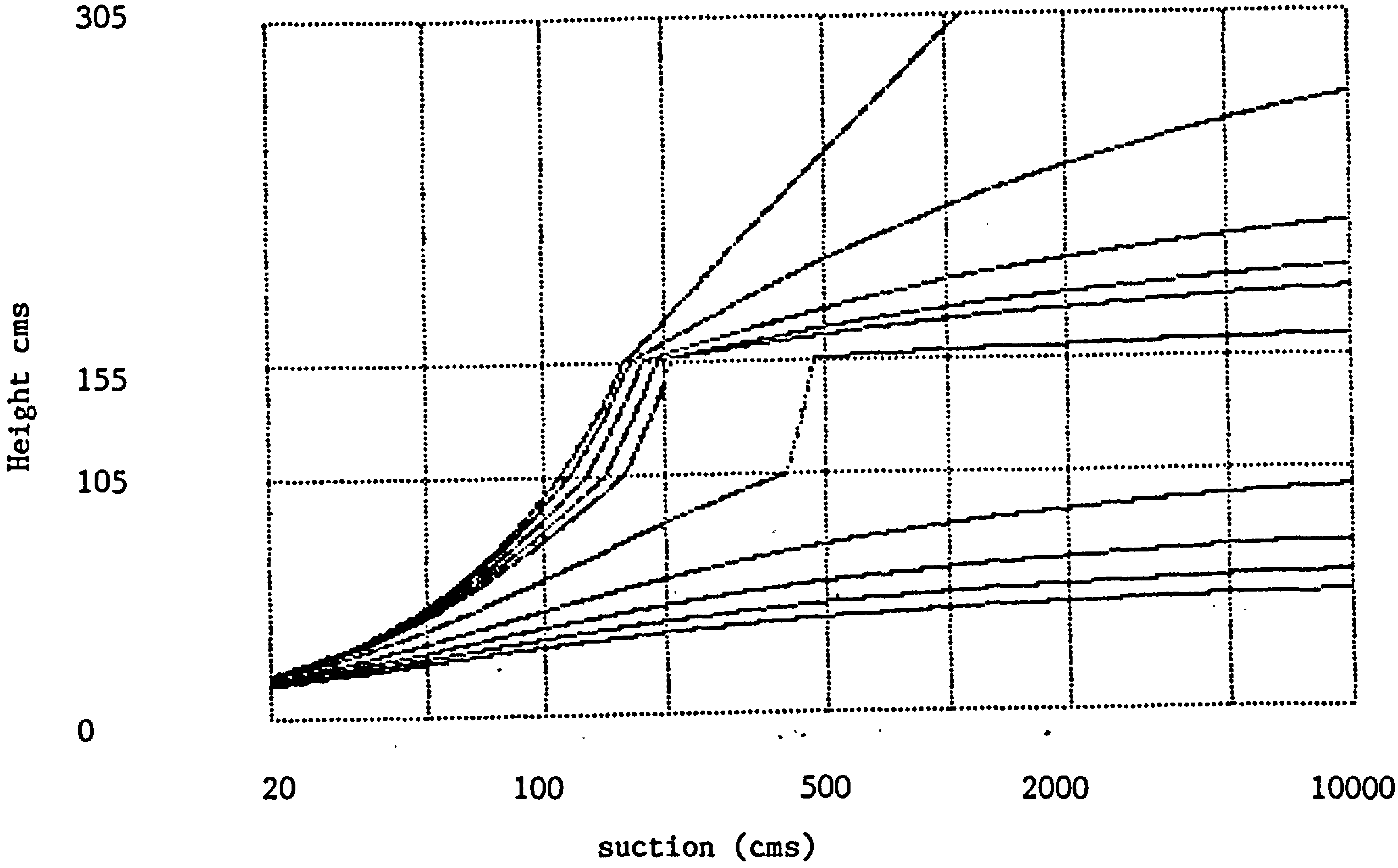


Table 2.19 Capillary rise through Material No 2 overlaid by PFA and Insitu Clay

```
Layer Height  ns      ke      hw      hw'
  1     0.0   1.00   4.610   0.70    0.70
  2   105.0   1.62   7.530  21.00   28.43
  3   155.0   1.31   0.026   9.80    0.19

Ground-water depth is 305 cm

 100 integration steps/suction level

==========================================================================
                Flux (cm/day)
                0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
==========================================================================
Suction (cm)          Height (cm)
          20     15.6  16.2  17.0  17.9  18.9  19.5  19.6  19.8  19.9  20.0
          50     30.2  32.5  35.3  38.9  43.6  47.1  47.8  48.5  49.2  49.7
         100     45.5  50.3  56.5  65.0  77.8  89.3  91.7  94.3  97.0  98.8
         200     63.7  72.0  83.4 100.6 153.1 157.6 158.0 159.8 164.4 173.6
         500     90.4 104.7 156.0 157.7 159.7 167.2 170.7 178.4 199.2 246.8
        1000    133.6 156.3 156.7 158.9 162.0 173.0 178.4 189.8 221.5 299.0
        2000    155.9 156.7 157.4 159.8 163.9 177.7 184.6 199.2 240.1 305.0
        5000    156.3 157.2 158.0 160.8 165.8 182.6 191.1 209.0 259.5 305.0
       10000    156.6 157.5 158.4 161.4 167.0 185.5 195.0 214.7 271.0 305.0
```

Figure 2.18 Capillary rise through Material No 2 overlaid by PFA and Insitu Clay

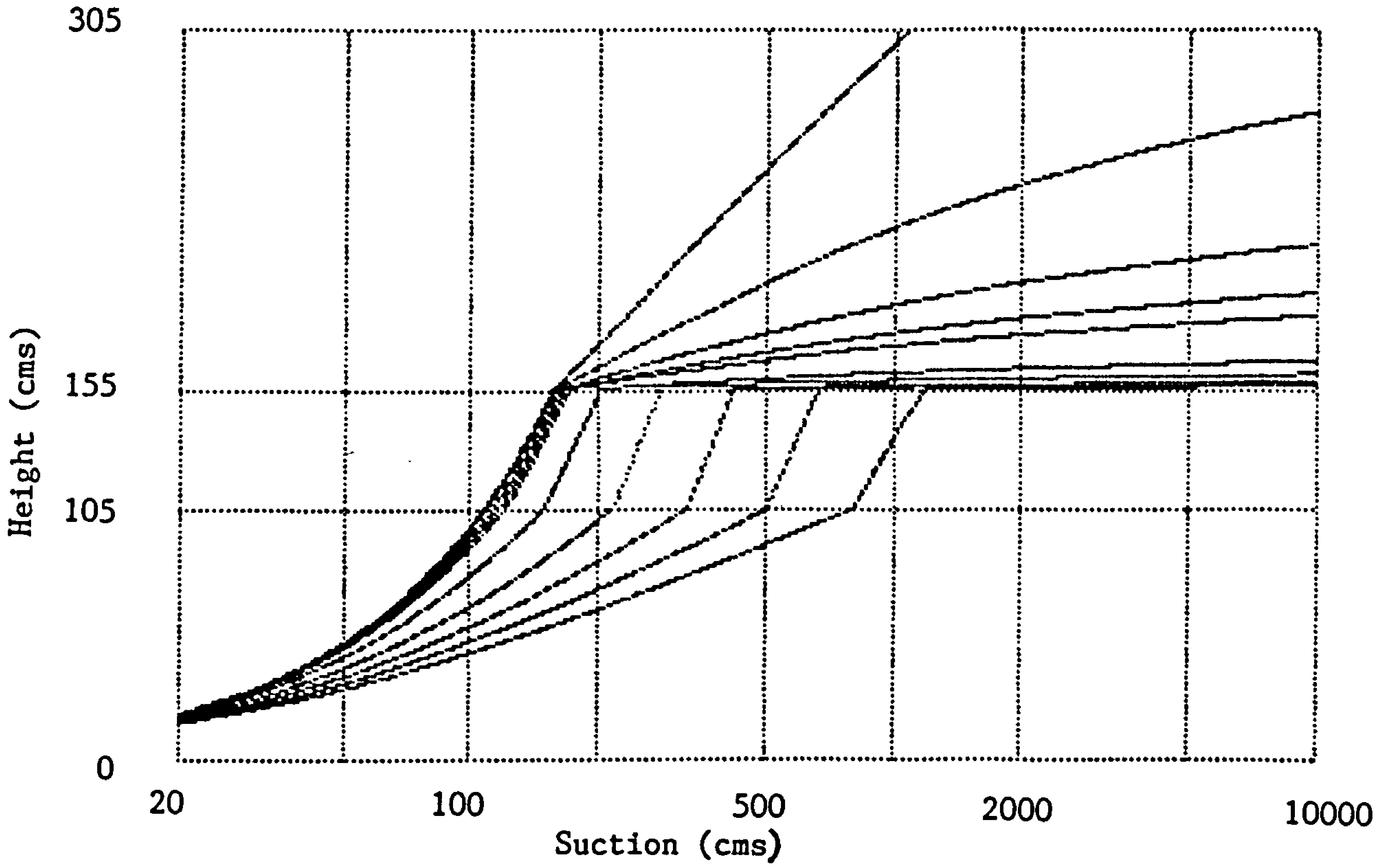


Table 2.20 Capillary rise through Material No 3 overlaid by PFA and Insitu Clay

Layer	Height	ns	ke	hw	hw'
1	0.0	1.03	0.860	0.60	0.60
2	105.0	1.62	7.530	21.00	80.15
3	155.0	1.31	0.026	9.80	0.68

Ground-water depth is 305 cm

100 integration steps/suction level

	Flux (cm/day)									
	0.100	0.080	0.060	0.040	0.020	0.008	0.006	0.004	0.002	0.001
Suction (cm)	Height (cm)									
100	14.4	16.8	20.2	26.1	38.4	57.6	63.6	71.6	82.7	92.0
200	17.3	20.4	25.1	33.1	51.5	84.9	96.9	129.7	158.4	169.3
300	19.1	22.5	27.9	37.3	59.5	102.8	156.5	161.1	174.3	201.5
400	20.3	24.1	29.9	40.2	65.3	156.0	160.4	166.8	185.1	224.7
500	21.2	25.2	31.4	42.6	69.8	158.1	163.2	171.0	193.1	242.5
600	22.0	26.2	32.7	44.4	73.5	159.7	165.4	174.2	199.4	256.8
700	22.6	27.0	33.8	46.0	76.6	161.0	167.1	176.8	204.5	268.6
800	23.2	27.7	34.7	47.4	79.3	162.1	168.6	179.0	208.7	278.6
900	23.7	28.3	35.5	48.6	81.7	163.1	169.8	180.8	212.3	287.2

Figure 2.19 Capillary rise through Material No 3 overlaid by PFA and Insitu Clay

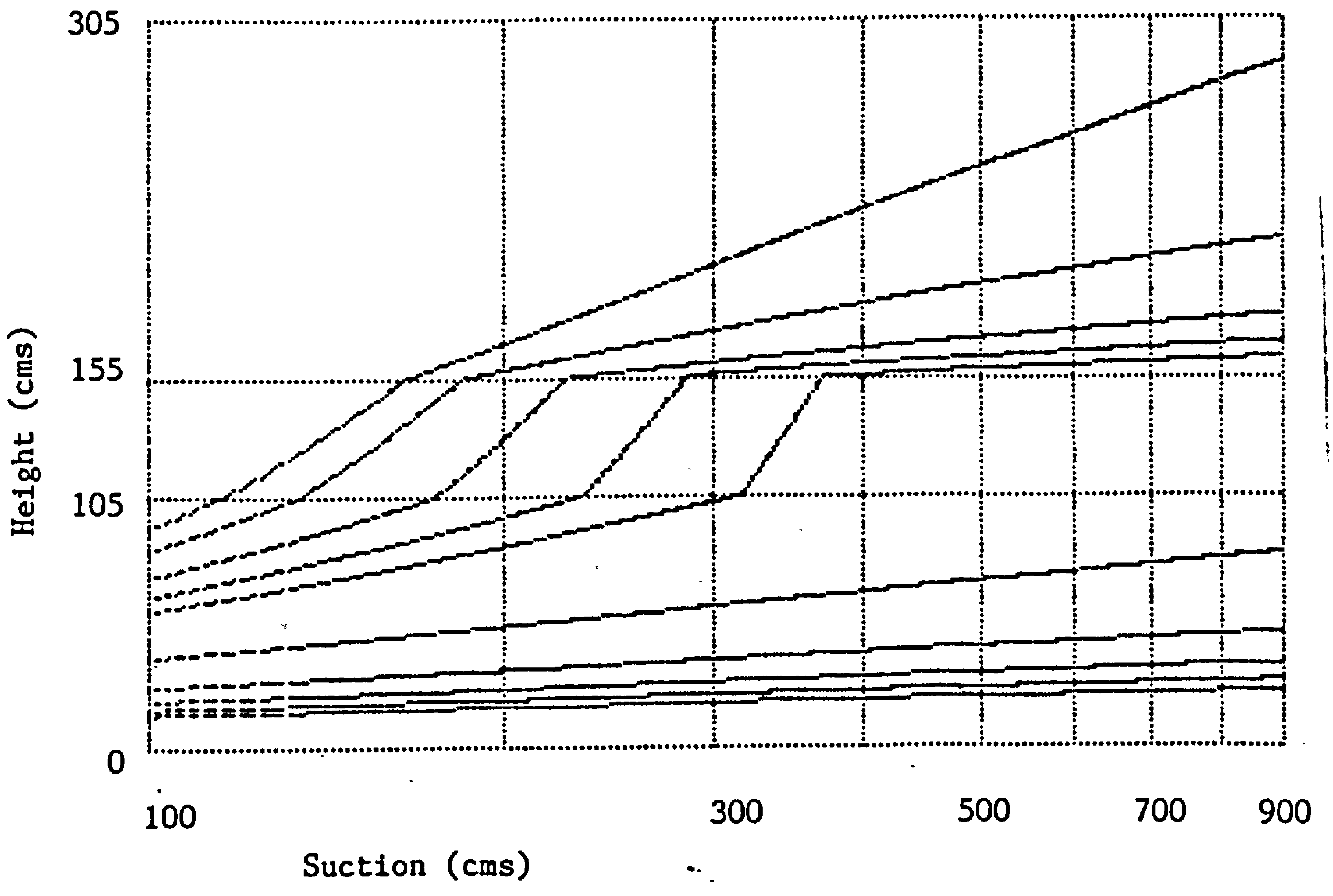


Table 2.21 Capillary rise through Material No 1 overlaid by PFA and Eighton Clay

```
Layer Height  ns       ke      hw      hw'
  1    0.0   1.40  13.030    0.60    0.60
  2  105.0   1.62   7.530   21.00   14.97
  3  155.0   1.03   3.860    2.90   -0.89

Ground-water depth is 305 cm

 100 integration steps/suction level

=======================================================================
                 Flux (cm/day)
                 0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
=======================================================================
Suction (cm)         Height (cm)
         20      14.6  15.4  16.2  17.2  18.5  19.3  19.5  19.7  19.8  19.9
         50      24.2  26.4  29.3  33.2  39.2  44.7  45.9  47.1  48.5  49.4
        100      31.1  34.7  39.7  47.8  61.1  77.6  81.8  86.7  92.7  96.9
        200      36.8  41.8  48.9  60.5  84.2 145.0 161.6 175.8 188.3 195.5
        500      42.6  48.9  58.4  74.4 169.0 305.0 305.0 305.0 305.0 305.0
       1000      45.8  52.9  63.7  82.3 305.0 305.0 305.0 305.0 305.0 305.0
       2000      48.2  55.9  67.7  88.4 305.0 305.0 305.0 305.0 305.0 305.0
       5000      50.5  58.9  71.6  94.2 305.0 305.0 305.0 305.0 305.0 305.0
      10000      51.8  60.5  73.7  97.4 305.0 305.0 305.0 305.0 305.0 305.0
```

Figure 2.20 Capillary rise through Material No 1 overlaid by PFA and Eighton Clay

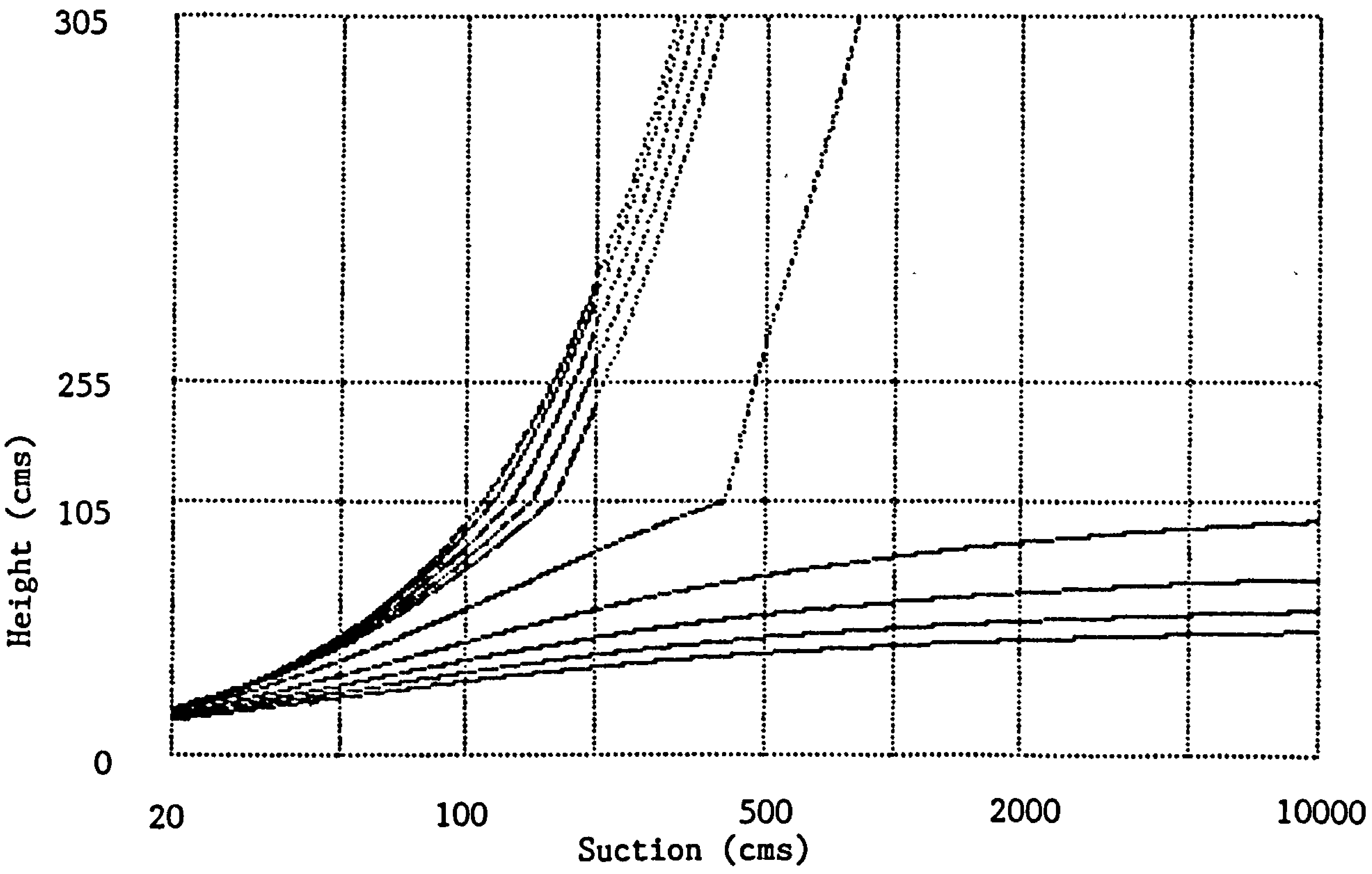


Table 2.22 Capillary rise through Material No 2 overlaid by PFA and Eighton Clay

```
Layer Height   ns       ke      hw      hw'
  1     0.0   1.00   4.610    0.70    0.70
  2   105.0   1.62   7.530   21.00   28.43
  3   155.0   1.03   3.860    2.90    2.44

Ground-water depth is 305 cm


 100 integration steps/suction level

===============================================================================
               Flux (cm/day)
               0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
===============================================================================
Suction (cm)        Height (cm)
          20    15.6  16.2  17.0  17.9  18.9  19.5  19.6  19.8  19.9  20.0
          50    30.2  32.5  35.3  38.9  43.6  47.1  47.8  48.5  49.2  49.7
         100    45.5  50.3  56.5  65.0  77.8  89.3  91.7  94.3  97.0  98.8
         200    63.7  72.0  83.4 100.6 153.1 180.1 184.9 189.7 194.8 197.9
         500    90.4 104.7 176.7 239.7 305.0 305.0 305.0 305.0 305.0 305.0
        1000   133.6 196.5 266.1 305.0 305.0 305.0 305.0 305.0 305.0 305.0
        2000   200.3 270.8 305.0 305.0 305.0 305.0 305.0 305.0 305.0 305.0
        5000   281.1 305.0 305.0 305.0 305.0 305.0 305.0 305.0 305.0 305.0
       10000   305.0 305.0 305.0 305.0 305.0 305.0 305.0 305.0 305.0 305.0
```

Figure 2.21 Capillary rise through Material No 2 overlaid by PFA and Eighton Clay

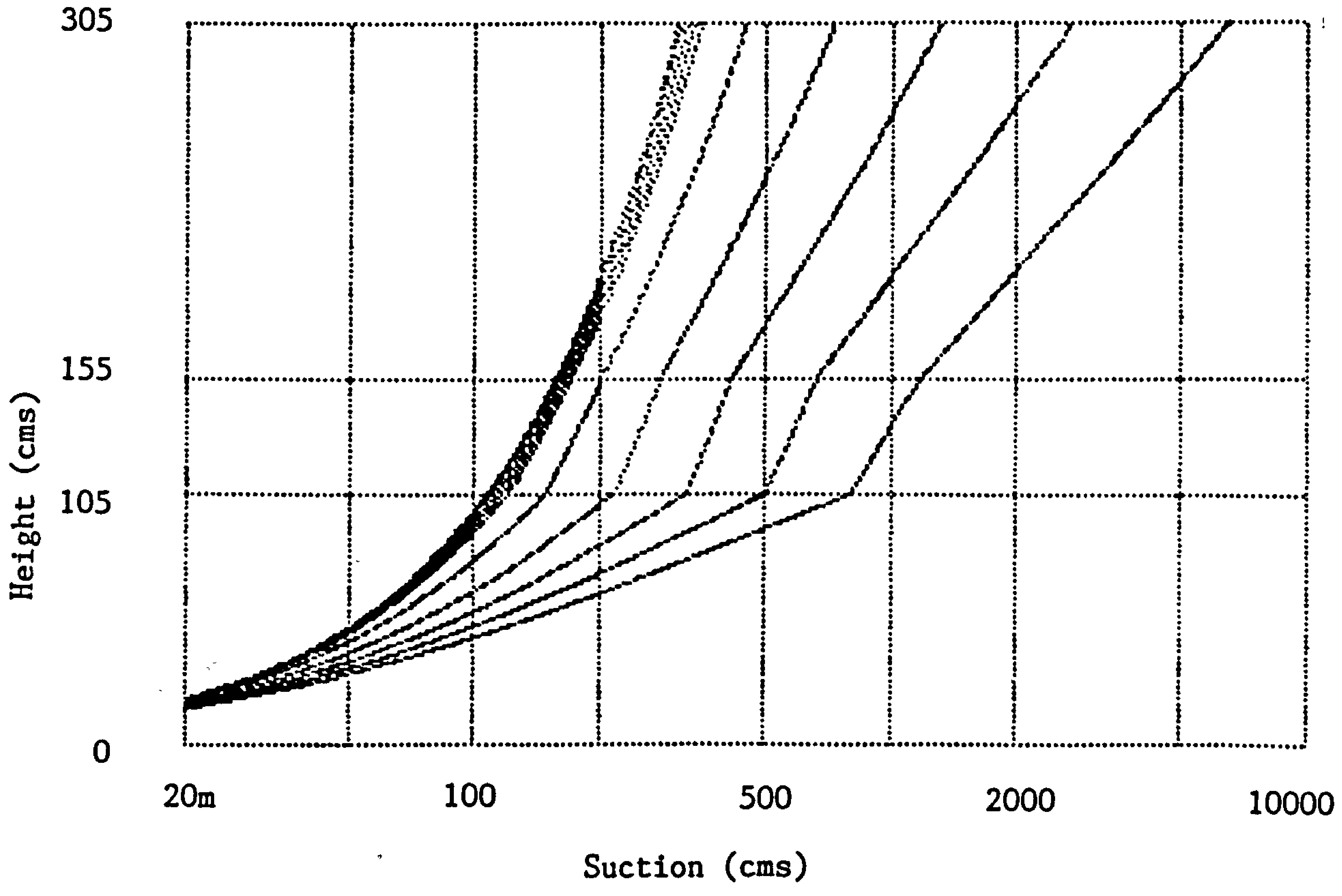


Table 2.23 Capillary rise through Material No 3 overlaid by PFA and Eighton Clay

```
Layer Height   ns       ke      hw      hw'
  1     0.0   1.03    0.860   0.60    0.60
  2   105.0   1.62    7.530  21.00   80.15
  3   155.0   1.03    3.860   2.90   12.46

Ground-water depth is 305 cm


 100 integration steps/suction level

==============================================================================
             Flux (cm/day)
             0.100 0.080 0.060 0.040 0.020 0.008 0.006 0.004 0.002 0.001
==============================================================================
Suction (cm)       Height (cm)
         20     7.8   8.7  10.0  11.7  14.5  17.2  17.8  18.5  19.2  19.7
         50    11.5  13.2  15.6  19.4  26.6  36.0  38.5  41.5  45.2  47.9
        100    14.4  16.8  20.2  26.1  38.4  57.6  63.6  71.6  82.7  92.0
        200    17.3  20.4  25.0  33.1  51.5  84.9  96.9 129.7 169.7 188.8
        500    21.2  25.2  31.4  42.6  69.8 249.6 305.0 305.0 305.0 305.0
       1000    24.1  28.8  36.2  49.7  83.8 305.0 305.0 305.0 305.0 305.0
       2000    26.9  32.3  40.9  56.7  97.8 305.0 305.0 305.0 305.0 305.0
       5000    30.6  36.9  47.0  65.8 305.0 305.0 305.0 305.0 305.0 305.0
      10000    33.3  40.3  51.5  72.6 305.0 305.0 305.0 305.0 305.0 305.0
```

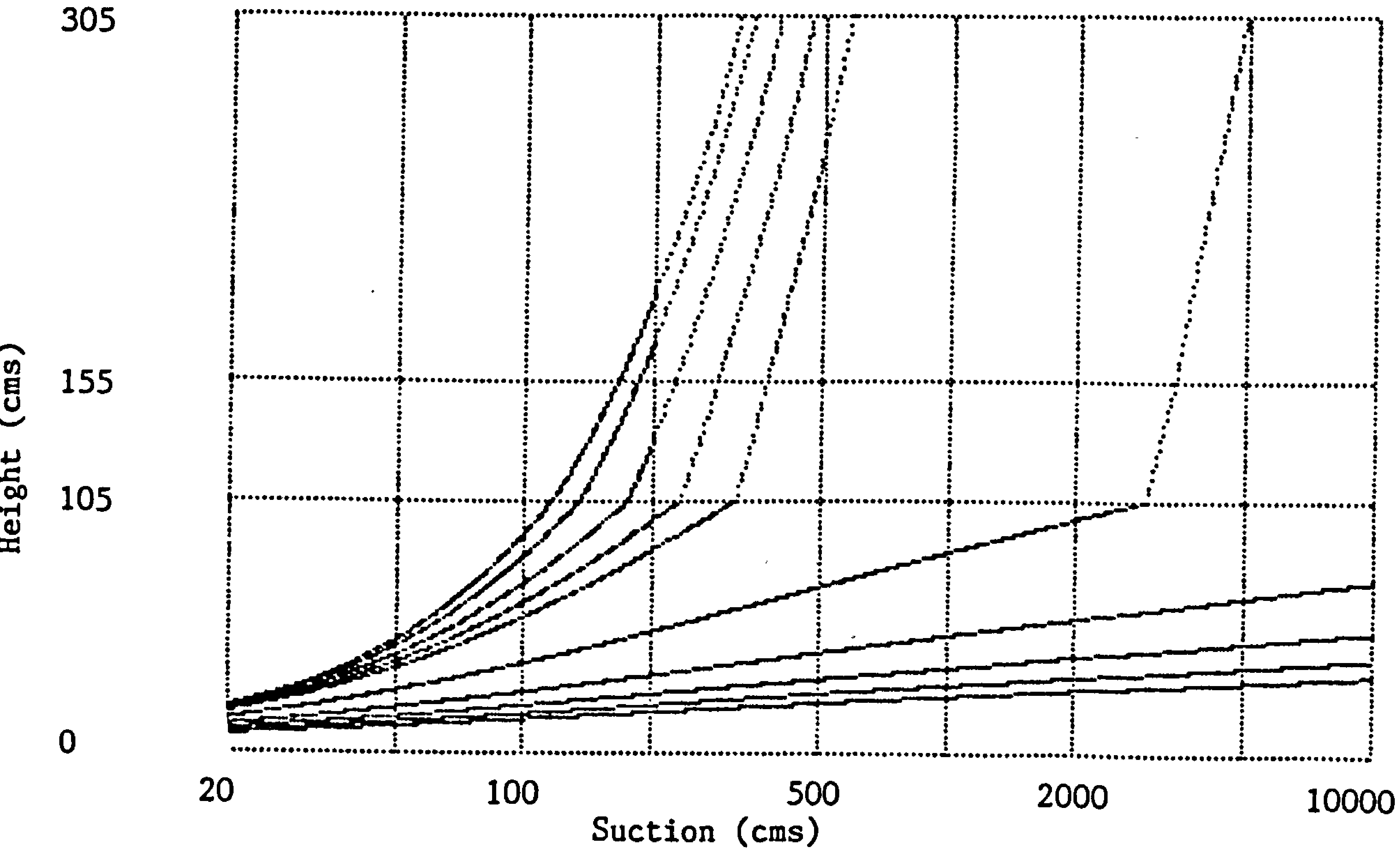


Figure 2.22 Capillary rise through Material No 3 overlaid by PFA and Eighton Clay

The fluxes indicate the amount of water able to reach a given height, z cms, under a given suction. In order to calculate the amount of contaminant arriving at height 'z' in the soil water we need the following simple equation:

$$C = \frac{c.\rho.d}{\rho s} \cdot \frac{dv}{dz} \qquad \text{eq 2.7}$$

Where: C = the concentration of contaminant arriving at height 'z' (mg/kg)

c = the concentration of contaminant in the ground water (mg/l)

ρ = the density of the soil water (kg/m ^{3})

d = the length of time, (in days) a suction of 1000cm of water is sustained at the soil surface

ρ s = the bulk density of the soil cover material (Kg/M ^{3})

$\frac{dv}{dz}$ = The slope of the graph of flux against capillary rise (See figure 2.5)

This equation does not take account of any contamination adsorbed by soil particles during transportation of the soil water up the soil profile and is therefore considered to be a worst case value and not necessarily the actual value that would occur at the surface under specified the drought conditions.

The results of contaminant rise for each of the possible covers can be seen in table 2.24.

Table 2.24 Concentrations of contaminant able to rise through the soil cover to the soil surface in a design drought

Proposed soil cover	Depth (metres)	Concentration of sulphate (mg/kg)
Insitu-clay	1.50	0.905
Material No 2	1.05	
Imported clay	1.50	24.00
Material No 2	1.05	
Eighton clay	1.50	25.11
Material No 2	1.05	
Insitu-clay	1.50	0.596
PFA	0.50	
Material No 2	1.05	
Imported clay	1.50	14.65
PFA	0.50	
Material No 2	1.05	
Eighton clay	1.50	13.38
PFA	0.50	
Material No 2	1.05	

The trigger levels for sulphates in surface materials, where land is to be used for domestic housing, is 200 ppm. (ref 2.15). As can be seen from table 2.24 predicted concentrations of sulphates arriving at the site surface during a once in one hundred year drought, where a suction of 1000 cms of water is sustained at the surface for 100 days, are, at most, 25.11 ppm, i.e. where 1.5 meters of Eighton clay overlies the most conductive site material, surface material No.2. Therefore the worst case possible, using the available data is well within the ICRCL guidelines and so any of the proposed soil materials would provide a safe cover for the site if it were used for housing development.

2.4 Conclusion

The computer model shows that any of the available soil materials would be suitable for use as a soil cover.
The computer can, however, only give such predictions on the basis of its input information. If the input data are accurate then the reclamation design appears safe, however, if the input data is incorrect serious environmental harm could result.
Additionally the accuracy of the computer model itself has to be questioned, as does its sensitivity
In the following chapters the tolerance of the computer model to variations in the input data will be examined, as will the laboratory analysis on which this data is

based.

The results of the computer analysis will be compared to column studies in order to evaluate the accuracy of the models prediction.

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Chapter Three: The Sensitivity Of The CRISP Computer Model

3.1 Introduction

Whilst the processes detailed in Chapter 2 apparently predict the concentration of a contaminant (sulphate) that will be added to the upper layer of a soil cover in a particular design drought, it must be emphasised that all computer model results need to be confirmed.

Computer models can have in-built limitations, they may have been derived from empirical data and so be inaccurate when used for situations outside of their empirical origin, or they may be either insensitive or overly-sensitive to variations in the input data.

The sensitivity of the CRISP model (ref 3.1) is considered first, since it seems illogical to attempt to prove the models' accuracy against physical tests (see Chapter 4) until one is sure that such a comparison can be handled consistently and appropriately.

As Chapter 2 detailed, the CRISP model requires five separate choices from its operator, i.e.

the value chosen for the depth down to the ground water table

the number of integration steps the computer model makes in moving from a soil at one state of wetness to the

same soil at a different moisture content (obviously in a design drought a single material soil cover will become progressively
drier from the water table up to the exposed surface of the soil cover

and the input values chosen to typify the parameters 'Ke', 'hw' and 'ns'

3.2 Effect of the selected ground water depth on the output from the CRISP model

The modified D'Arcy equation (eq. 3.1)

$$V = K(h) \left(\frac{dh}{dz} - 1 \right) \qquad \text{eq.3.1}$$

makes it obvious that the depth 'z' down to the ground water table is an important control on the distance that any flux (V) can rise, and on the highest flux value that can reach any selected level in the soil cover. Figure 3.1 and table 3.1 merely emphasise this and show, in the case of Downhill Sand, a 37 % error in the predicted sulphate value is incurred when a 10 cm error in the depth of the water table is made, whilst with Eighton Clay an error of 50 - 55 % in the predicted sulphate concentration results if a 10 cm. error in predicting the water table depth (at 40 cm. below ground surface) is included.

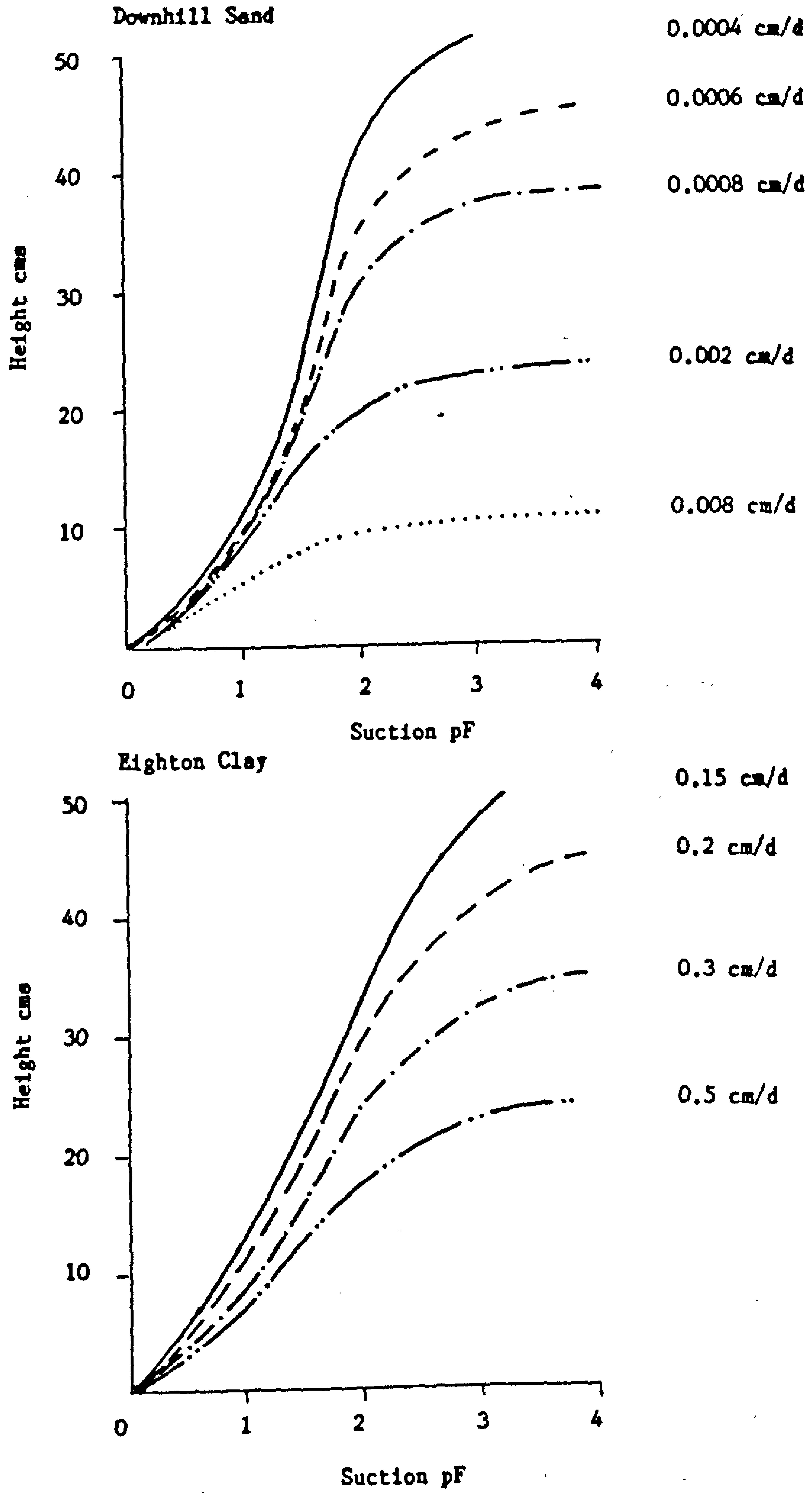
This sensitivity does not, however, pose any real difficulties, if the ground water level is controlled by adequate drainage works (ref 3.2). Normal UK practice in soil cover reclamations is to include such ground water controls and thus the utilisation of the model is not adversely affected.

Table 3.1 Variation in the concentration of sulphate reaching the soil surface as the depth to the water table increases

Water table depth (cms)	Downhill Sand contaminant concentration (mg/kg)	Eighton Clay contaminant concentration (mg/kg)
10	22.22	-
20	7.22	-
30	4.17	794.00
40	2.20	529.00
50	1.39	235.00

(All values were obtained for 1000 cms of suction at the soil surface)

Figure 3.1 Variation in the size of flux reaching the soil surface as the depth to the water table increases



3.3 Effect of the chosen integration step on the output from the CRISP model

Figure 3.1 makes it obvious that the graphs of flux against suction increase (at a soil cover's surface) are not linear, whilst the equation for the height that a particular flux reaches, i.e. (equation 3.2)

$$z_2 = z_1 + \frac{k \frac{h_1 + h_2}{2} \cdot (h_2 - h_1)}{v + k(\bar{h})} \qquad \text{eq } 3.2$$

is of course the mathematical description of a straight line. Thus for the CRISP model to predict accurate data implies that a number of computational integration steps must take place, as the model moves from a soil at one suction to the same soil at a higher suction (i.e. to a drier soil further up the soil cover profile). How many integration steps are in fact necessary to produce reliable data is not specified in Bloemen's original paper (ref 3.1) and so the matter had to be investigated.

The integration step describes how many integrations are performed between chosen suction values. The number of integration steps required to obtain accurate results is therefore controlled by the suction interval.
This is demonstrated in figures 3.2 and 3.3 from which it can be seen that where suction values are increased

Figure 3.2 Number of integration steps required to produce accurate values for capillary rise (suction step 100 cms)

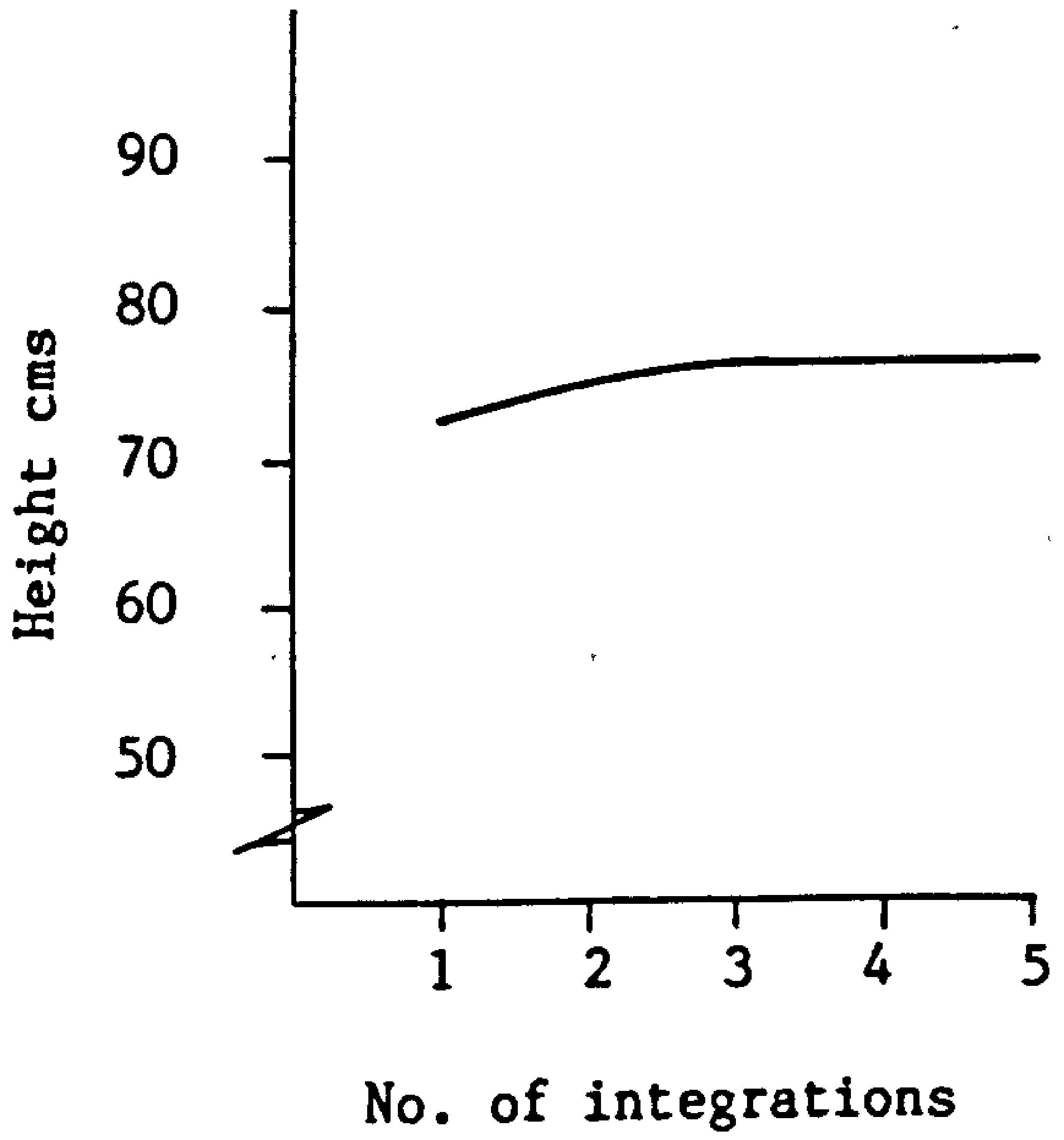
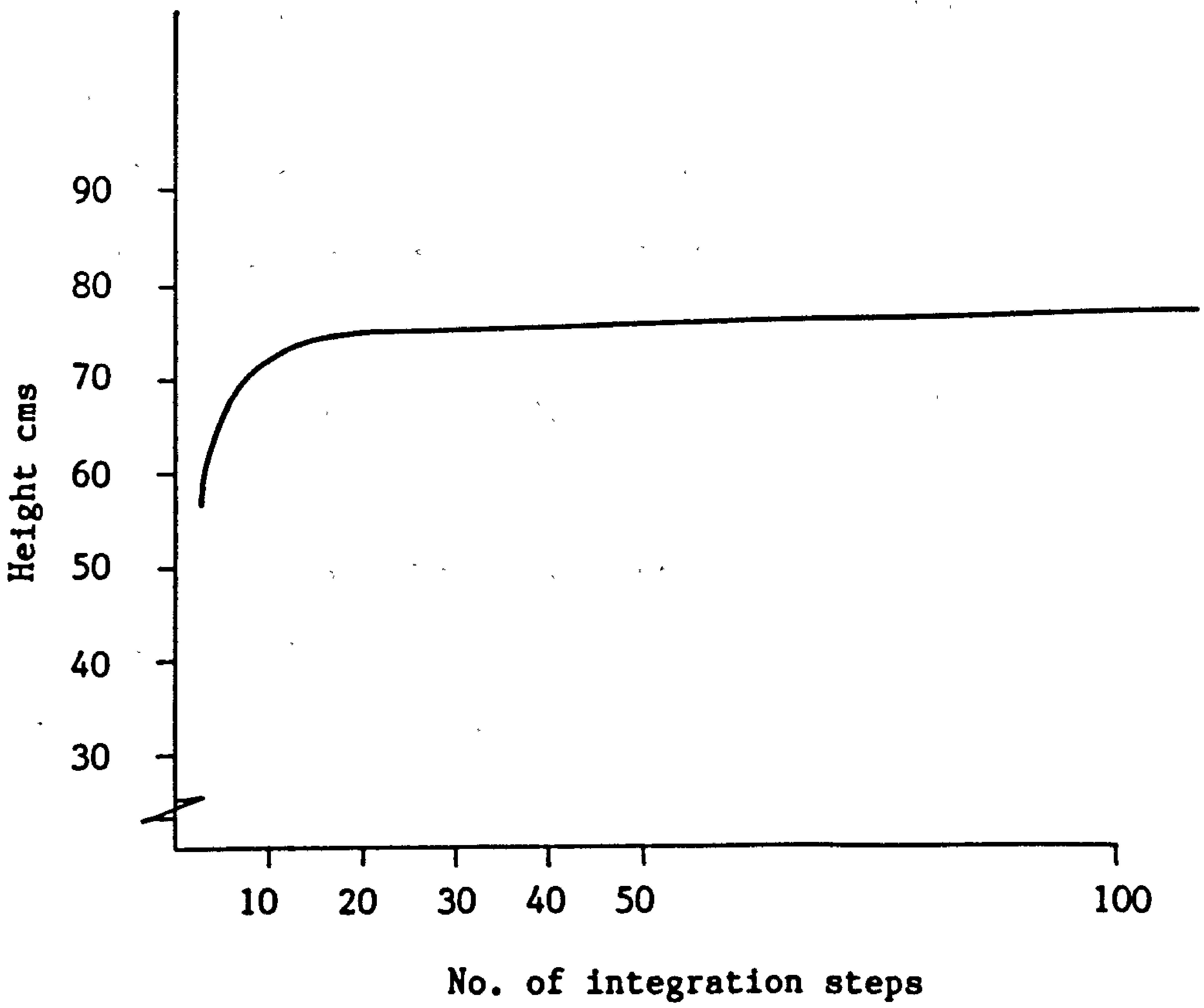


Figure 3.3 Number of integration steps required to produce accurate values for capillary rise (suction step 1000 cms)



by steps of 100 cms at a time (figure 3.2) only three integration steps are required in order to obtain accurate results, however, where the suction step is increased to 1000 cm intervals (figure 3.3) a minimum of 100 integration steps are required to obtain accurate results.

It is therefore essential that the accuracy of results obtained from the computer are checked by increasing the integration step such that replicate values are obtained.

3.4 The effect of including an error in the value of 'Ke' on the output of the CRISP model

'Ke' was defined in Chapter 2 as half the value of the saturated conductivity, 'Ks'. In the CRISP model the actual hydraulic conductivity ('K(h)') at any point in the soil profile where a particular soil moisture content occurs is given by the relationship:-

$$K(h) = Ke\left(\frac{hw}{h}\right)^{ns} \qquad \text{eq 3.3}$$

Where: hw = the water entry suction head on the re-wetting cycle

h = the suction value of the soil

ns = the gradient of the average scanning curve of sorption and desorption

Thus the correct value of 'K(h)' and so the correct size of flux that will be able to rise to any level above the ground water table is dependant upon the selected value of 'Ke'.

Tests (figure 3.4) reveal that this is indeed the case and that increasing 'Ke' by a factor of 2 doubles the size of the flux and therefore the amount of contamination able to reach the soil surface, similarly, halving the value of Ke produces a 50% reduction in the amount of contamination arriving at the soil surface, and so on (table 3.2)

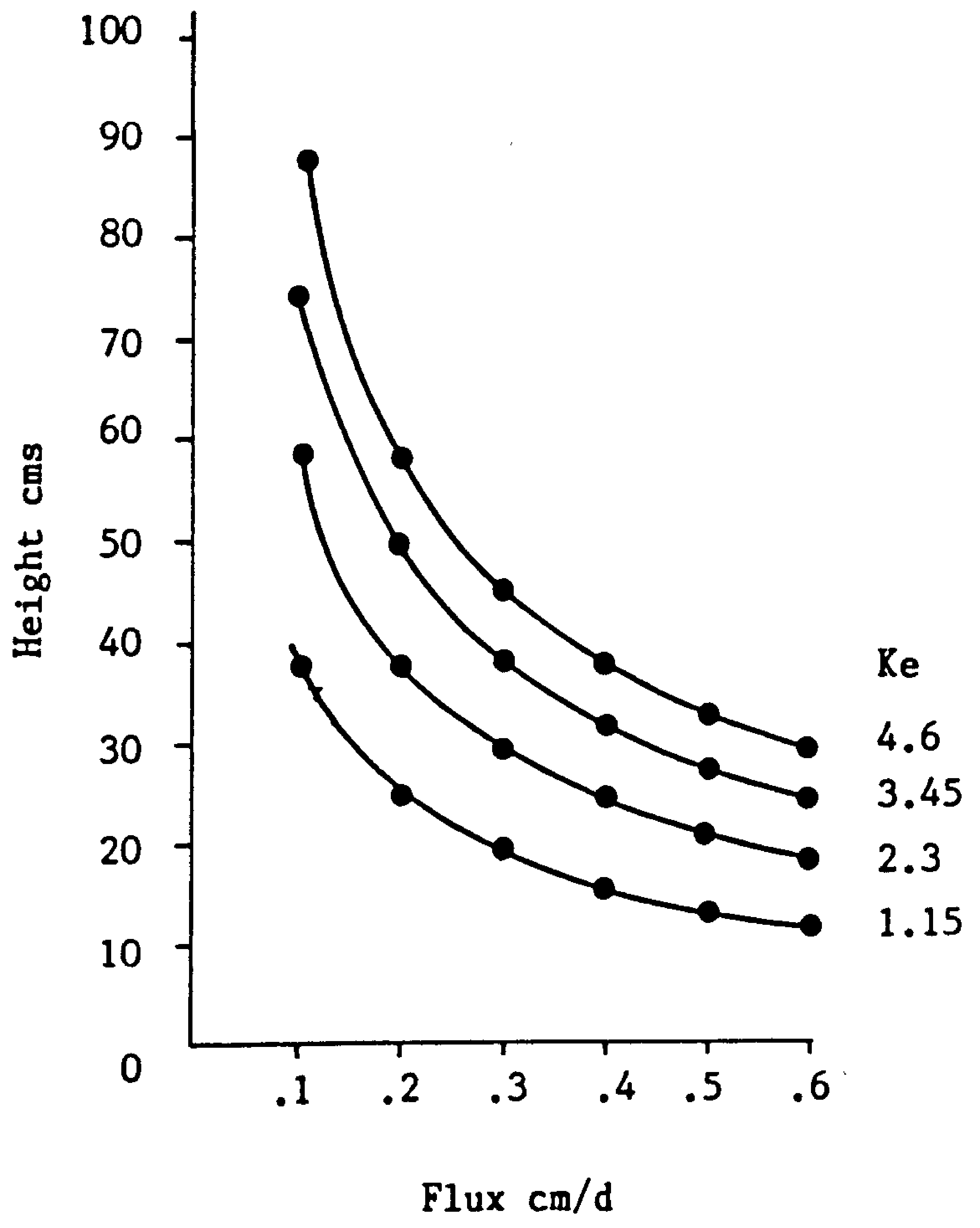
Table 3.2 Variation in the concentration of sulphate reaching the soil surface with changes in the value of Ke

Downhill Sand		Eighton Clay	
Ke	Sulphate (mg/kg)	Ke	Sulphate (mg/kg)
1.15	0.24	1.93	0.23
2.3	0.49	3.86	0.461
3.45	0.731	5.79	0.692
4.6	0.975	7.72	0.923

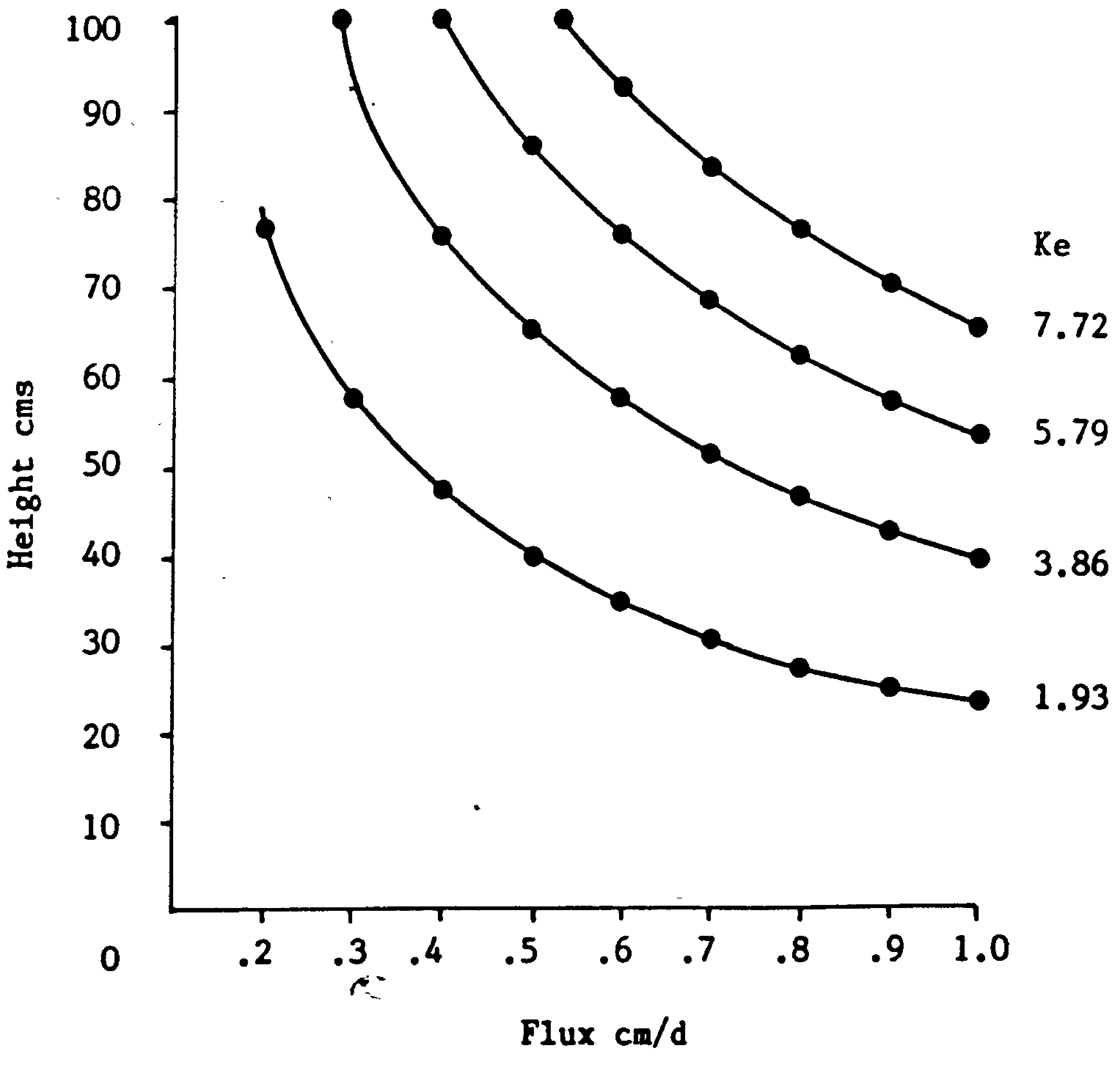
This sensitivity is not seen as a practical problem, since all 'Ke' values used in this work have been

Figure 3.4 The effect of varying Ke on the height of capillary rise

Downhill Sand



Eighton Clay



derived from replicated tests of 'Ks'. No attempt has been made to include any 'Ke' values predicted from grain size distribution and organic matter content, since such predictions have a variable and unpredictable accuracy (ref 3.3)

3.5 The effect of including an error in the value of 'hw' on the output of the CRISP model

'hw' - the water entry head (see Chapter 2) has only been measured by Kuntze (ref 3.4) who adapted the standard air entry test apparatus (i.e. the method of measuring 'ha') for this purpose. However the Kuntze method is both time consuming and expensive in manpower and material terms, and so has apparently not been followed up by later workers.

Instead use is generally made of the relationship between soil grain size distribution, organic matter content and the coefficient C (section 2.3.3).

Obviously this process is less exact than was the procedure for evaluating the actual value of 'Ke' and the effect of selecting a wrong value for hw, on the height of capillary rise, should be investigated.

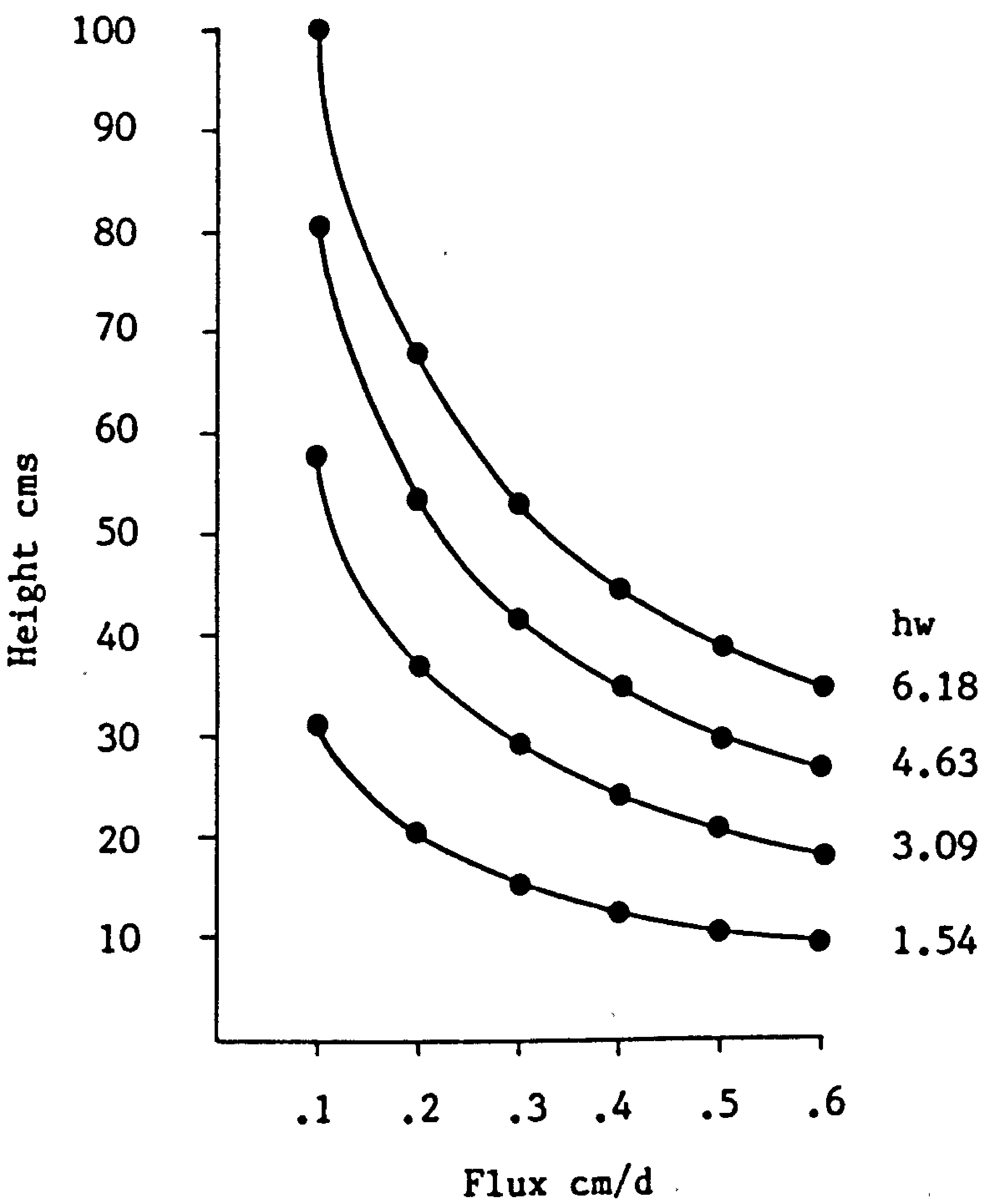
Varying the input value of 'hw' (figure 3.5) obviously affects the height to which a particular flux can rise, the increases being slightly larger than those for corresponding variations in Ke, and thus affect the amount of contaminant carried up into particular layers of a soil cover (table 3.3).

Obviously, the CRISP model is very sensitive to one term whose quantification is, unfortunately, difficult to achieve exactly. This must obviously be seen as a major limitation of the CRISP model.

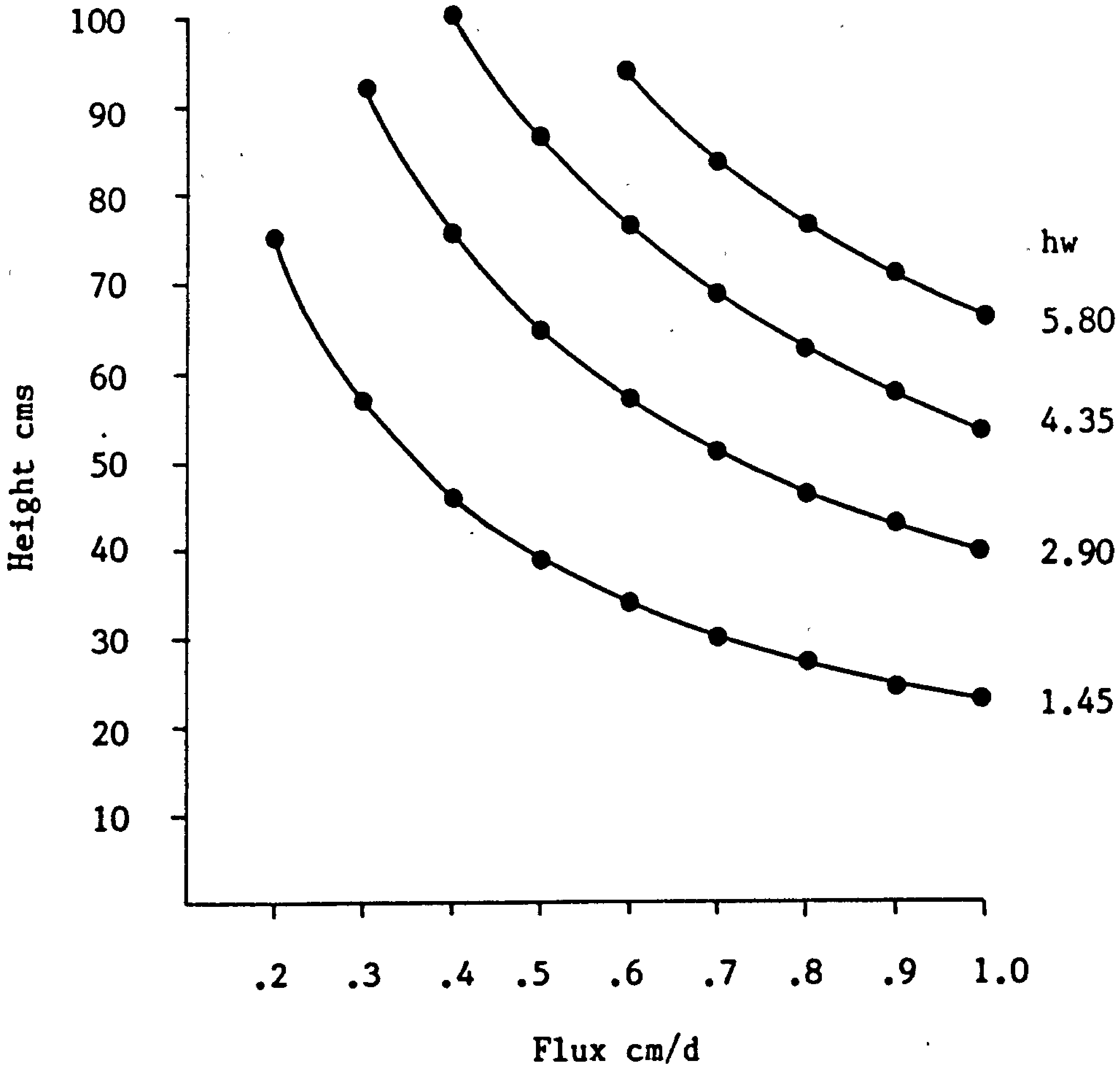
Table 3.3 Variation in the concentration of sulphate reaching the soil surface with changes in the value of hw

Downhill Sand		Eighton Clay	
hw	Sulphate (mg/kg)	hw	Sulphate (mg/kg)
1.54	0.24	1.45	0.23
3.09	0.49	2.90	0.461
4.635	0.694	4.35	0.71
6.18	1.70	5.80	0.933

Figure 3.5 The effect of varying hw on the height of capillary rise



Downhill Sand



Eighton Clay

3.6 Effect of including an error in the value of 'ns' on the output from the CRISP model

The value of 'ns' was defined in Chapter 2 as the gradient of the average scanning curve between sorption and desorption. Whilst simple laboratory methods have been developed to measure a soils unsaturated hydraulic conductivity (Chapter 5), and suction (Chapter 6), they are only capable of obtaining values for soils which are being dried. Also the methods are less accurate towards the extremes of saturation and air dryness. Obviously this means that there is insufficient laboratory data to predict a value for 'ns'. For this reason 'ns' is derived from the relationship between soil grain size and organic matter content as described in Chapter 2 (section 2.3.3). Values derived from other soil data rather than by direct measurement are obviously subject to error and so the effect of predicting a wrong value for 'ns' was investigated.

The results obtained from varying the 'ns' value are recorded in figure 3.6. From this it is obvious that increasing the value of 'ns' results in a decrease in the height to which any flux can rise and consequently decreases the amount of contamination arriving at the soil surface. Indeed from table 3.4 it is obvious that by doubling the value of 'ns' the amount of contamination arriving at the soil surface is decreased by a factor of 22, in the case of Downhill Sand, and a

Figure 3.6 The effect of varying ns on the height of capillary rise

Downhill Sand

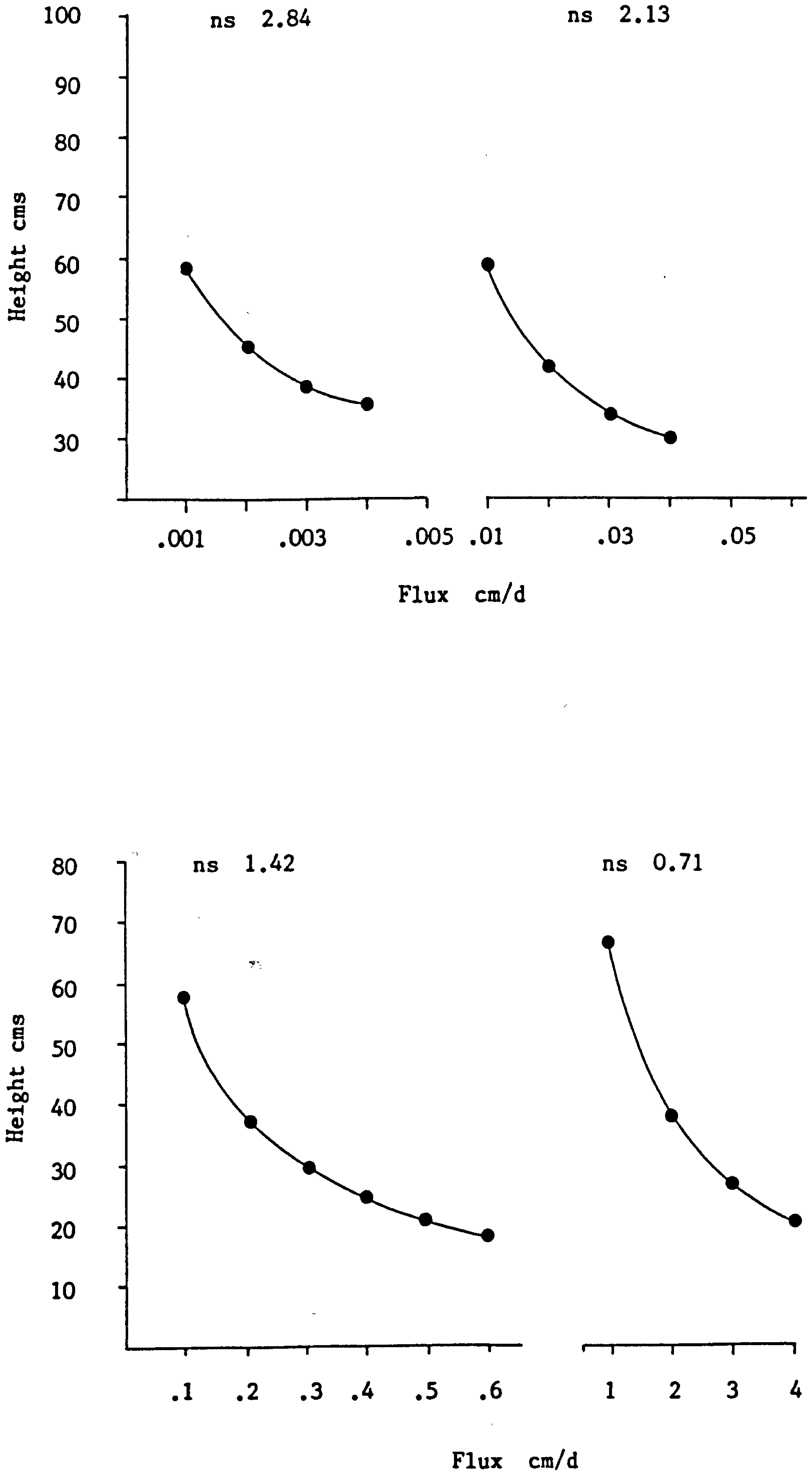
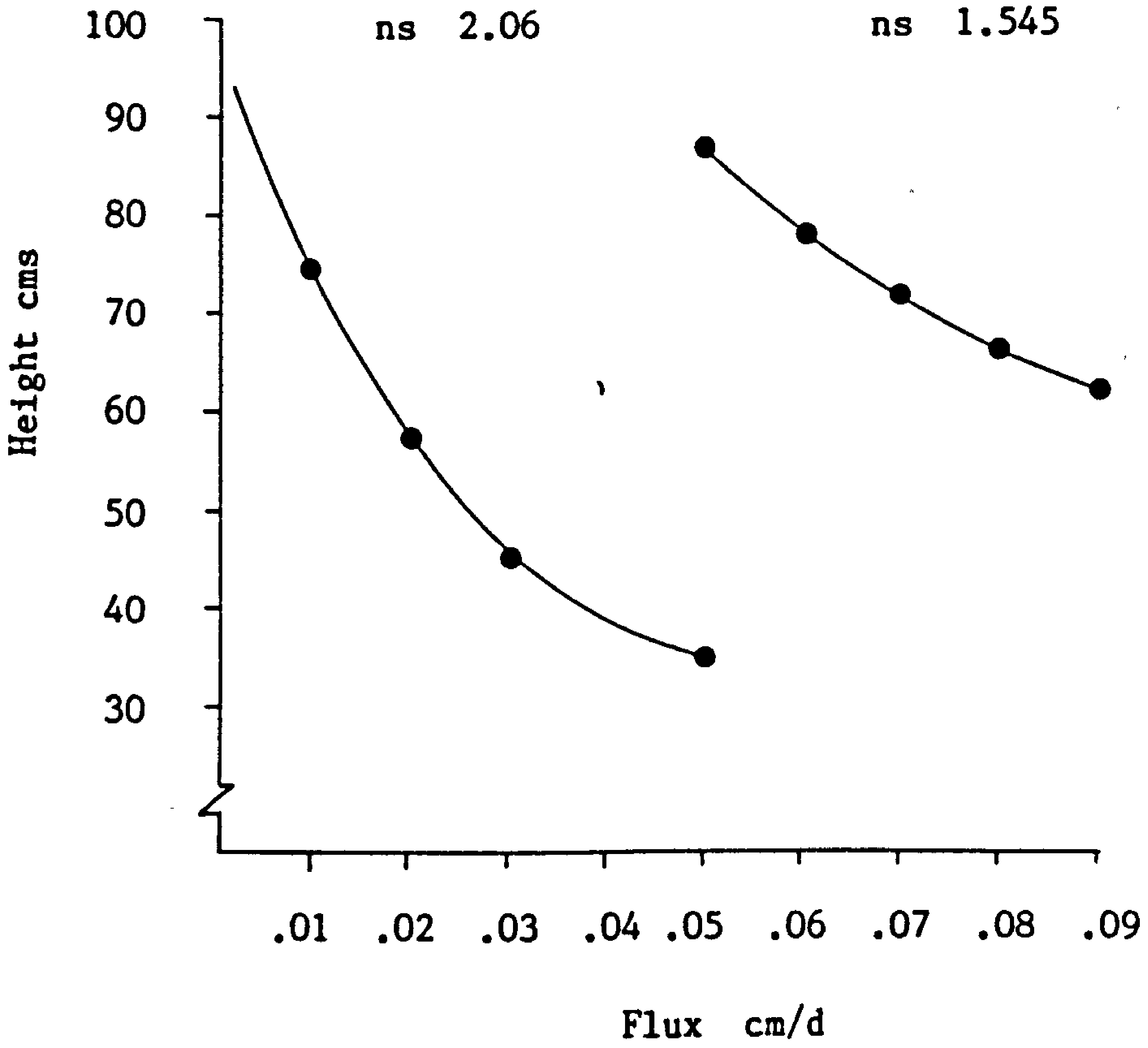
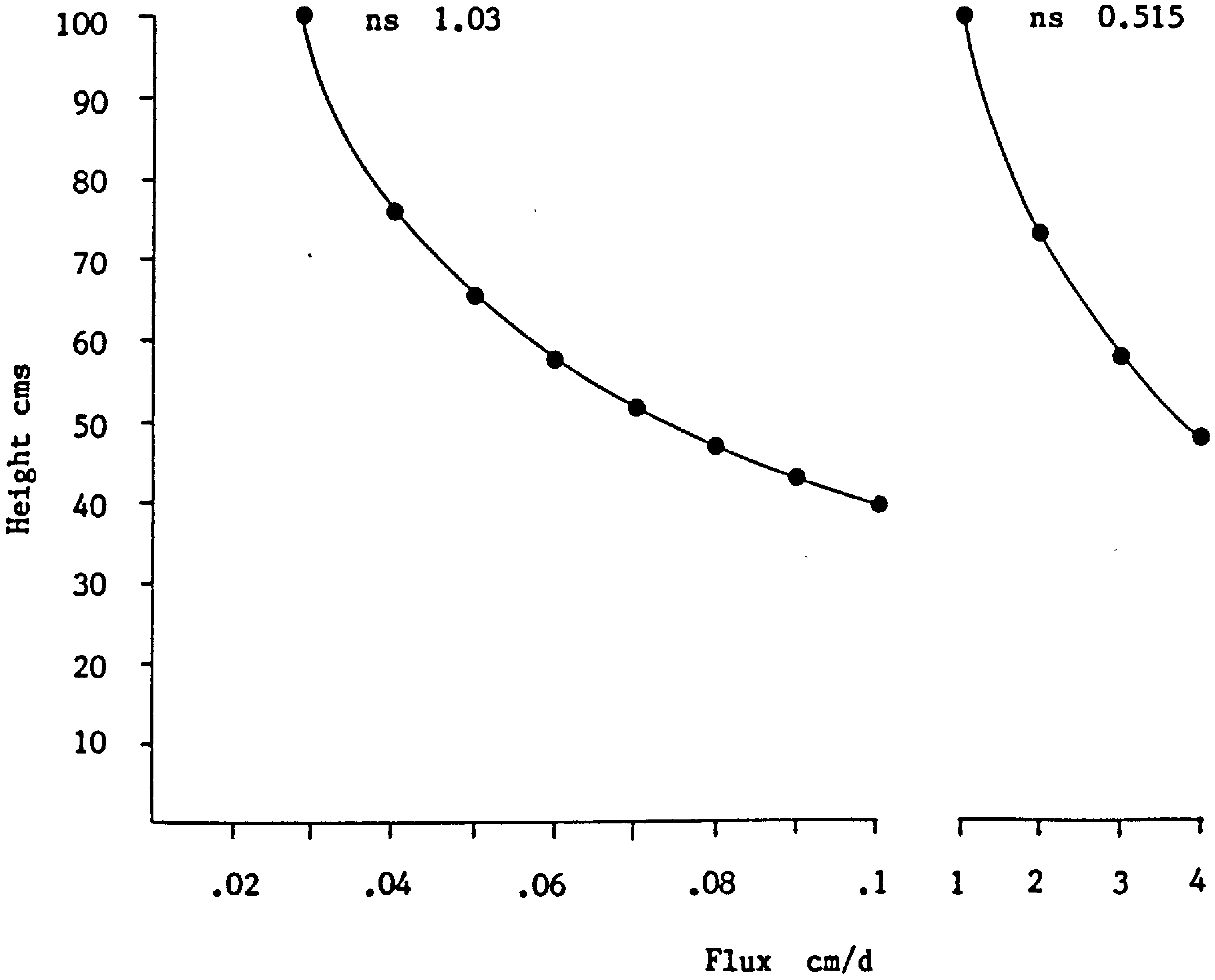


Figure 3.6 ....cont.

Eighton Clay





factor of 17 in the case of Eighton Clay. However, decreasing the value of 'ns' by a factor of 2 increases the amount of contamination able to reach the soil surface by approximately six times for both Downhill Sand and Eighton Clay. This is obviously due to the fact that the value 'ns' is a power, thus any results obtained by increasing or decreasing 'ns' will vary according to a geometric progression.

Table 3.4 Variation in the concentration of sulphate reaching the soil surface with changes in the value of ns

Downhill Sand		Eighton Clay	
ns	Sulphate (mg/kg)	ns	Sulphate (mg/kg)
0.71	2.89	0.515	2.86
1.42	0.49	1.03	0.461
2.13	0.062	1.545	0.09
2.84	0.011	2.06	0.027

This is a serious consequence as quite small variations in 'ns' can produce very large errors in the data produced.

3.7 Summary

From the above analyses it is obvious that the computer model is sensitive to the input data. Where the input data can be measured, (Ke), there is no real threat to the accuracy of the results obtained. Similarly, where the parameters can be controlled, (the depth of the water table and the number of integration steps), it is possible to achieve accurate results. But, where there is no check on parameters (hw and ns) it is very difficult to ascertain whether or not the correct value has been predicted for a parameter, and thus the validity of the results obtained using 'estimated' parameters must be questioned.

It was therefore considered necessary to test the accuracy of the CRISP model, and to this end, a number of soil column experiments were designed, (using soils from actual reclamations) in which upward migration of contaminated soil water was encouraged and its' progress up the soil column monitored, allowing comparison of these results with the computer predicted values.

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Chapter Four: The Accuracy Of The Model

4.1 Soil Column Experiments

4.1.1 Designing The Soil Columns

Having outlined the main areas of sensitivity, and therefore of possible errors, in the CRISP computer model (Chapter 3) it is necessary to test the accuracy of the predicted values of capillary rise against reality.

Ideally field trials would allow the performance of a soil cover to be monitored and give actual results with which to compare the computer predictions. However, field trials are expensive to set up and run, and may have to be monitored for many years before a drought of any significance is recorded.

A cheaper and easier method is to set up soil column experiments in the laboratory where adverse conditions (i.e. drought) can be applied to the proposed soil cover as required.

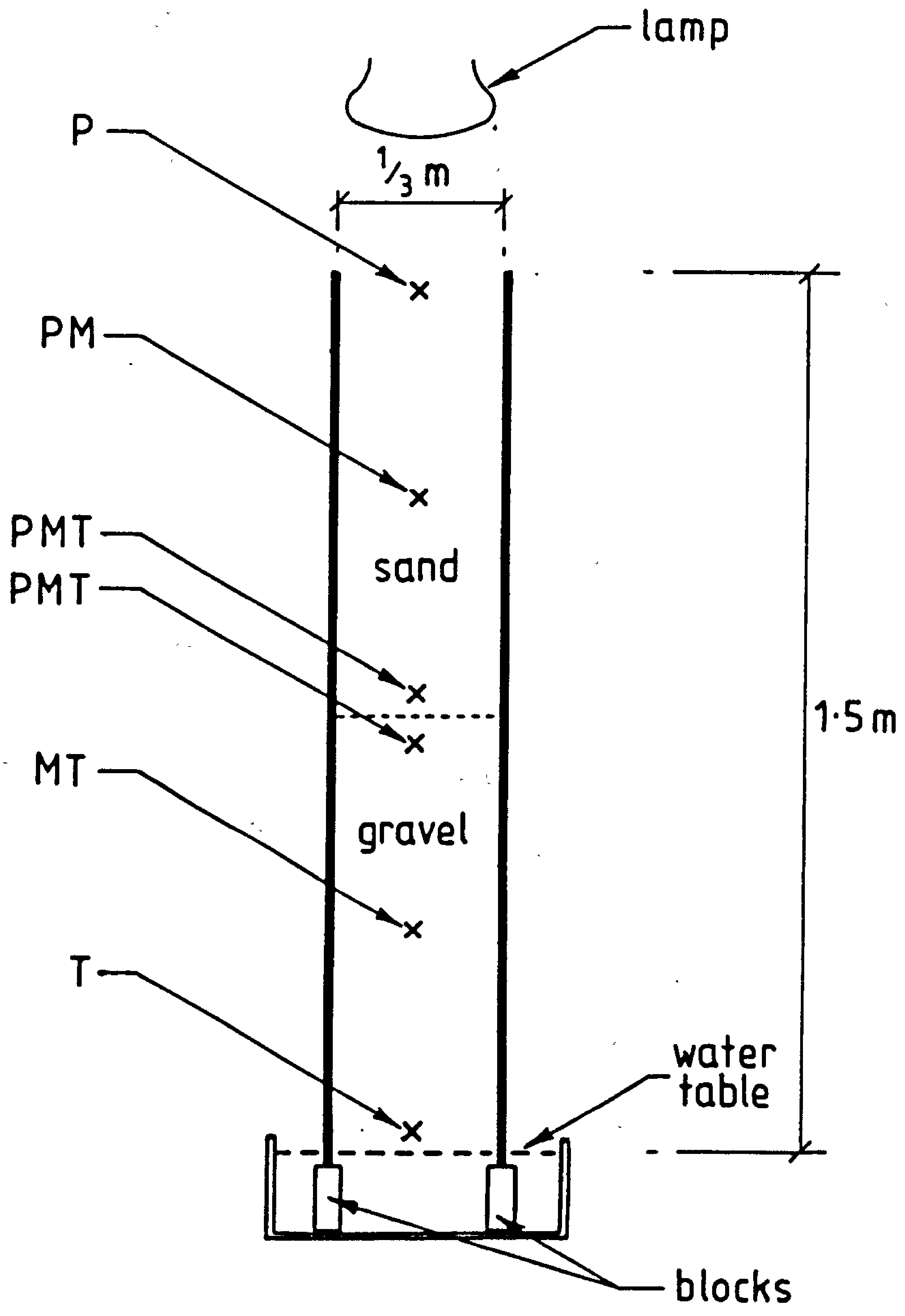
The soil columns are essentially lengths of plastic piping (one third of a meter in diameter), packed with soil materials to a given depth, and density. Each column stands in a water reservoir with water level with the base of the soil cover. The water in the reservoir contains the most important contaminant detected on site, at its highest recorded concentration, in order to produce a worst case situation. Heat lamps are placed above the columns to induce upward migration of soil water and the contaminants therein (see figure 4.1). Such columns can be considered as realistic representations of vertical elements in a soil cover, especially if all measurement and sampling is taken well away from the column walls to avoid abnormal edge effects (ref 4.1)

Three soil columns were considered to be the minimum number necessary to replicate any soil cover. Obviously, if only one soil column is used there is no way of knowing whether or not the results obtained are accurate, similarly, if two columns are used and each gives different results it is not possible to determine which result is correct. However, where three columns are used it is likely that at least two of the three would give similar results, as long as the columns were treated identically.

4.1.2 Redheugh Soil Columns

Reclamation of a gasworks site (Redheugh) in Gateshead (figure 4.2) using the soil cover method has already

Figure 4,1 Soil column design



Key :~

P = Psychrometer

M = Soil moisture cell

T = Tensiometer

Figure 4.2 Location map of the Redheugh gasworks site

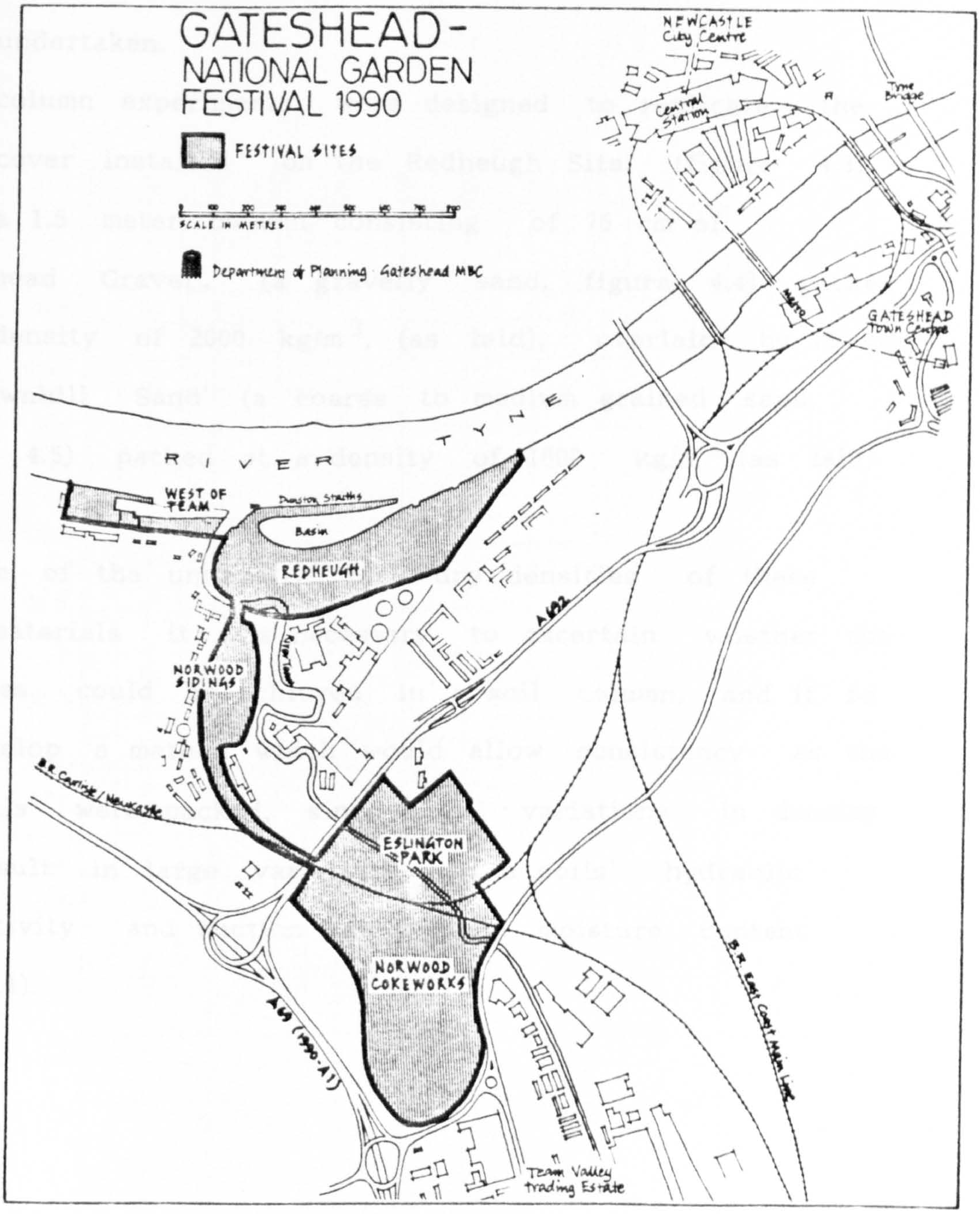
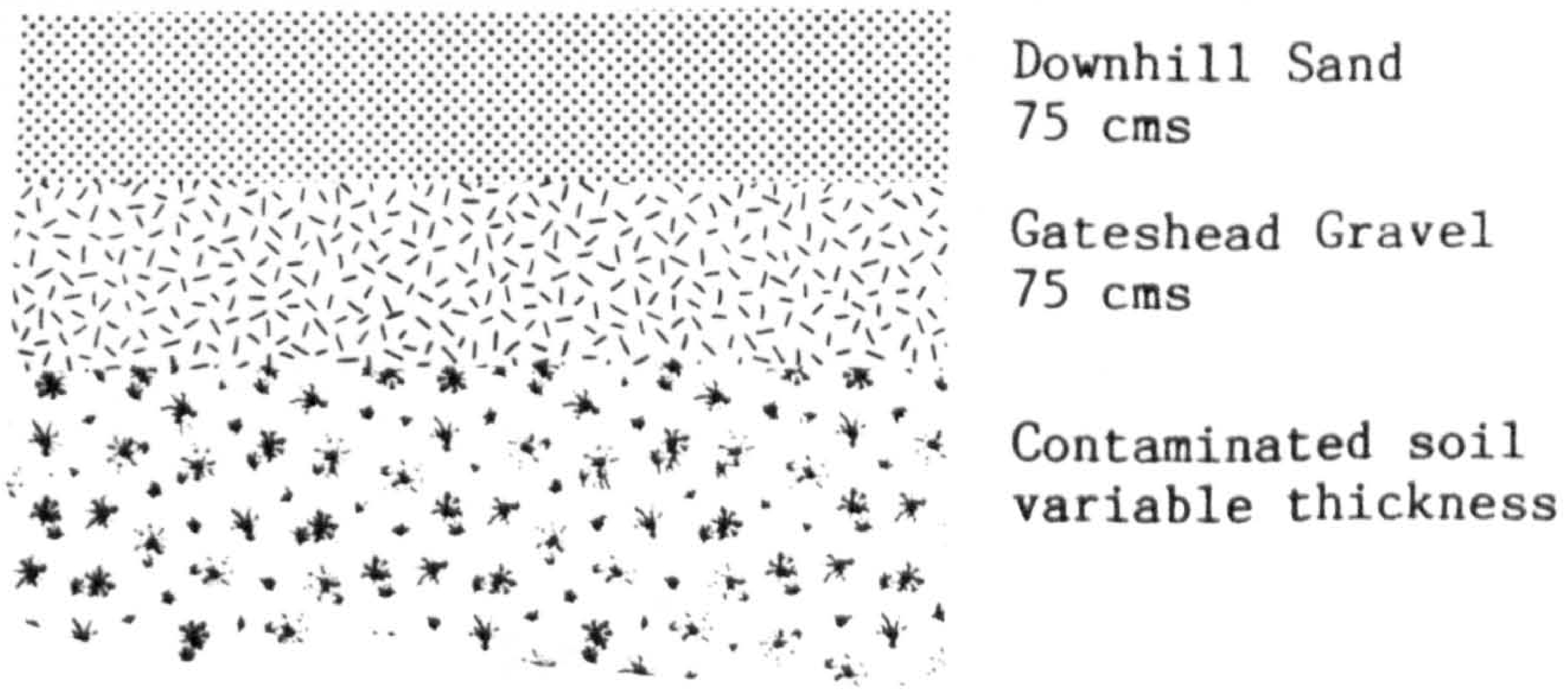


Figure 4.3 Soil cover installed on the Redheugh Site



been undertaken.

Soil column experiments were designed to replicate the soil cover installed on the Redheugh Site, (figure 4.3), i.e. a 1.5 meter column consisting of 75 cm of 'Gateshead Gravel', (a gravelly sand, figure 4.4) packed to a density of 2000 kg/m^3, (as laid), overlaid by 75 cms of 'Downhill Sand' (a coarse to medium grained sand, figure 4.5) packed at a density of 1800 kg/m^3 (as laid).

Because of the unusually high dry densities of these soil materials it was necessary to ascertain whether the densities could be achieved in a soil column, and if so to develop a method which would allow consistency as the materials were packed, since small variations in density can result in large variations in a soils' hydraulic conductivity and suction at a given moisture content (ref 4.1).

Figure 4.4 Particle size distribution curve for Gateshead Gravel

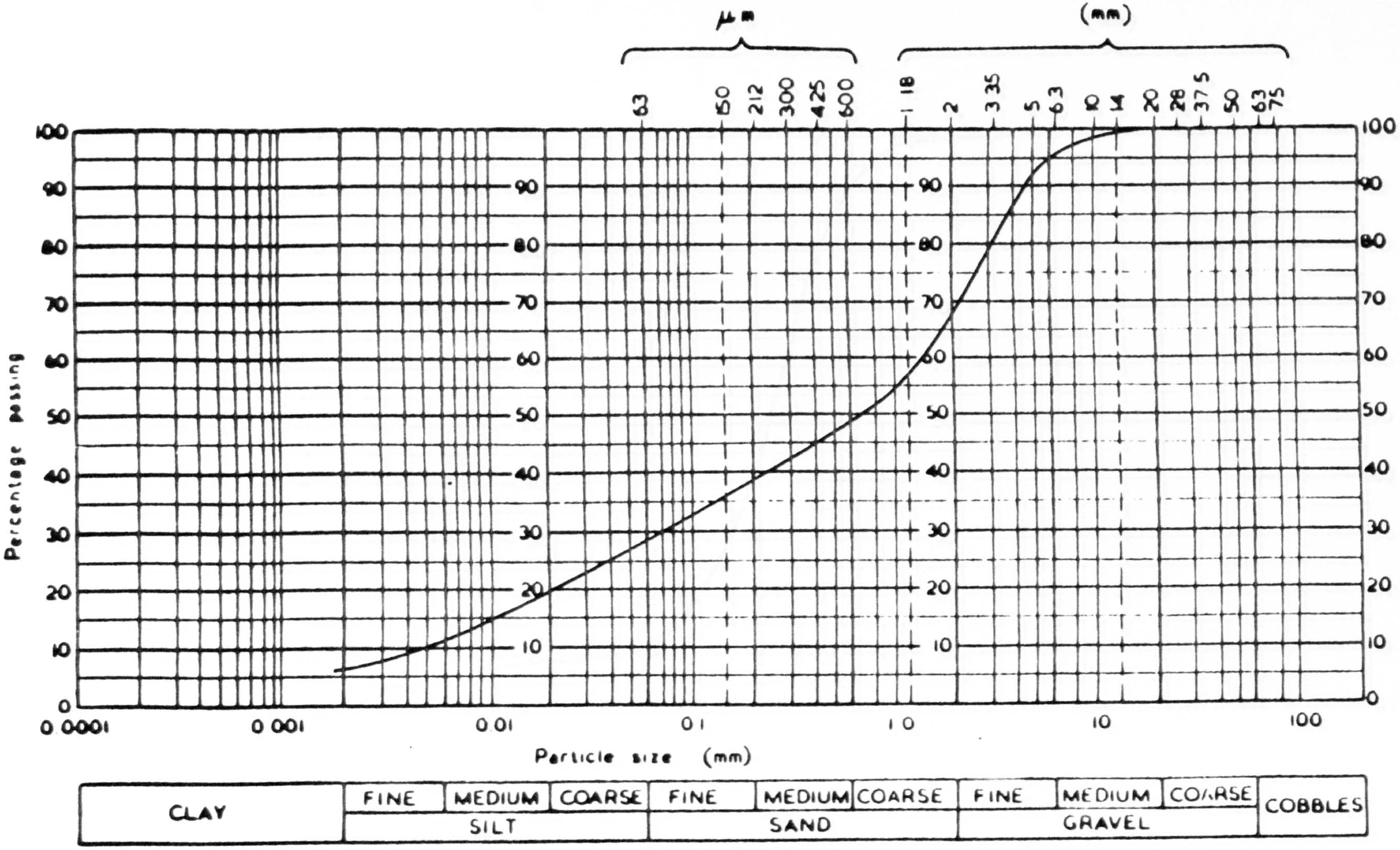
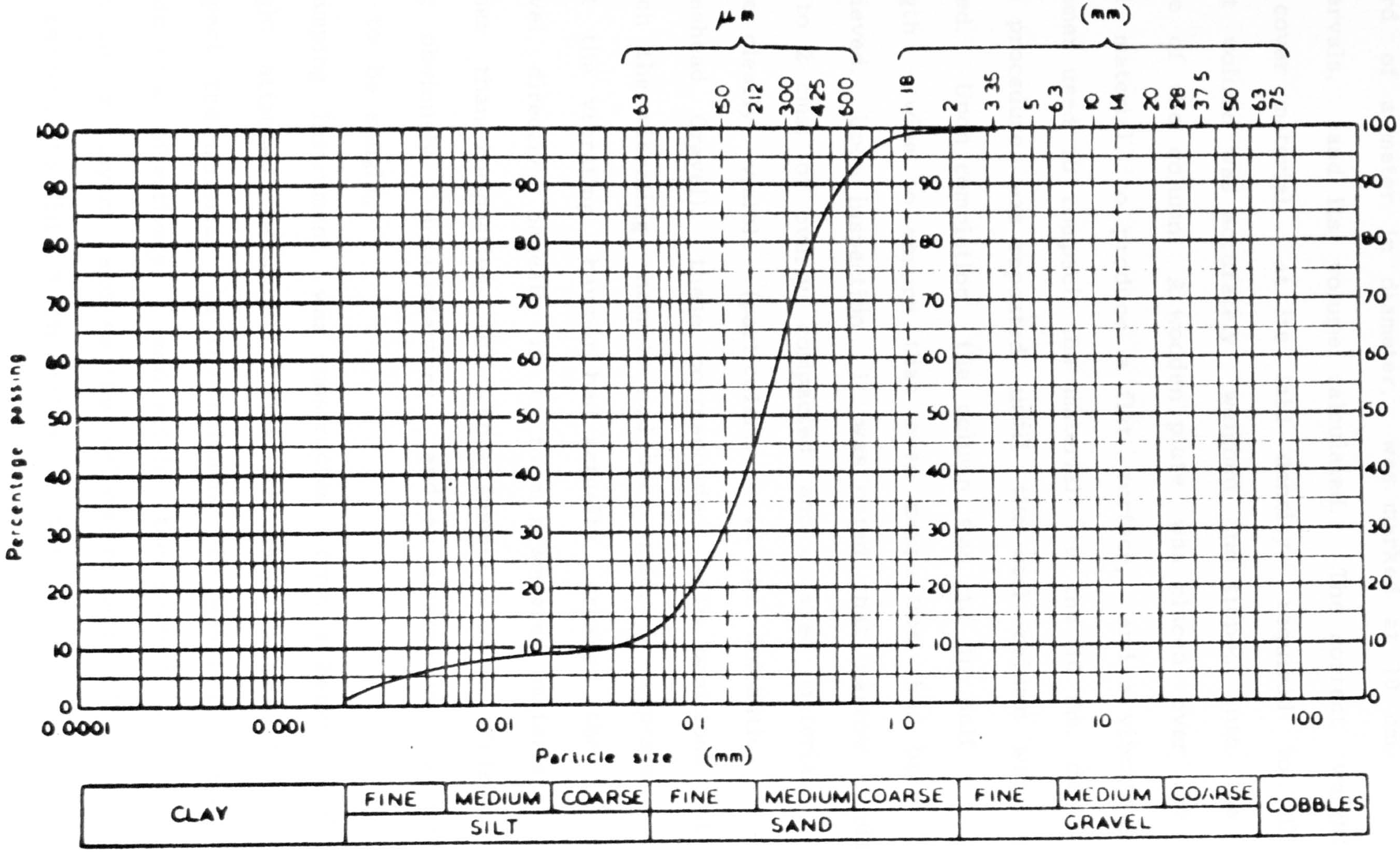


Figure 4.5 Particle size distribution curve for Downhill Sand



The interior of a column, half a meter in height and one third of a meter in diameter, was marked at 10 cm. intervals, and its volume calculated. The correct weight of cover material, at its laid density, required to fill that volume was accurately weighed and tipped into the base of the column. A wooden plate was placed over the soil material to produce a flat surface, and a vibrating hammer used to compact the material to the 10 cm. depth. The procedure was repeated until the soil column was filled. Upon completion the column was cut in half length - wise to ensure that even compaction had been achieved. Upon inspection it was noted that narrow bands (1 to 2 cms) of overly compacted and crushed material were clearly visible (particularly in the dolomitic Gateshead Gravel), these corresponded with positions at which the vibrating hammer had been used. It appears that the vibrating hammer had actually crushed the gravel directly beneath it to form a smeared material, rather than compacting the whole sample evenly. This was, obviously, unsatisfactory and an alternative method had to be sought.

A tamping instrument was constructed from a heavy metal weight attached to a pole. This was used to manually compact the material in the columns. It was not possible to do this effectively, and attain the correct densities with 10 cm. layers and so the volume of material used was reduced to fill 5 cm depths at a time.

Again, upon completion of packing the trial column was cut in half to allow inspection of the soil material. In this case it was found to be much more satisfactory.

Prior to the soil columns being packed a series of holes were drilled through the columns at heights of 5, 37.5, 70, 80, 112.5 and 145 cm from the base to allow soil instruments to be inserted.

As the soil in the column approached each of the pre-drilled holes the soil instruments were inserted and the soil packed around them carefully so as not to damage the instruments. At each instrumentation point a sample of the soil material was taken for chemical and moisture content analysis (table 4.1).

<u>Table 4.1</u> Initial water content and sulphate concentration of soil materials.

Height above water table	Column 1		Column 2		Column 3	
	H_2O*	SO_4	H_2O	SO_4	H_2O	SO_4
cms.	%	mg/kg	%	mg/k	%	mg/kg
145.0	6.0	0	6.1	0	6.2	0
112.5	6.2	0	6.3	0	6.4	0
80.0	5.8	0	6.3	0	6.1	0
70.0	12.2	0	12.1	0	11.9	0
37.5	12.1	0	12.1	0	12.1	0
5.0	11.9	0	12.3	0	12.2	0

(* the two soil materials were packed at water contents which ensured that no suction difference occured at the

material boundary)
Each column stood in a bath of water containing 7,000 mg/kg of sulphate, (obtained by dosing the water with Na_2SO_4) the worst sulphate concentration actually found on site. The water table was kept level with the base of the soil cover material by daily topping up. This represented a worst case situation where the drainage layer on site failed and the contaminated ground water could rise to the level at which drainage to the River Tyne took place.
Heat lamps were placed above the soil surface, to induce drying and therefore capillary movement of soil water.

Each soil instrument was read two or three times daily, and soil samples were removed from each of the columns at monthly intervals (at heights corresponding to instrumentation), for both chemical and moisture content analyses.

4.1.3 Instrumentation used in the soil columns

From the outset a variety of soil moisture / soil suction measuring devices were available for use in the column studies. It was essential that the instruments chosen could cope with the likely range of suction - water contents which would occur in the columns.
From previous similar column studies (ref 4.1) it was anticipated that the soil at the base of each column

would remain quite wet due to its proximity to the water table, whilst the soil surface would become very dry due to the heating effect. It could therefore be assumed that a moisture gradient would exist between the soil surface and the water table.

It was therefore necessary to use instruments which would provide accurate readings across the range from near saturation to very dry.

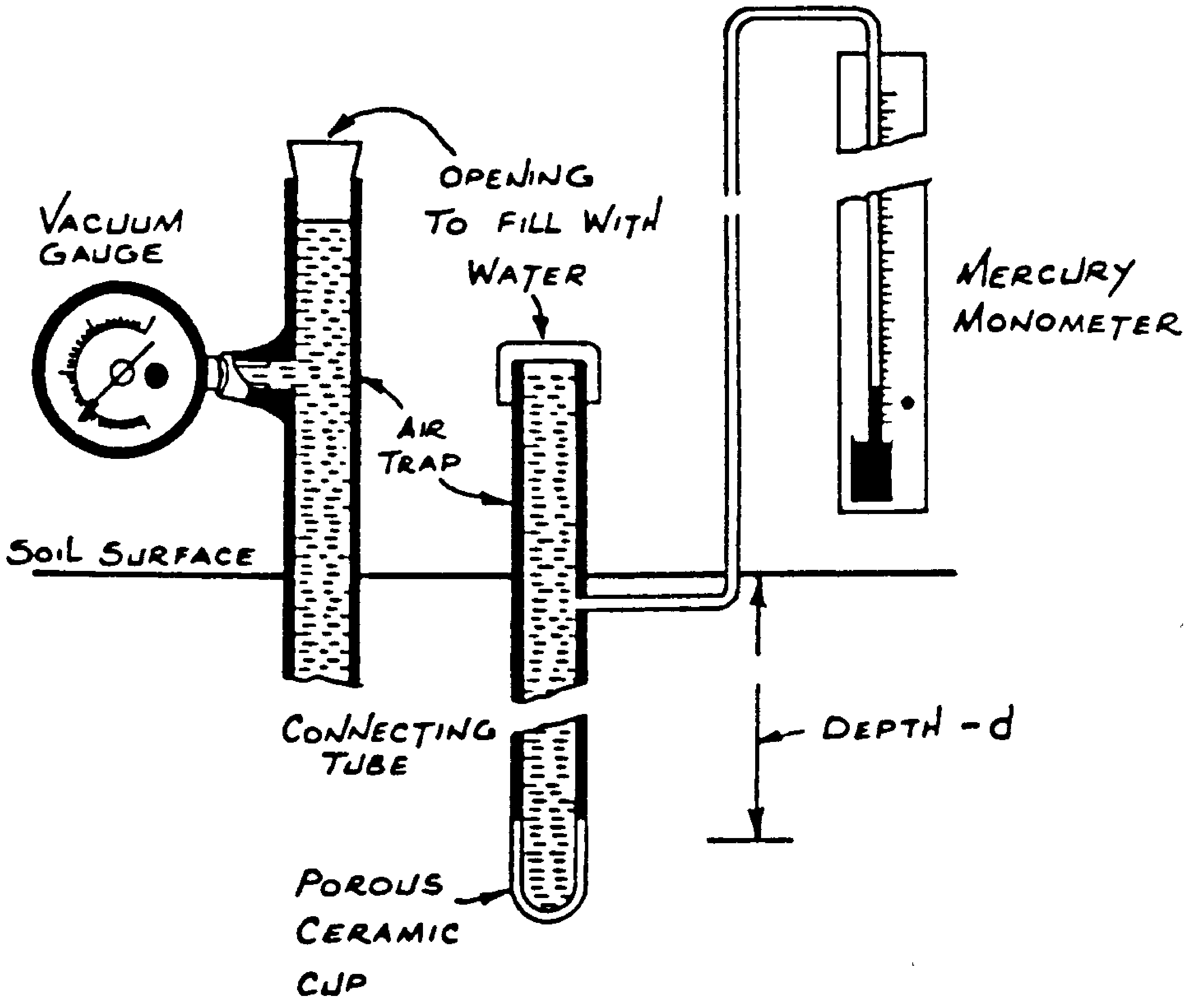
Three main groups of instruments were available: tensiometers; gypsum blocks and soil moisture cells; and psychrometers.

(i) Tensiometers

The discovery by Buckingham, 1907, (ref 4.2) that the suction developed in a soil was related to the water content of that soil led a number of later workers (refs 4.3 to 4.5) to develop devices which could measure soil suction. These early instruments contained all the elements which are recognised as essential for modern tensiometers, i.e. a water filled column with a porous tip attached to one end and a suction measuring device (i.e. a gauge or a manometer) attached to the other, (figure 4.6). The porous tip is placed in the soil and as water is drawn through the tip into the soil a partial vacuum is created in the water filled column and this activates the suction measuring device.

Tensiometers are, however, only capable of measuring suction values in the range zero (i.e. fully saturated) to 900 cms of water suction (i.e. about one atmosphere). This is because at suction values greater than one atmosphere water cavitates, allowing water vapour into the water column which interrupts the vacuum, making subsequent readings inaccurate.

Figure 4.6 Schematic illustration of the essential parts of a tensiometer (after Richards, 1965)



(ii) Gypsum blocks and soil moisture cells

The limited suction range covered by tensiometers prompted Bouyoucos, 1940, to consider using electrical resistance to determine soil suction values over a greater range than had previously been achieved.
In his early work (ref 4.6) the electrodes were coated with gypsum to ensure proper contact between the soil and the electrodes. The gypsum also shielded the electrodes from naturally occurring eddy current within the soil, restricting erroneous readings.

These early gypsum blocks had two main problems:

(1) they only gave accurate readings in the drier range of the soil

(2) the gypsum coating was likely to dissolve with time

Bouyoucos experimented with a variety of different types of coating materials and soon developed an improved block (ref 4.7) which consisted of two electrodes wrapped in nylon cloth and coated with either a layer of gypsum (the gypsum block) or a pierced metal casing (the soil moisture cell). This improved block was capable of producing accurate readings in the range 305 cm to 20380 cm of suction.
Soil moisture cells from commercial suppliers were used in this research.

(iii) Psychrometers

Psychrometers are the most recently developed device for measuring soil suction.

Essentially a psychrometer consists of a small thermocouple, having both measuring and reference junctions, located within a porous ceramic cup (figure 4.7).

Water migrates through the bulb, moistens the measuring junction, and produces an electrical voltage which is proportional to the difference between wet and dry bulb temperatures of the pore vapour.

If the ambient temperature is known and an accurate calibration of the psychrometer has been attained, then the soils' suction and relative humidity can be determined from the thermocouples voltage reading.

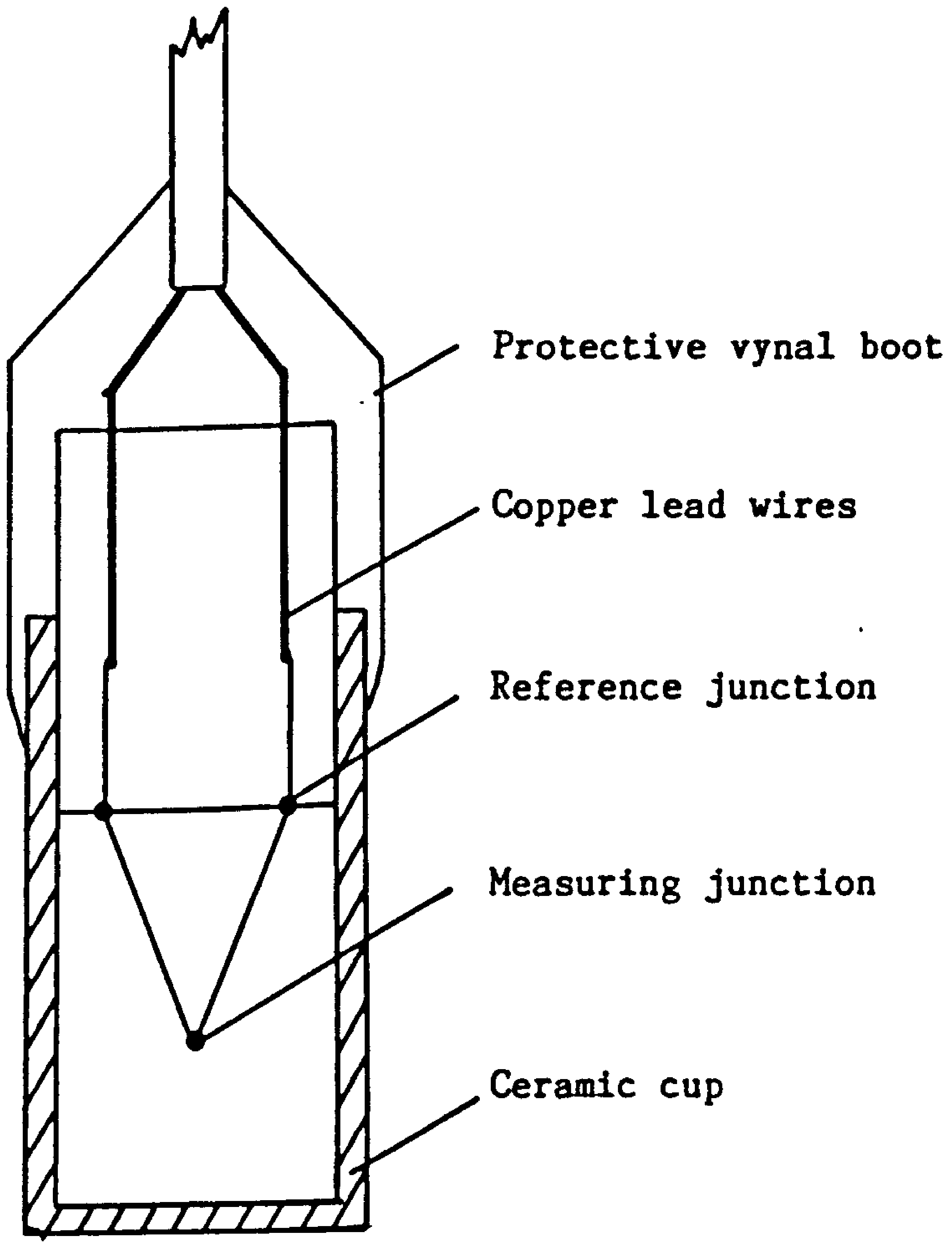
Psychrometers are capable of providing accurate readings in the range 1000 cm to 81520 cm of suction, however, for accurate readings to be attained a minimum humidity of 95% must exist in the soil pores.

From the above section it is obvious that no single instrument would provide accurate readings over the entire suction range anticipated in the soil columns.

Instruments were therefore chosen to cover the range of suction values likely to occur at each instrumentation height in the columns, as shown in figure 4.1.

The tensiometers were connected to mercury manometers,

Figure 4.7 Schematic diagram of the basic components of a psychrometer



which had been made at the Polytechnic, however it was necessary to purchase suitable meters to read the soil moisture cells and the psychrometers. After surveying the available literature a soil moisture temperature meter and a water potential data system were purchased. The former was a manually operated meter for use with the soil moisture cells. Essentially it consisted of a thermocouple which output a reading corresponding to the electrical current produced by each individual cell. This could be converted to moisture content using the cells' calibration curve (section 4.1.4).
The water potential data system was essentially a data logger which could automatically read up to fifteen psychrometers and store up to sixty days data in the memory until accessed via a computer.

4.1.4 Calibration of soil instruments.

Prior to installing the soil moisture cells and psychrometers in the soil it was necessary to obtain a calibration curve for each instrument.
Soil moisture cells have to be calibrated in the soil in which they are to be used. This is done by packing a known weight of the soil material around the cell at the required density. The sample is then saturated and placed in a constant temperature environment (25 °C) where water is evaporated from the sample. Regular monitoring of the resistance, and weighing of the sample, allows

the relationship between resistance and water content to be determined for that particular cell, (figure 4.8)
The psychrometers were supplied with a manufacturers calibration curve. However, as a precautionary measure the psychrometers were calibrated in the soil in which they were to be used, using the same method as had been used to calibrate the moisture cells (figure 4.9).

4.1.5 Analytical method

The sulphate ion in each 10 gram soil sample, taken from the soil column, was extracted with 5 ml of distilled water. The sample was centrifuged to separate the aliquot from the solid matter.
The amount of sulphate present in each sample was determined by reverse phase ion-pair chromatography, where, the sulphate (which is non-uv active) is encouraged to pair with another ion (in this case tetra-n-butylammonium hydroxide), and, when passed through a detector cell the non-uv absorbing pair is detected by a reduction in the uv signal. The reduction being proportional to the amount of sulphate ion present. The amount of sulphate can then be determined from a standard calibration obtained using known concentrations of sulphate.

Figure 4.8 Calibration curve for moisture cell No. 6 in Gateshead Gravel

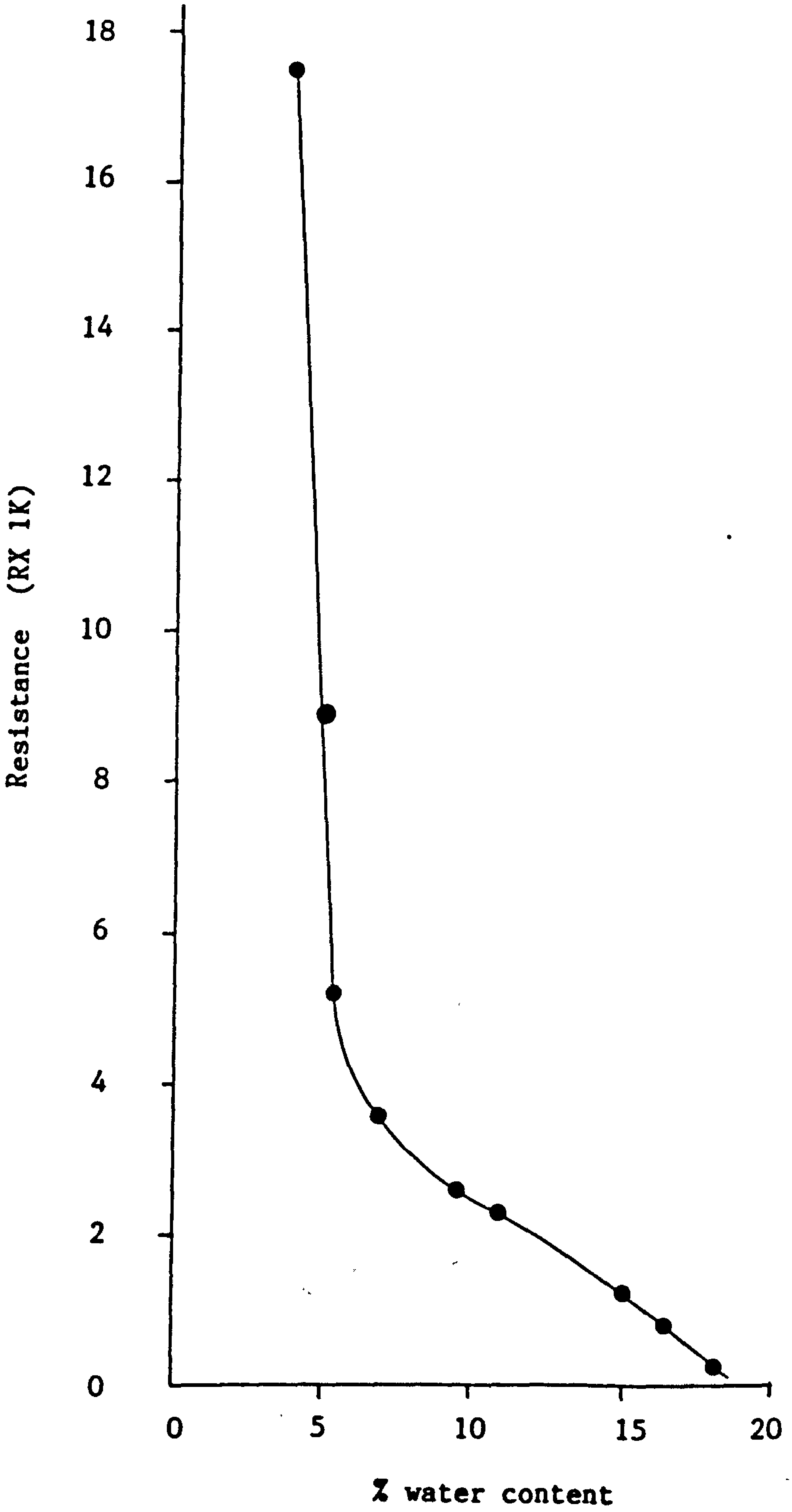
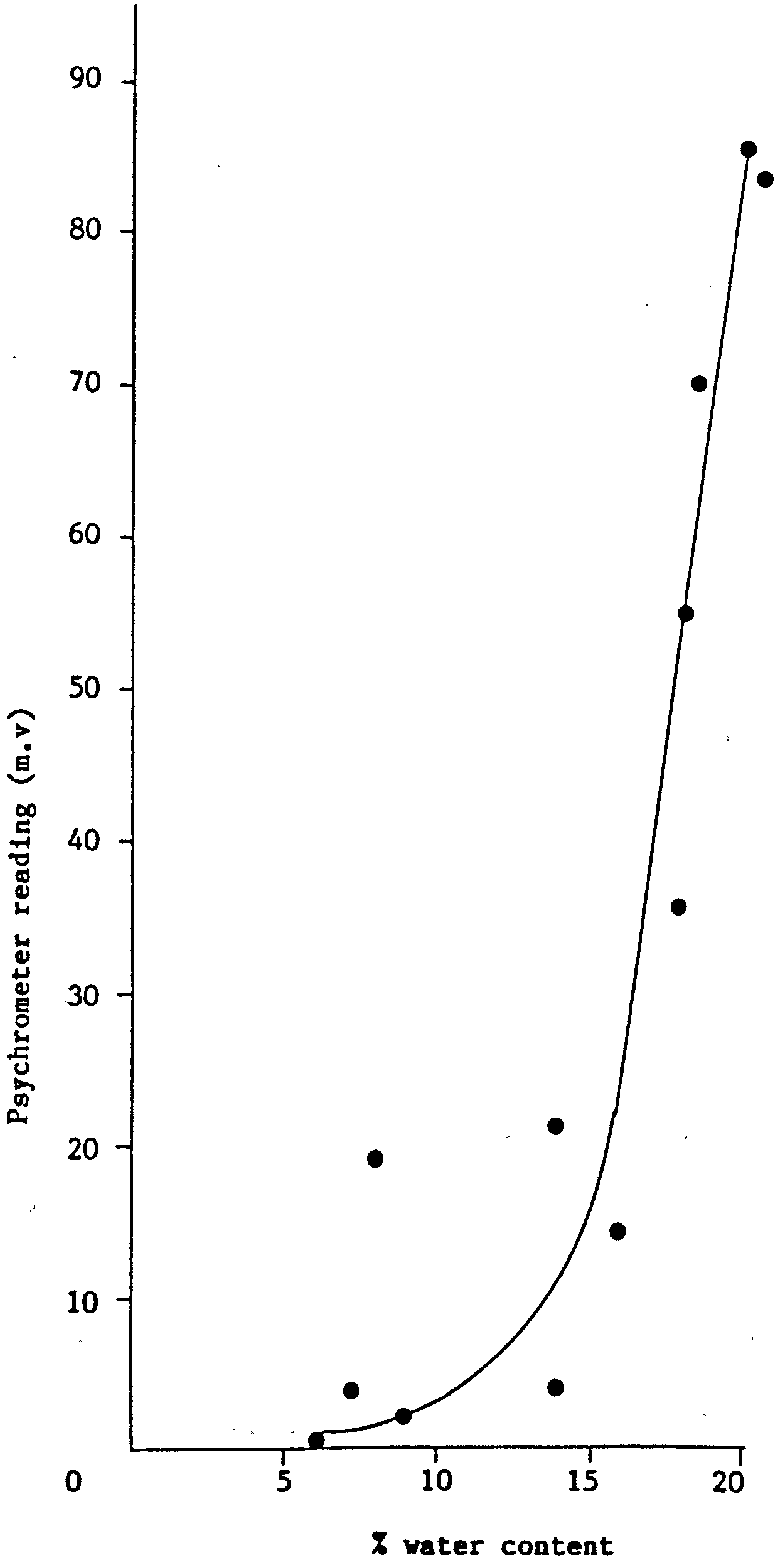


Figure 4.9 Calibration curve for psychrometer No. 1 in Downhill Sand



4.1.6 Results of the soil column experiments

In hind sight, the data logger proved to be a bad investment. It was prone to malfunctioning which neither ourselves nor the U.K. distributors were able to rectify. Consequently the majority of the psychrometer results obtained were spurious, this data has, therefore, not been included in the following discussion.

The soil moisture cells worked without interruption throughout the experiment, as did all but two tensiometers. The results obtained from both sets of instruments were in good agreement with each other and the water content data taken at monthly intervals, (table 4.2)

Table 4.2 Comparison of water content values predicted by various methods

	Tensiometer	Moisture cell	Measured
Month 1	13.31	13.24	13.43
Month 2	13.80	14.41	14.13
Month 3	14.20	14.6	15.00

All readings were taken in column 1 at 37.5 cms

The water content profiles of each of the columns are shown in figures 4.10 to 4.12.

From these figures it can be seen that the overall trend is for each column to become progressively wetter at all heights except near the soil surface. Here the soil is dried due to the proximity of the heat lamps.

The boundary between the Gateshead Gravel and Downhill Sand (at 75 cm from the base) is clearly identifiable throughout the experiment, the sand being consistently drier than the gravel.

However, upon closer inspection it is obvious that, despite identical treatment of all three columns, the water content profile near the surface of column 3 differs from that of the other two columns. During the first month it was noticed that the soil surface temperature of column 3 was approximately 2°C less than the temperatures recorded for columns 1 and 2. This infact was due to the geometry of the room. The room chosen was situated in a basement, it had no widows and a single door which was kept locked. It was therefore possible to control the column experiments without having the added complications of solar gain, or other external influences. However, the one feature of the room which had not been taken into account was its sloping celing. This infact produced a chimney effect, allowing hot air to rise to the highest point and then descend as a column of cool air. Column 3 was situated beneath this descending cool air current and has been

Figure 4.10 Change in water content with height at monthly intervals

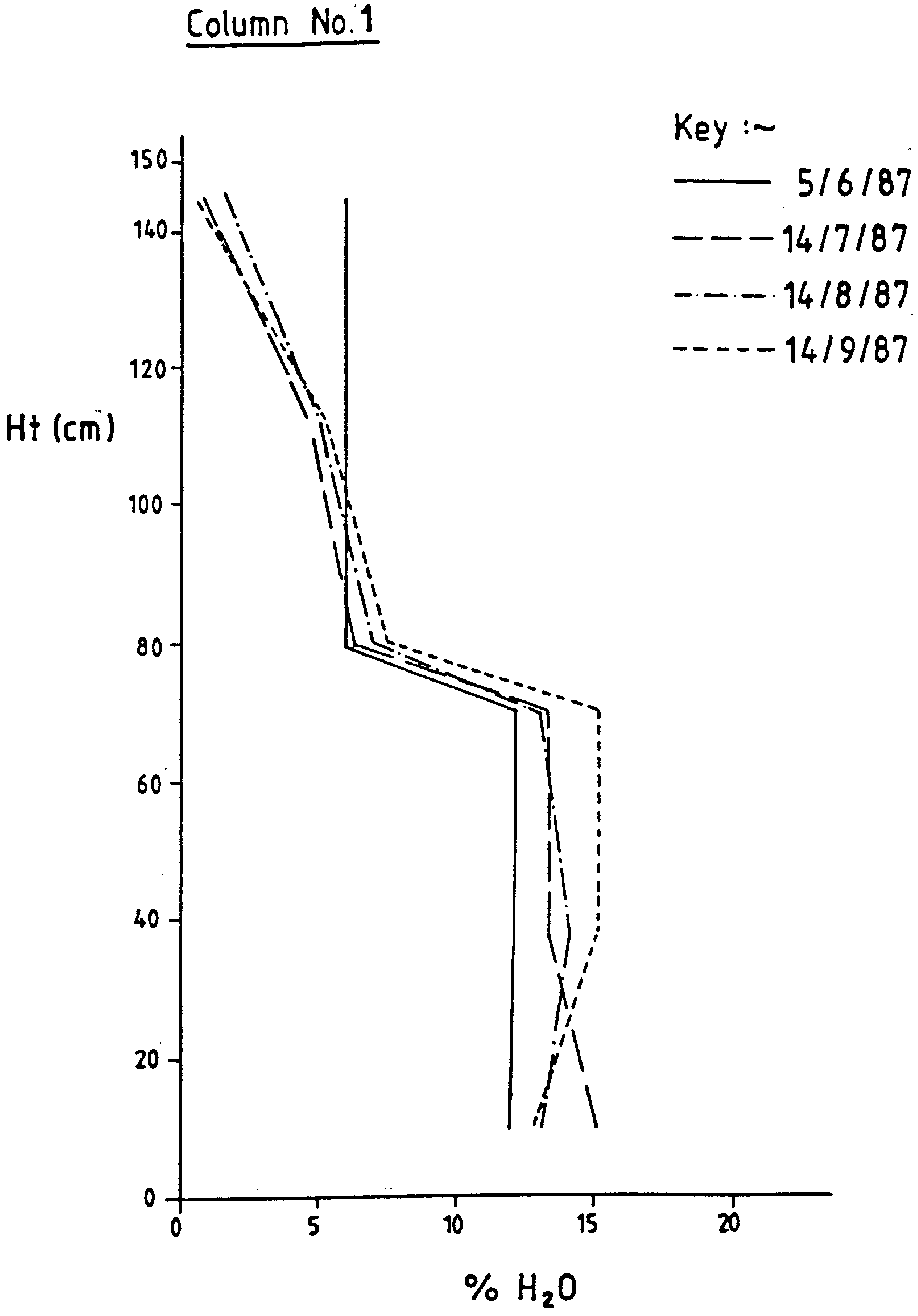


Figure 4.11 Change in water content with height at monthly intervals

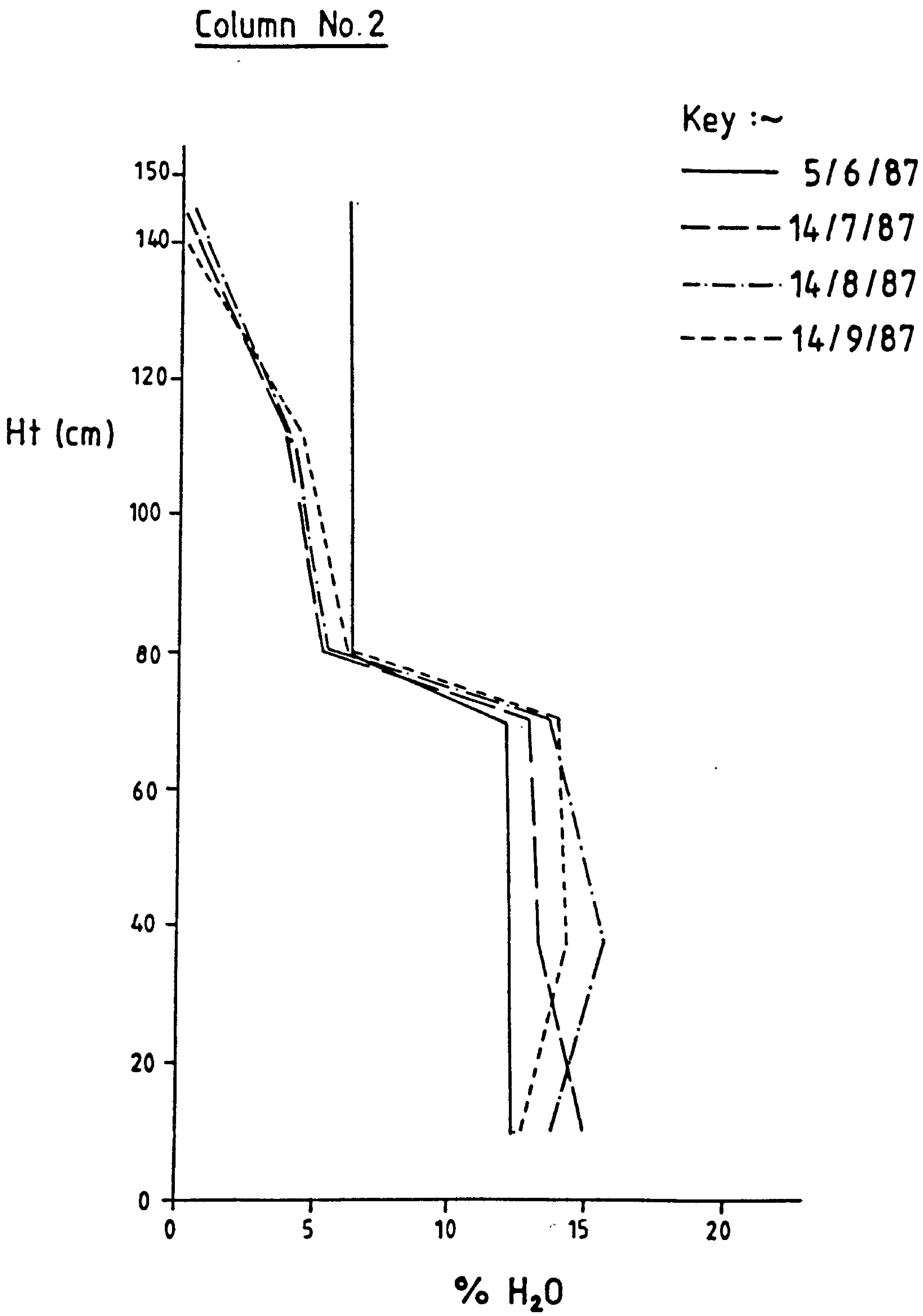
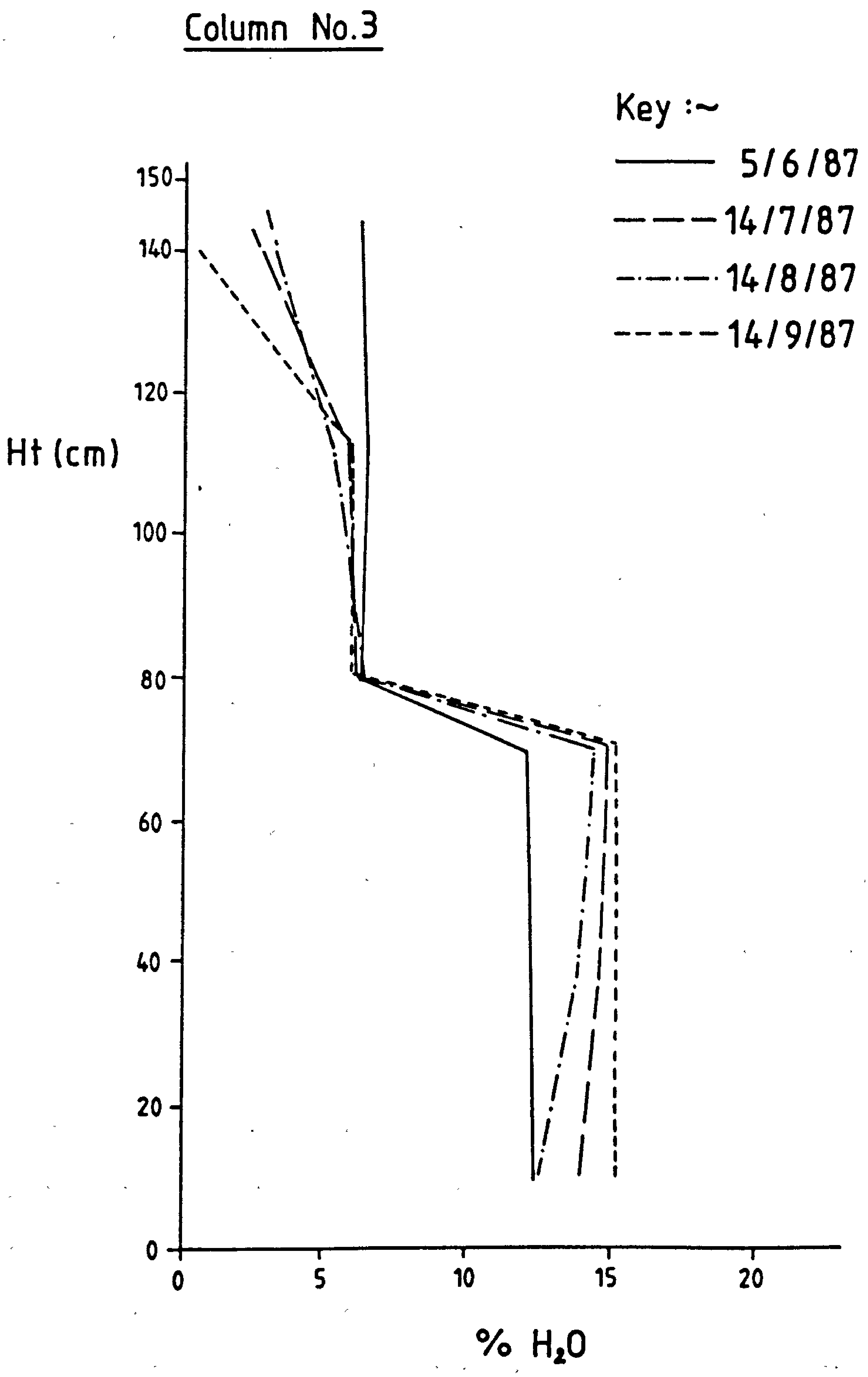


Figure 4.12 Change in water content with height at monthly intervals



prevented from heating to the same extent as columns 1 and 2.

Still looking at the soil surface, it is obvious that the soil material did not become progressively drier as one would have expected, but that all three columns show some rewetting of the soil surface during month two. This was due to a reduction of 2 hours in the length of time for which the columns were heated after the first month. (this reduction was necessary due to the earlier closing time of the Polytechnic during the summer vacation.)

Another annomoly within the columns is the variable water content recorded for the gravel material. Despite this material being described as a gravel it is obvious from figure 4.4 that the range of particle size of the materials is very large. This It was therefore very difficult to obtain a truly representative sample of soil, especially when one considers that soil samples were only 10 g. Obviously the greater the silt content the higher the water content of the sample would be and vice versa.

The values of contaminant rise monitored in the soil columns are recorded in table 4.3

It was anticipated that the sulphate concentrations would decrease with distance from the water table, reflecting the general pattern of the water content profile, and that the amount of sulphate at any given

Table 4.3 Contaminant concentration (ppm) recorded in the soil columns at monthly intervals

Column 1

Height (cms)	Month 1	Month 2	Month 3
145	1.99	2.04	3.99
112.5	1.97	2.75	5.96
80	2.96	3.42	3.96
70	8.91	7.91	11.89
37.5	11.91	9.90	10.90
5	221.89	382.09	395.91

Column 2

Height (cms)	Month 1	Month 2	Month 3
145	4.00	3.99	12.00
112.5	8.97	2.97	9.97
80	7.96	6.96	10.96
770	9.91	12.90	19.90
37.5	11.91	9.89	12.90
5	111.90	223.90	339.91

Column 3

Height (cms)	Month 1	Month 2	Month 3
145	4.98	6.98	17.00
112.5	2.96	2.96	4.96
80	3.96	2.96	6.96
70	13.90	10.90	13.89
37.5	16.90	13.90	12.89
5	136.90	144.91	206.89

height would increase with time.

From table 4.3 it is can be seen that although the general trend within each column followed these principles, a number of anomalies had occurred These anomolies reflect the variable of particle size of the materials, which will affect the concentration of sulphate recorded in the columns. Again a more silty sample would have a higher concentration of sulphate than would a sandy sample.

The problem of soil variability has obviously devalued the soil column results slightly, it is therefore suggested that subsequent workers should obtain multiple samples, or very large soil samples for analysis in order to obtain accurate results. Obviously this was not possible in this research as the structure of the soil columns would have been disrupted, however had many small columns be used then it would have been possible to dismantle one column a month and conduct a detailed water content and sulphate analysis on the material.

4.2 Results obtained from the computer model

Data for each of the soils in the columns (table 4.4) were entered into the computer, together with the suction values which occurred at the soil surface of each column at the time of sampling.

Table 4.4 Data required to run the CRISP computer model

Soil	Height above water table (cms)	Ke	hw	ns
Downhill Sand	75 to 150	2.30	3.09	1.42
Gateshead Gravel	0 to 75	4.10	0.55	1.80

From the computer output, graphs of flux against height, for each suction value, were constructed (figures 4.13 to 4.15) and the gradient dv/dz determined. This gradient was then used in the equation (eq 4.1)

$$C = \frac{c.\rho.}{\rho s} d . \frac{dv}{dz} \qquad \text{eq. } 4.1$$

to calculate the concentration of contamination arriving at the soil surface under the observed drying conditions (table 4.5).

Figure 4.13 Height of flux rise for final suction values recorded in Column 1

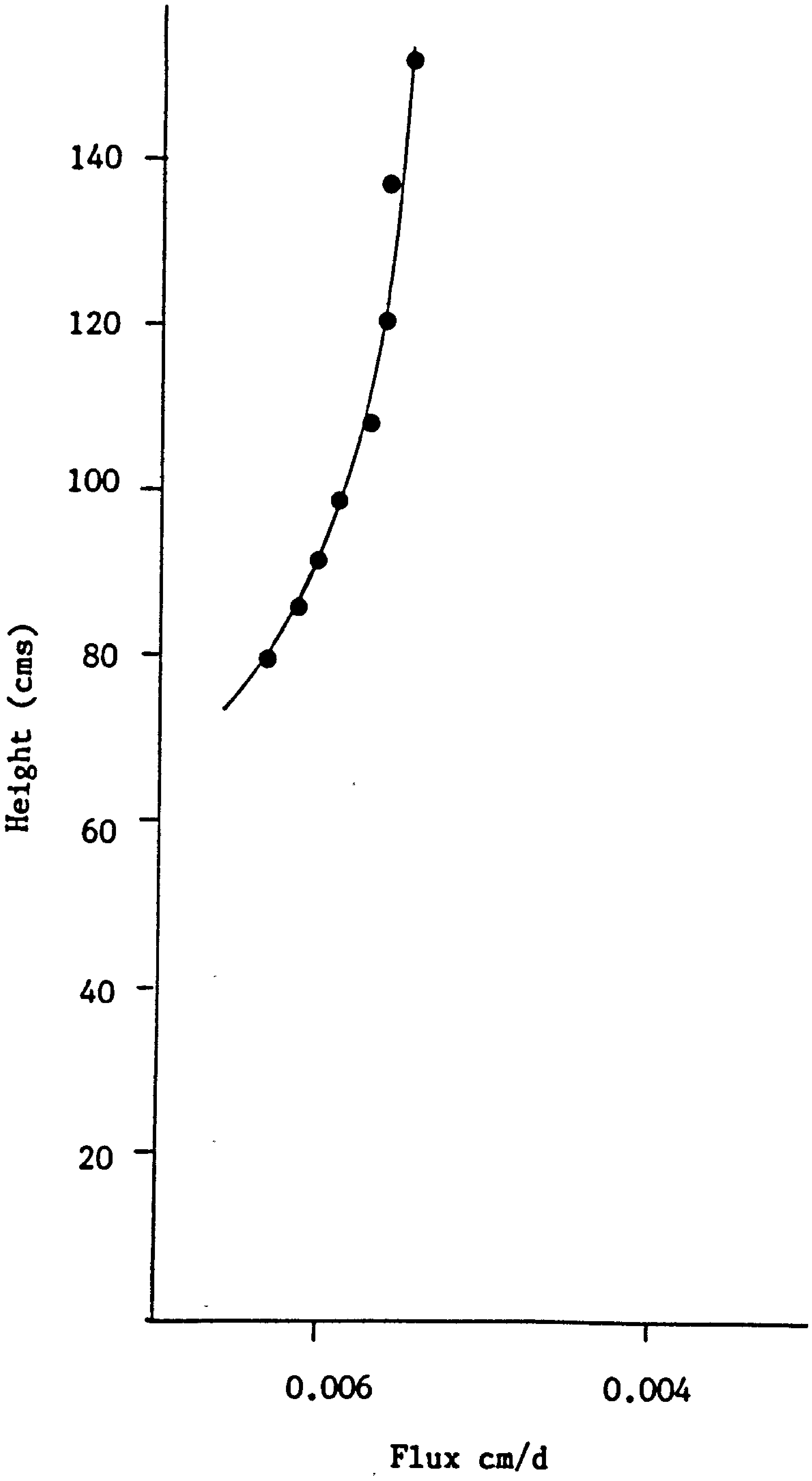


Figure 4.14 Height of flux rise for final suction values recorded in Column 2

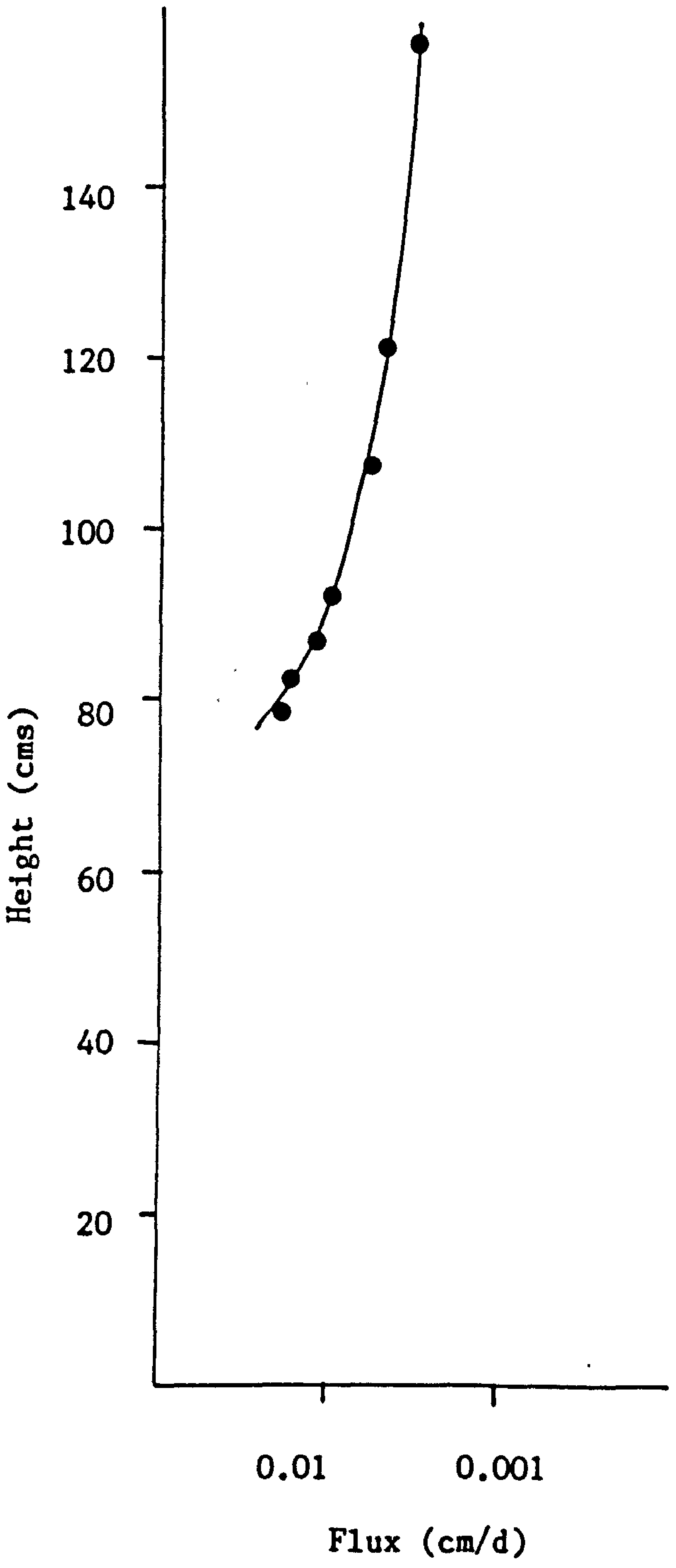
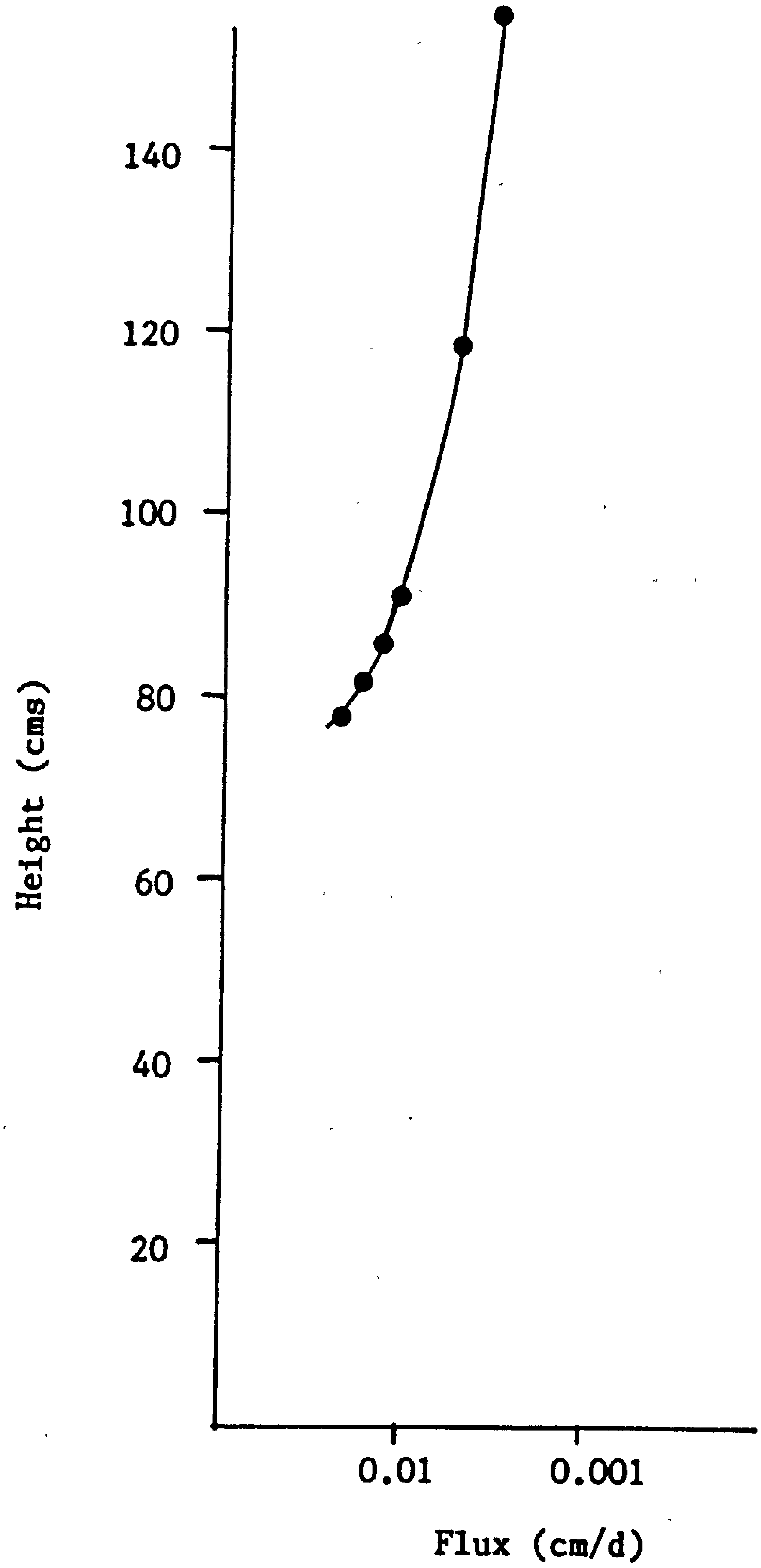


Figure 4.15 Height of flux rise for final suction values recorded in Column 3



4.3 Comparison of computer result with soil column values.

The computed and measured values of contaminant rise are recorded in table 4.5. From this table it can be seen that all of the computer predicted values are between 0.5 and seven times greater than the measured values obtained from the soil columns. Whilst this over prediction may seem like a serious error in the model, it is not considered detrimental to the study as, when considered from the point of view of designing a soil cover, this 'built in' error is viewed as an added safety factor.

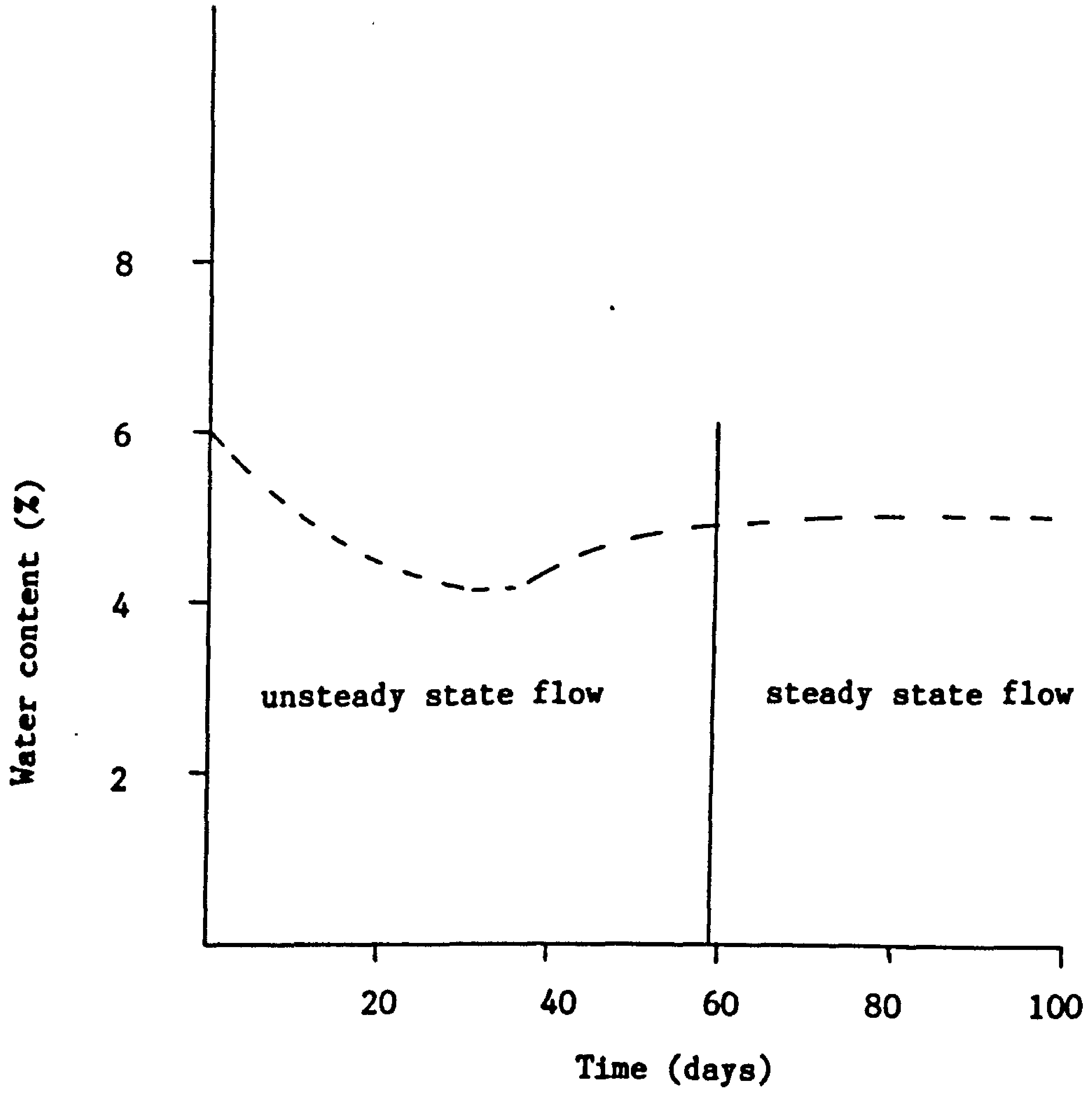
The probable reason for the discrepancy between the results in the soil column and those from the CRISP model is that the model was specifically designed for steady state flow conditions.

Moisture changes within the soil columns (figure 4.16) show quite clearly that moisture equilibrium was not fully attained throughout the soil column experimental period.

It may therefore be argued that the use of a steady state model is unwarranted in such conditions. However, steady state models are much simpler to utilise than are the very few dynamic flow models that have been attempted, and this research is specifically aimed at evaluating the practical use of soil cover reclamation methods.

In a real design office time is always of the essence, and designers do choose to utilise simpler design approaches, particularly where they include a specified factor of safety.

Figure 4.16 Steady and unsteady state flow in the soil columns (moisture cell 1)



An additional and important fact is that the state of dryness attained at the end of a design drought is not achieved uniformly within that drought period and it would be difficult for any designer to establish the scientific detail of precicely how much dryness is attained by particular times.

Thus their practical alternative would be to ascribe a particular state of surface dryness to that drought and to apply it throuought the length of the drought period.

The CRISP model and the design process which accompanies it is thus seen as a useful tool which allows a prediction of the capillary rise of contaminants to be determined with an in-built safety factor

Table 4.5 Comparison of computer predicted results with measured soil column results

Column 1

Height	Month 1		Month 2		Month 3	
cms	Meas.	Comp.	Meas.	Comp.	Meas.	Comp
145	1.99	7.00	2.04	14.00	3.99	19.00
112.5	1.97	8.51	2.75	17.25	5.96	25.60
80	2.96	12.41	3.42	19.90	3.96	-
70	8.91	-	7.91	-	11.89	-
37.5	11.91	-	9.90	-	10.90	-
5	221.89	-	382.09	-	395.91	-

Column 2

Height	Month 1		Month 2		Month 3	
cms	Meas.	Comp.	Meas.	Comp.	Meas.	Comp
145	4.00	7.80	3.99	13.67	12.00	19.94
112.5	8.97	9.54	2.97	19.57	9.97	28.59
80	7.96	15.30	6.96	30.11	10.96	43.13
70	9.91	-	12.90	-	19.90	-
37.5	11.91	44.10	9.89	-	12.90	-
5	111.90	-	223.90	-	339.91	-

cont...

Column 3

Height cms	Meas.	Comp.	Meas.	Comp.	Meas.	Comp
145	4.98	6.40	6.98	11.31	17.00	22.78
112.5	2.96	9.89	2.96	21.63	4.96	27.00
80	3.96	-	2.96	12.96	6.96	39.92
70	13.90	-	10.90	-	13.89	-
37.5	16.90	-	13.90	-	12.89	-
5	136.90	-	144.91	-	206.89	-

All values expressed in mg/kg

- denotes suctions developed within the soil which were less than the height of instrumentation, therefore the computer could not calculate capillary rise to these heights

Meas. - measured values
Comp. - computed values

4.4 Additional Soil Column Experiments

Two additional sets of soil column tests were run to confirm the accuracy of the CRISP model.

The columns used in these experiments were 40 cms in height and 10 cms in diameter. Again each test was run in triplicate. The first set of columns contained Eighton Clay, packed at a density of 1700 kg/m^3 (a silty sand with a 12% clay fraction, figure 4.17)

The second set of columns contained In-situ Clay, packed to a density of 1530 kg/m^3 (a silty sand with a 28% clay fraction, figure 4.18)

Each of the six columns was instrumented with both tensiometers and soil moisture cells at heights of 5, 20, and 35 cm from the water table, which was situated at the base of the soil column, and contained 2000 ppm of dissolved sulphate (the most worrying contaminant on the Norwood site, see section 2.3.1).

The experiment was run for one month, and samples of soil material from each of the columns were taken at the start and end of the experiment for water content and sulphate analysis. The results of these analyses and the computer predicted values can be seen in table 4.6.

Both soil materials contained a small amount of sulphate prior to the start of the experiment, obviously this initial sulphate value has to be added to the computed values when comparing the column results with the

Fig 4.17 Eighton Clay~ Norwood.

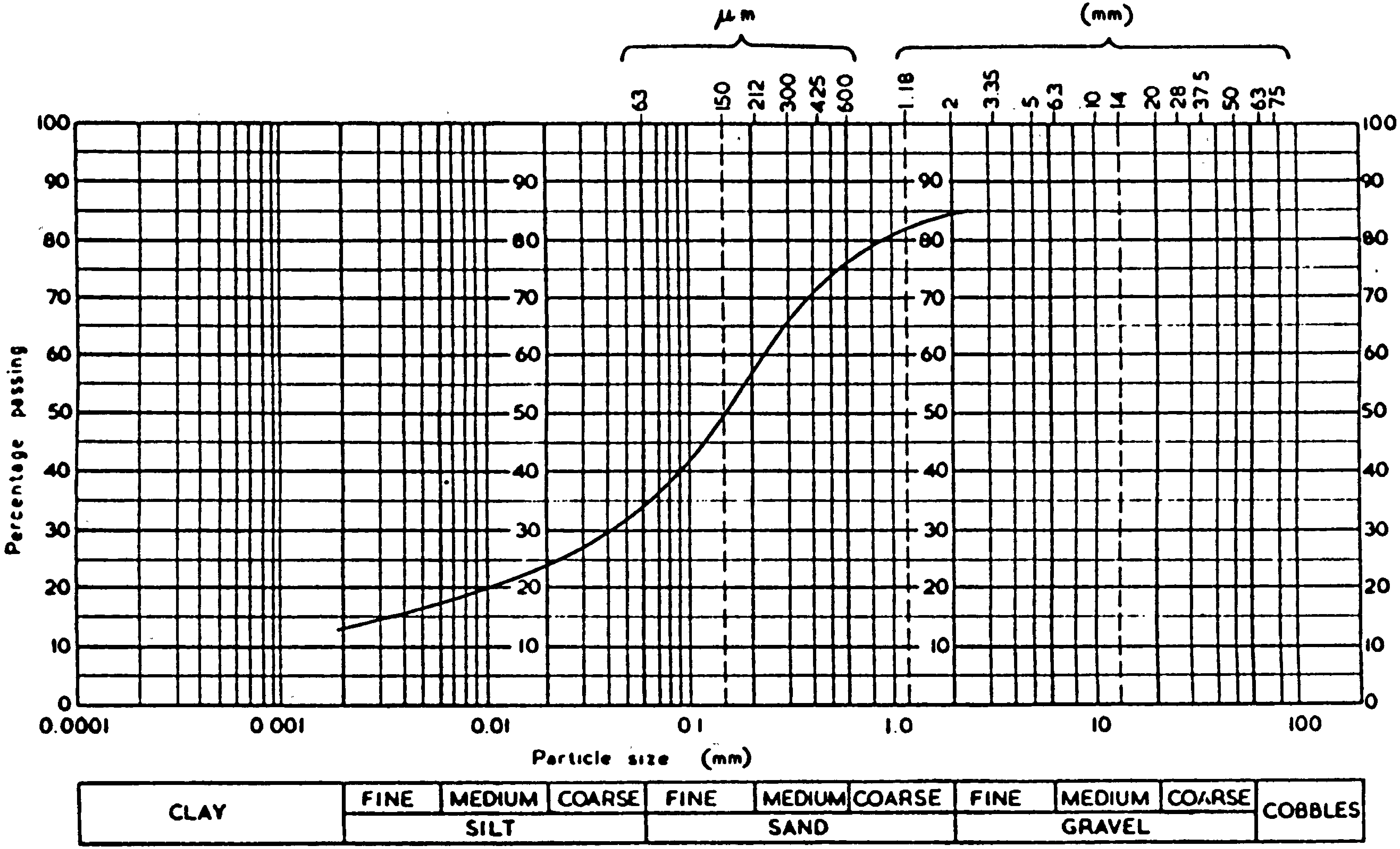


Fig 4.18 In Situ Clay~ Norwood

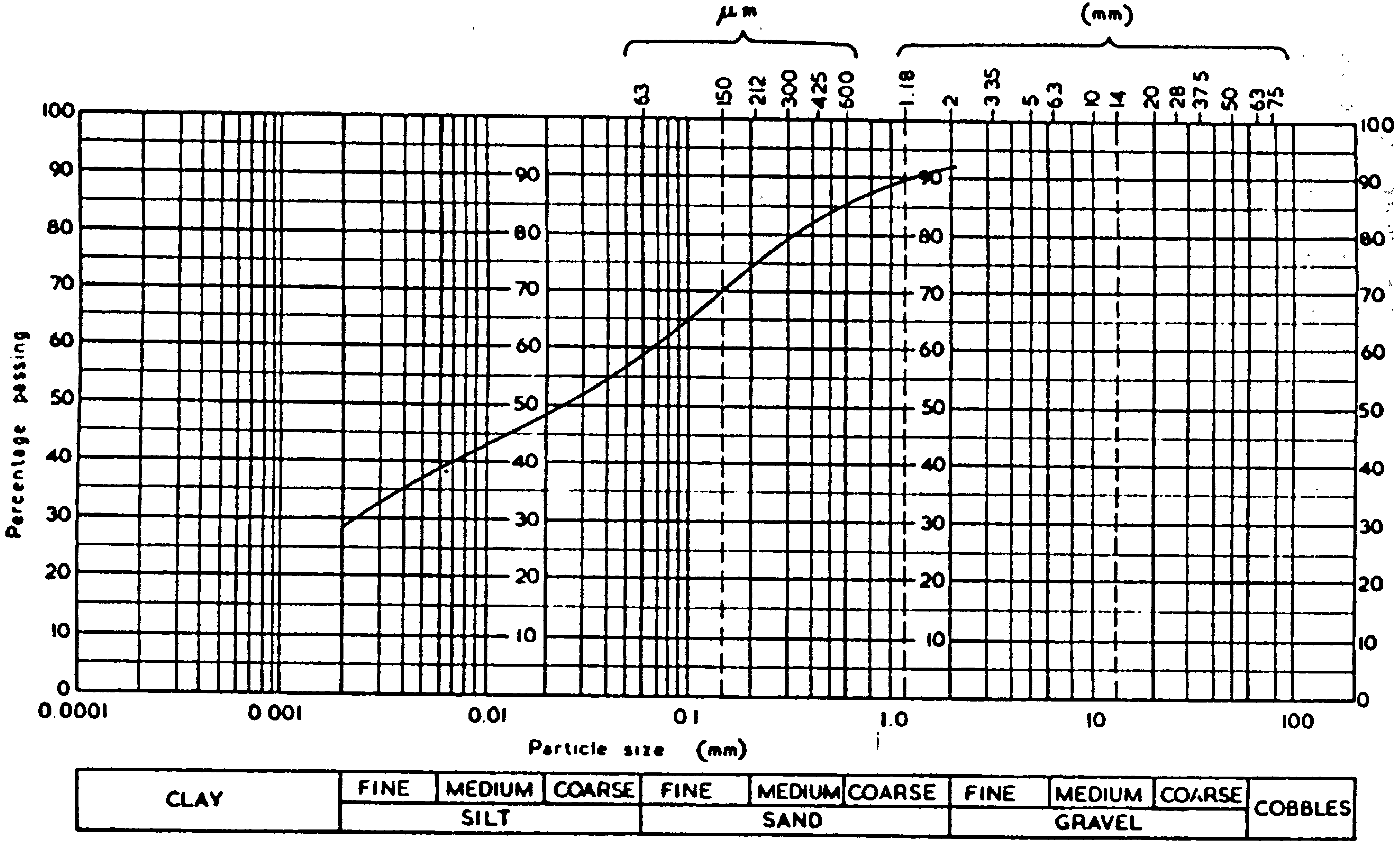


Table 4.6 Contaminant concentrations measured at the soil surface in each column at the start and end of the soil column experiment, also showing the computer predicted results

	Start of expt.		End of expt.		
	% H_2O	Sulphate	% H_2O	Sulphate	Computed
Column 1	15.00	120	7.38	450	334.2
Column 2	14.86	170	10.48	450	325.4
Column 3	15.41	80	8.74	260	303.0
Column 4	19.88	280	11.85	530	418.3
Column 5	19.57	170	15.34	680	425.7
Column 6	20.01	160	10.09	270	367.7

Columns 1-3 contained In-situ Clay
Columns 4-6 contained Eighton Clay

All sulphate values expressed as ppm of dry soil.

computer prediction. Once this is done one can see that in all cases except column 5 the computed figures for contaminant rise are greater than the measured results. Unfortunately, the soil column data from the initial soil samples was not received until after the soil columns had been stripped down, and therefore the initial presence of sulphate in the soils was not detected until it was too late to obtain futher samples. The soil columns do however help to substantiate the validity of the CRISP model, however, in hind sight the author would suggest that it is imperative that multiple samples of soil material are taken at each location in order that a representative figure for contamination can be achieved.

Because of the limited amount of soil column data used to substantiate the validity of the CRISP computer model it was felt that a further independent check of the model was necessary. This was done using the approach detailed by De Latt, (ref 4.8), who showed that by plotting the height of rise of any flux against the water content of a soil, the maximum steady state flux reaching any height in the soil profile can be determined.

A range of suction values were used in the CRISP model, and the model run using the data appertaining to the soils in the Redheugh columns.

The water content of the soil at corresponding suction values was determined from relationship between water content and suction (figures 4.19 and 4.20) for the soil as determined by the filter paper method (see Chapter 6).

The rise of the flux which reached the soil surface was then plotted against the water content of the soil (figure 4.21).

If the soil moisture profiles from the columns are also plotted it can be seen that a flux of 0.005 cm/d would roughly correspond with the soil water profiles. In the gravel material the flux is lower than the water content

Figure 4.19 Suction water content curve for Gateshead Gravel

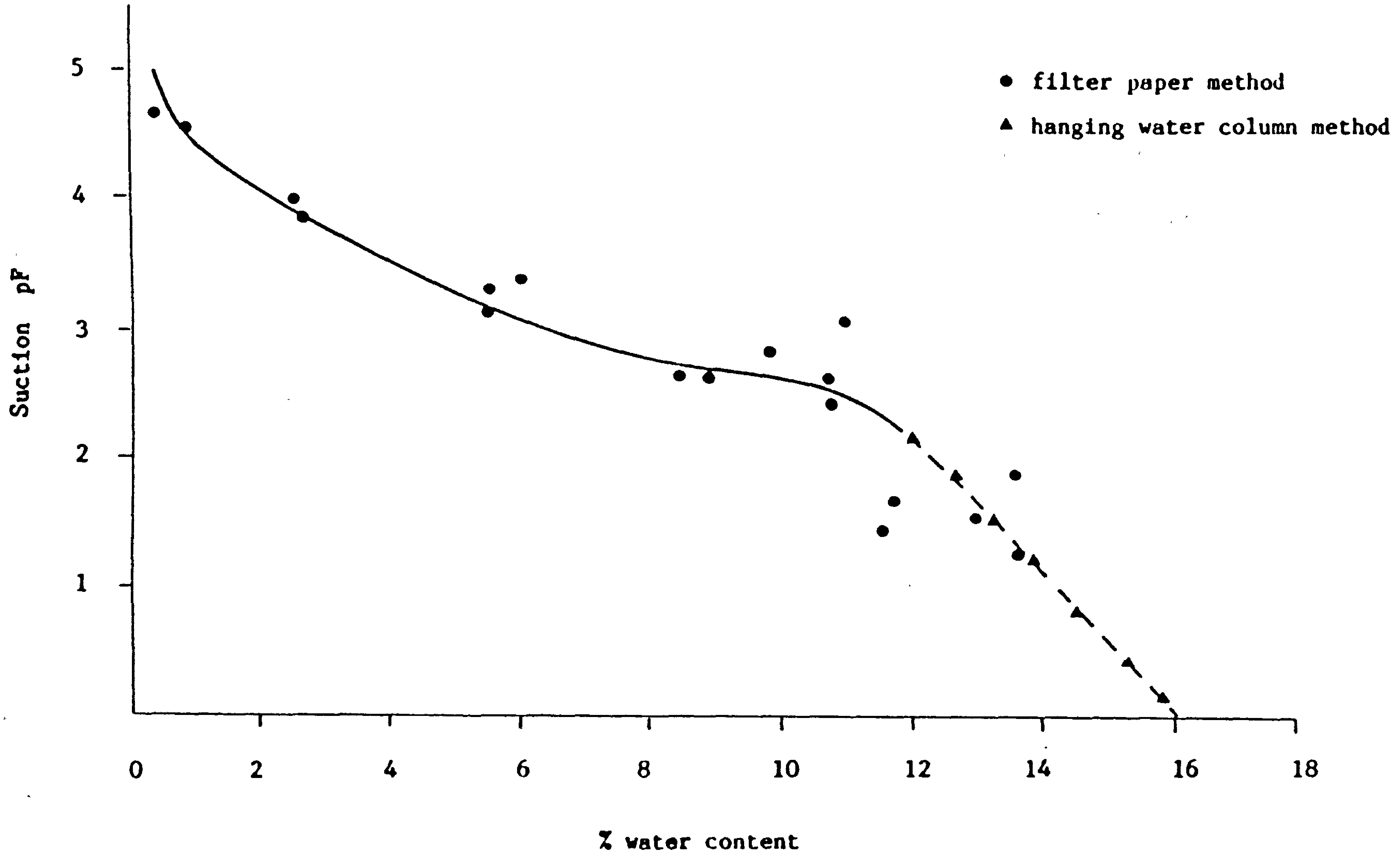


Figure 4.20 Suction water content curve for Downhill Sand

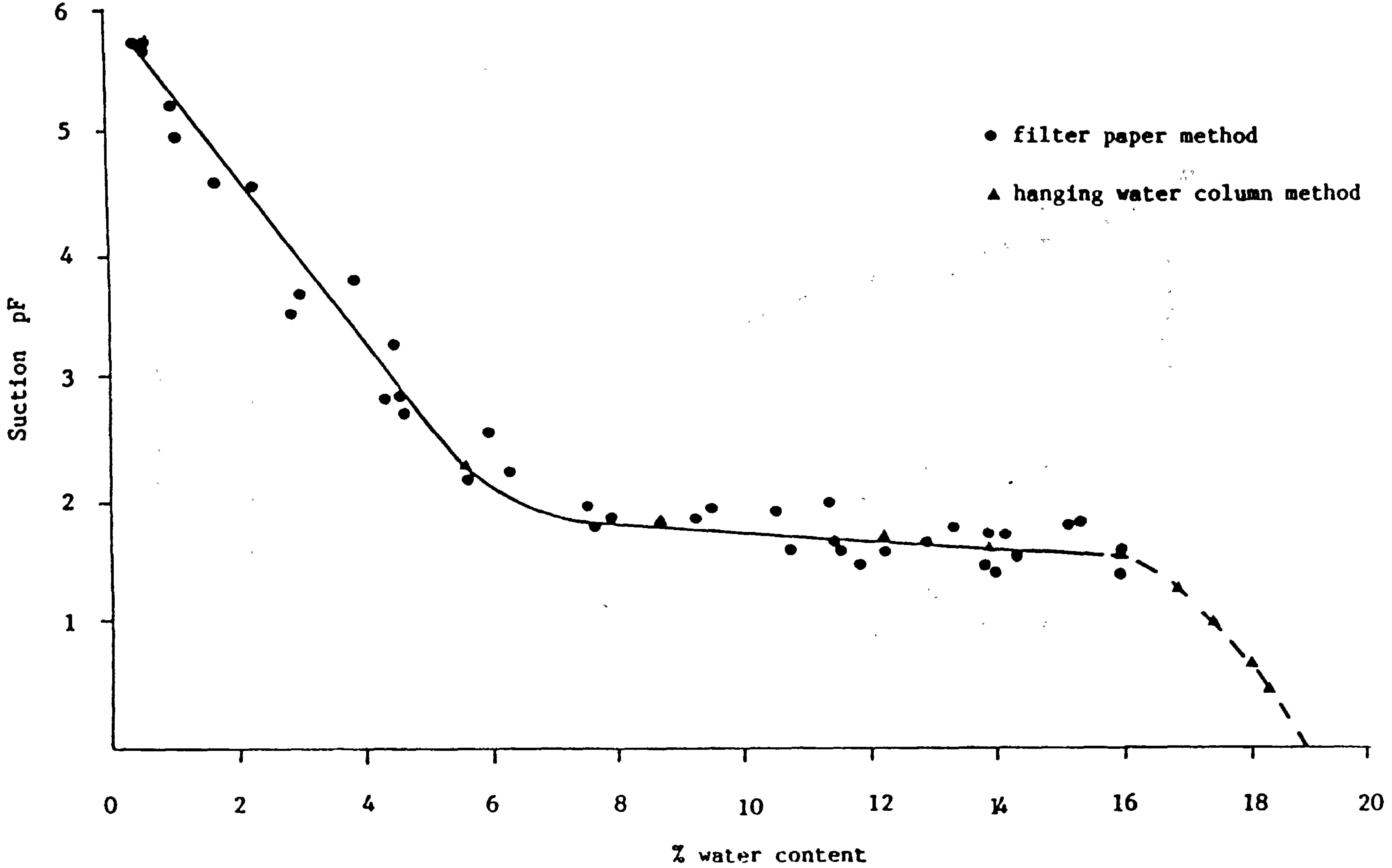
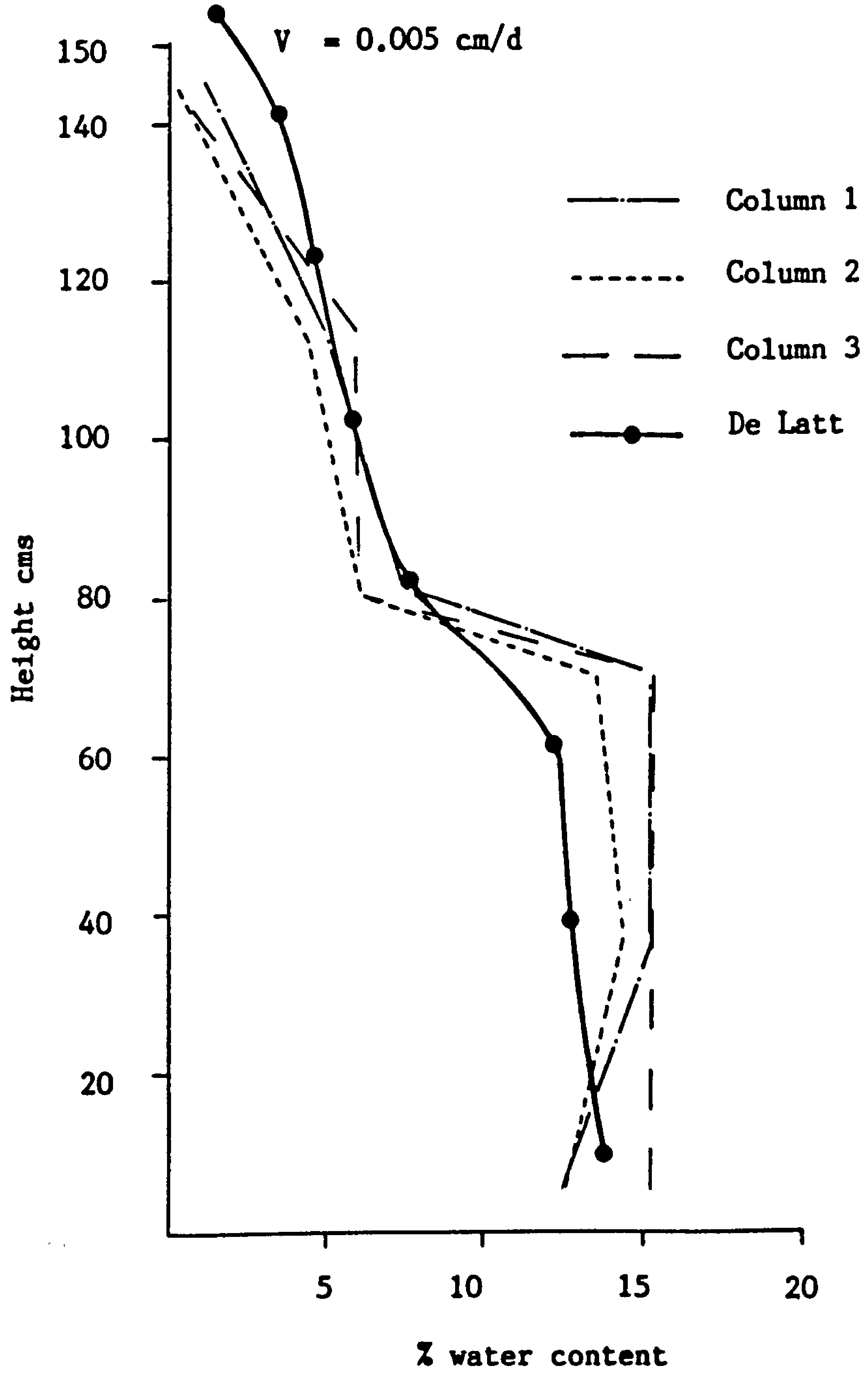


Figure 4.21 Comparison of the soil water content profile of the soil columns with the steady state flux predicted using the De Latt method



curve, this is to be expected as the flux represents the flow of water through the soil however, larger fluxes would be able to rise to these lower levels, so increasing the water content.

At the column surface the flux is slightly higher than the water content graphs, it is possible that this reflects overdrying of the soil surface, or that true steady state conditions were not in operation at the end of the column experiment.

Referring back to the original computer results it can be seen that a flux of 0.005 cm/d arrived at the soil surface, and indeed it was from this flux that the values of dv/dz were obtained.

A final check on the column materials was conducted after completion of the column studies. One soil column was cut in half length - wise to ensure that even packing had been achieved, and that the taking of samples had not interfered with the column structures. The column was found to be in order.

The other two columns were cut into a number of smaller lengths, such that the conductivity of the materials could be assessed. This would ensure that even packing and densities had been achieved, and that the columns were identical.

Minimal variations in conductivity were recorded, and these are not considered to have had any major impact on the column results.

4.5 Conclusion

When analytical values from the soil columns are compared to the output from the CRISP model, an obvious (though not excessive) over prediction is apparent from the computer model.

This probably reflects no more than the deliberate choice of a surface suction for the computer model, despite the fact that this actual suction was not achieved at the soil column surface until a particular state of dryness had been occured and a steady state flux established. This choice was made to reflect the likely attitudes in a commercial design office which would neither have the time or inclination to enter into futher scientific detail.

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4.8 De Latt Development Of A Model For Unsaturated Flow

Chapter Five: Evaluating Hydraulic Conductivity For Input Into The CRISP Computer Model

5.1 Introduction

Knowledge of the relationship between hydraulic conductivity and soil moisture content is a necessary pre-requisite to studying soil moisture flow.
The conductivity function of a soil is controlled by a number of factors including: soil structure, pore size distribution, organic matter content, and the chemical and temperature regimes of the soil.
Because of the difficulties of obtaining accurate replicates of soil structure in the laboratory, field measurements are considered to be the most reliable method of obtaining accurate conductivity data. Field methods are, however, laborious and require expensive instrumentation. There is therefore a need for simple laboratory techniques to accurately determine the relationship between conductivity and moisture content.
Measuring conductivity in the laboratory requires setting up a steady-state (ref 5.1) or a transient-state (ref 5.2) flow system, which are both expensive and time consuming, and are often not representative of soils in their field state.
Alternatively one can measure soil diffusivity and convert it to conductivity from the known relationship between the two (ref 5.3).

A variety of such methods are available (Table 5.1) the Hot Air Method proposed by Arya et al. (ref 5.4) was considered to be the most appropriate for this study because of its attractive simplicity, relatively short experimental time, cost and accuracy in the dry range of soil moisture.

Table 5.1 Methods available for predicting soil conductivity

Method	Range (-cm)	Ref.
Two Plate Method	0 - 700	5.1
Hot Air Method	30 - 10^5	5.4
Infiltration Column	0 - 100	5.5
One-Step Outflow	30 - 800	5.6
Evaporation Method	30 - 800	5.7
Calculation (h - θ_i Poiss)	0 - 10^5	5.8
Sorptivity Method	30 - 400	5.9

(after Bababe, ref. 5.10)

5.2 The Hot Air Method (HAM)

The HAM proposed by Arya et al., 1975, is based on the diffusivity equation of Bruce and Klute, 1956, (ref 5.3) (eq. 5.1).

$$D(\theta_x) = \frac{1}{2t} \frac{dx}{d\theta} \int_{\theta x}^{\theta i} x \frac{d\theta}{\theta x} \qquad \text{eq. 5.1}$$

Where: $D(\theta_x)$ is the diffusivity (cm ^{2}/min)

θ is water content

x is distance from the drying surface (cms)

θ_i is the initial water content

The equation describes one dimensional flow and can be solved for desorption (drying) by applying the following boundary conditions:

$$\theta = \theta_i \qquad t = 0 \qquad x > 0$$

$$\theta = \theta_0 \qquad t > 0 \qquad x = 0$$

Diffusivities calculated from the above equation can be converted to conductivities using equation 5.2

$$K(\theta) = D(\theta) \quad (d\theta/dh) \qquad \text{eq. 5.2}$$

Where: $K(\theta)$ is the hydraulic conductivity and $(d\theta/dh)$ is the slope of the suction water content curve of the soil.

5.2.2 Experimental Procedure

A representative sample of soil material was obtained by riffling and a soil sample tube (10 cms length and 3.8 cms I.D.) packed with the soil to the required density.

The sample was then placed with one end of the tube in contact with a free water surface, and the water level gradually increased until it was level with the surface of the soil, in this way air was driven out of the soil sample, and the sample became fully saturated.

The sample was removed from the water and the ends were sealed. The column was laid on its side to equilibrate and was turned regularly to ensure even distribution of water through out the sample. After twenty four hours the seal at the top of the column was removed and the sample placed on a digital balance (accurate to 0.01 g) and the weight recorded.

A hot air generator was used to blow hot air (approx 100 ^{o}C) across the surface of the column. At 55 second intervals the air current was removed and the weight of the sample recorded, the heating was continued after 5 seconds.

Evaporation was continued as long as the base of the soil column remained saturated and the plot of cumulative evaporation against $\sqrt{t}$ was linear (figure 5.1(a)).

Upon completion of the test the sample was rapidly extruded from the tube and divided into pre - weighed dishes (each slice being approximately 10mm thick). The weight of each sample was recorded the samples were dried and reweighed to obtain the gravimetric water content.

The initial water content of the sample was determined from the cumulative loss of water content from each slice plus the loss of water during evaporation.

The entire operation from extrusion to weighing of the slices took between 6 and 10 minutes depending upon the soil type. It was important to keep sampling time to a minimum in order to restrict redistribution of water through the soil and drying of the sample slices prior to weighing.

Material lost during sampling was negligible (less than 0.8% by weight)

The water content of each slice was plotted against the cumulative distance from the evaporating surface (figure 5.1b) (the distance 'x' was plotted as the centre of each slice), and a smoothed curve drawn.

5.3.1 The Results

The HAM was conducted on each of the four soils which were used in the soil column experiments (Chapter 4). The results obtained (figures 5.2 to 5.5) showed no clear pattern of increasing water content with distance from the drying surface and were therefore considered unsatisfactory.

As all four soils gave unsatisfactory results the test procedure was reviewed, the problems highlighted and the equipment modified as indicated below.

Figure 5.1 Schematic diagram of evaporation during heating (a) and water distribution through the soil profile (b)

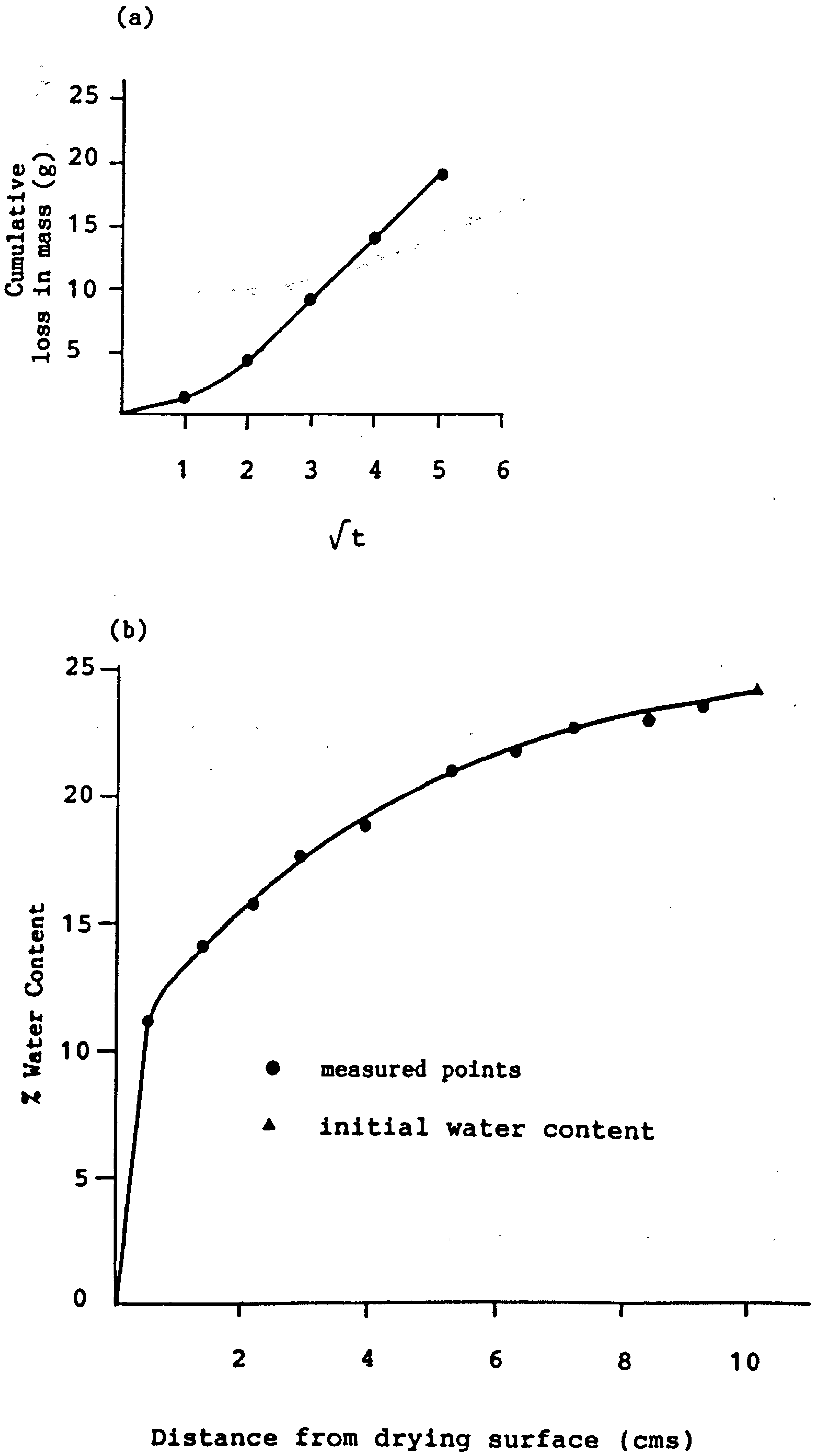


Figure 5.2 Drying pattern and water content distribution for Gateshead Gravel

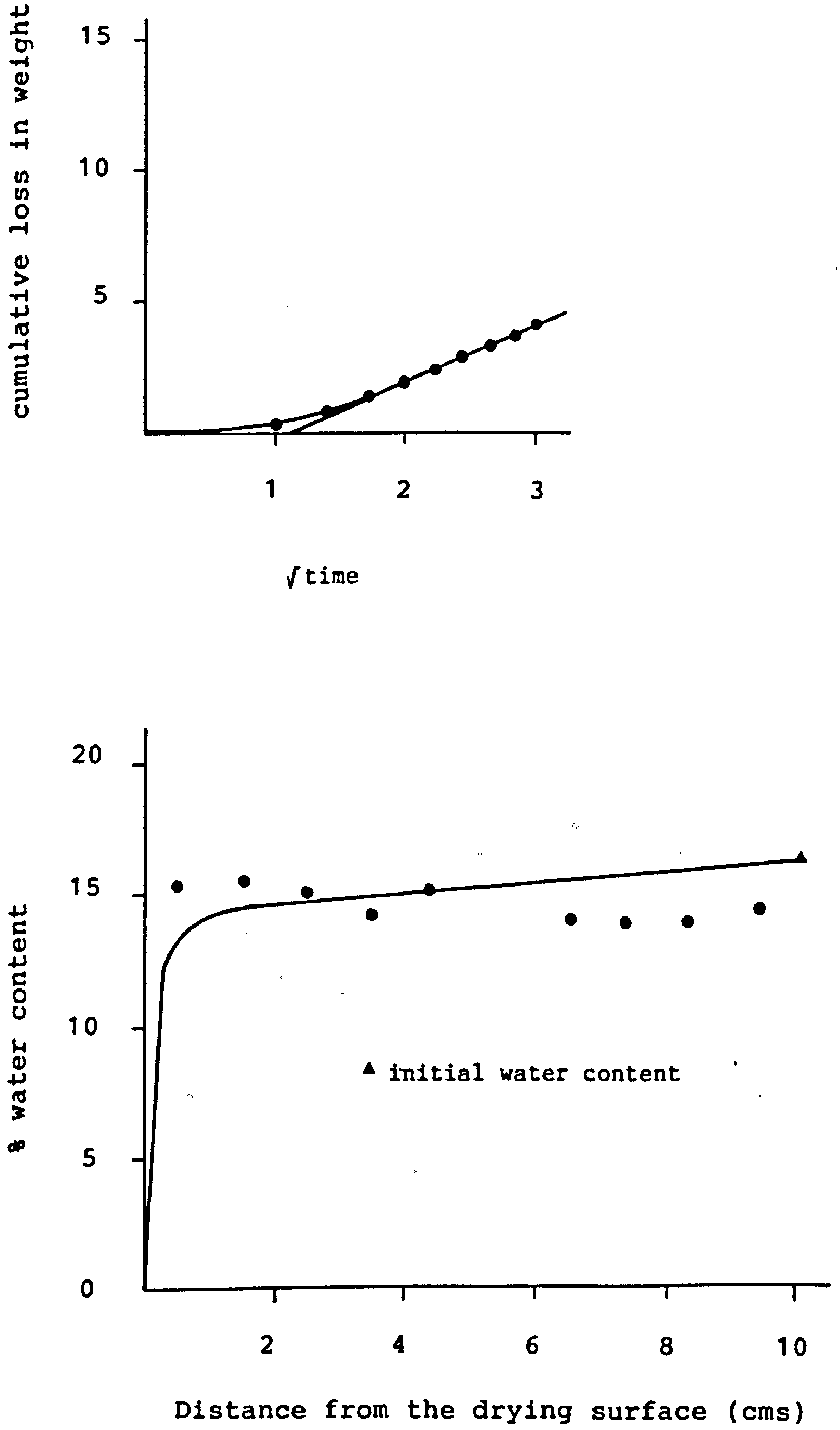


Figure 5,3 Drying pattern and water content distribution for Downhill Sand

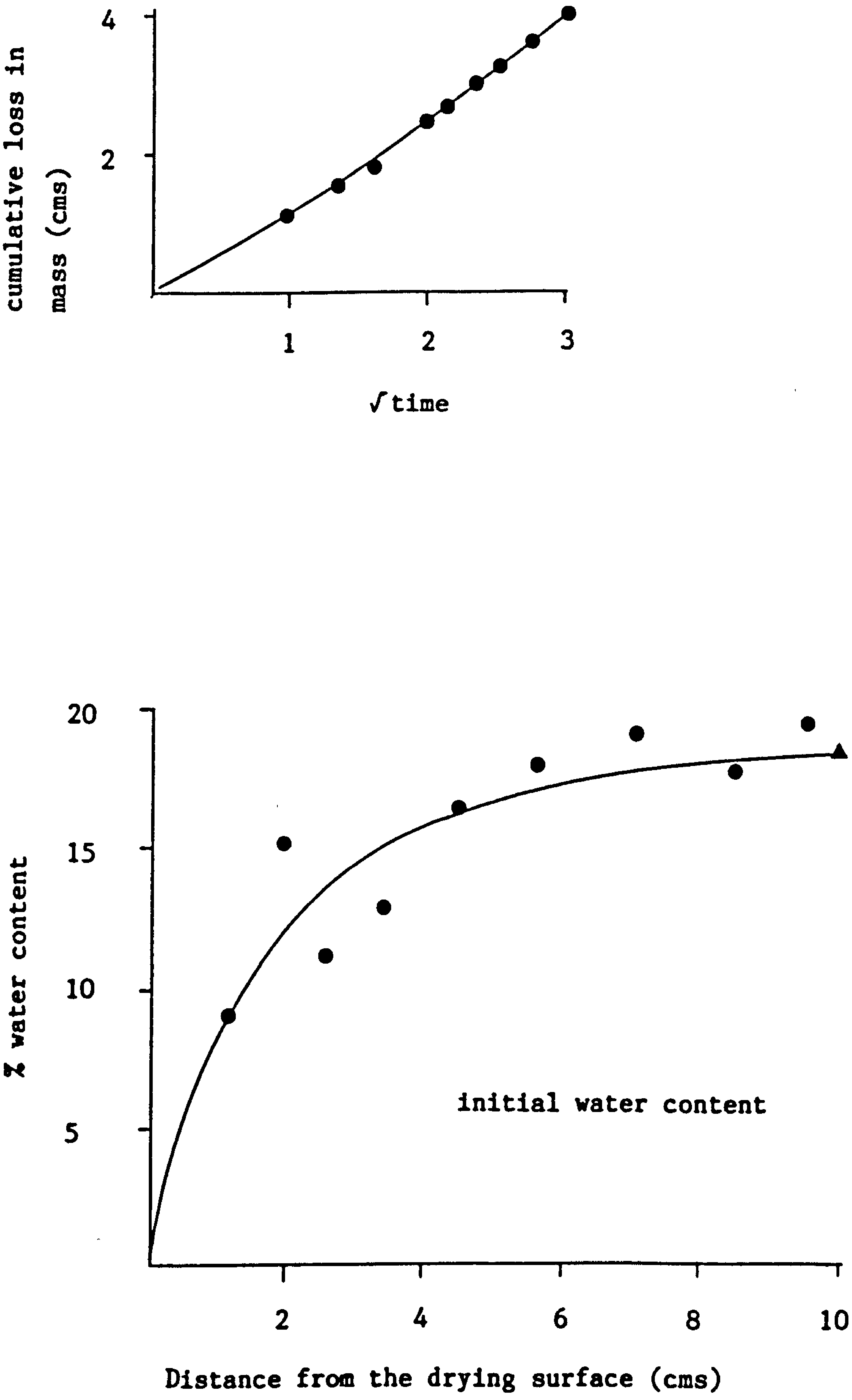


Figure 5.4 Drying pattern and water content distribution for Eighton Clay

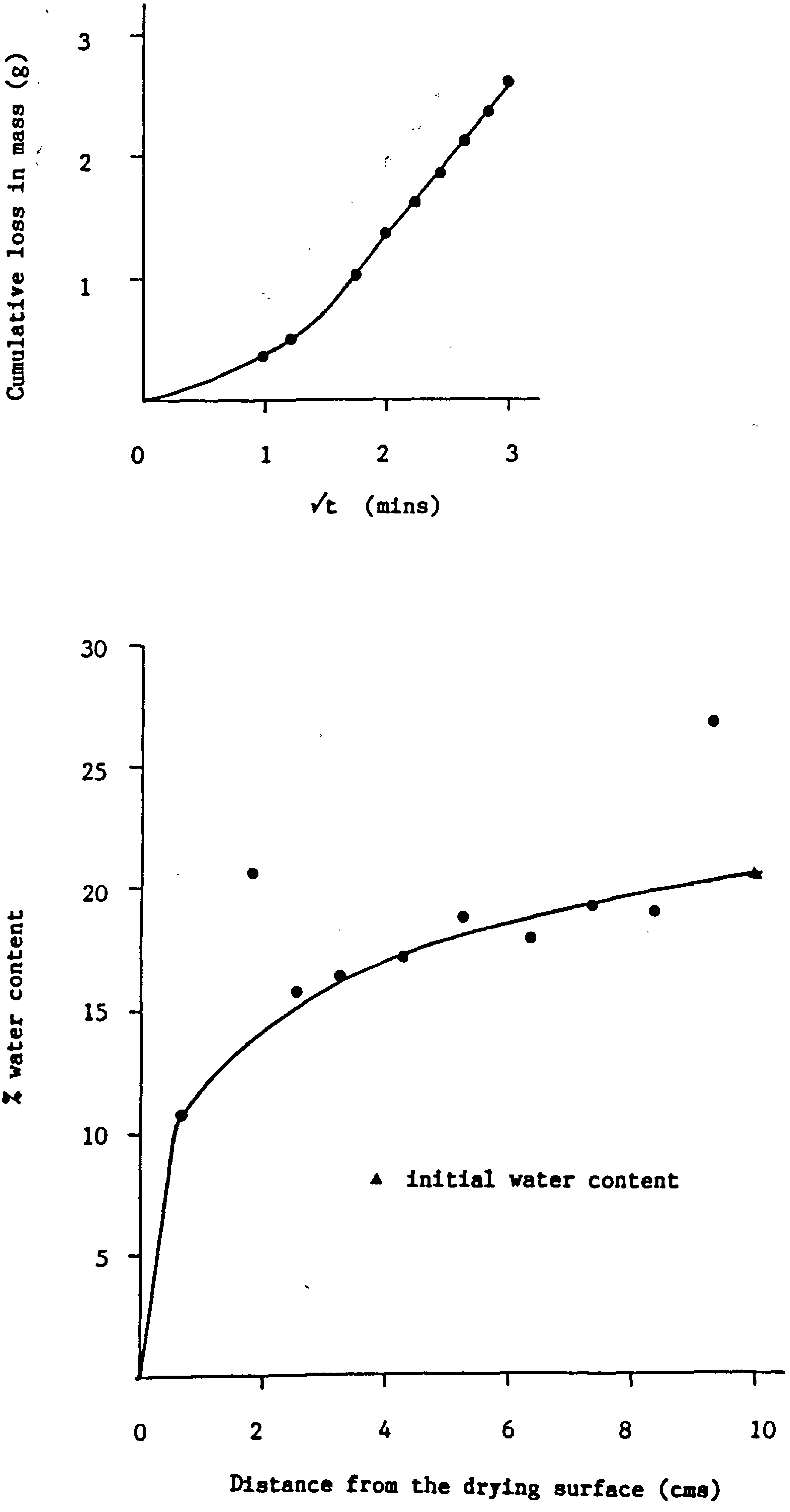
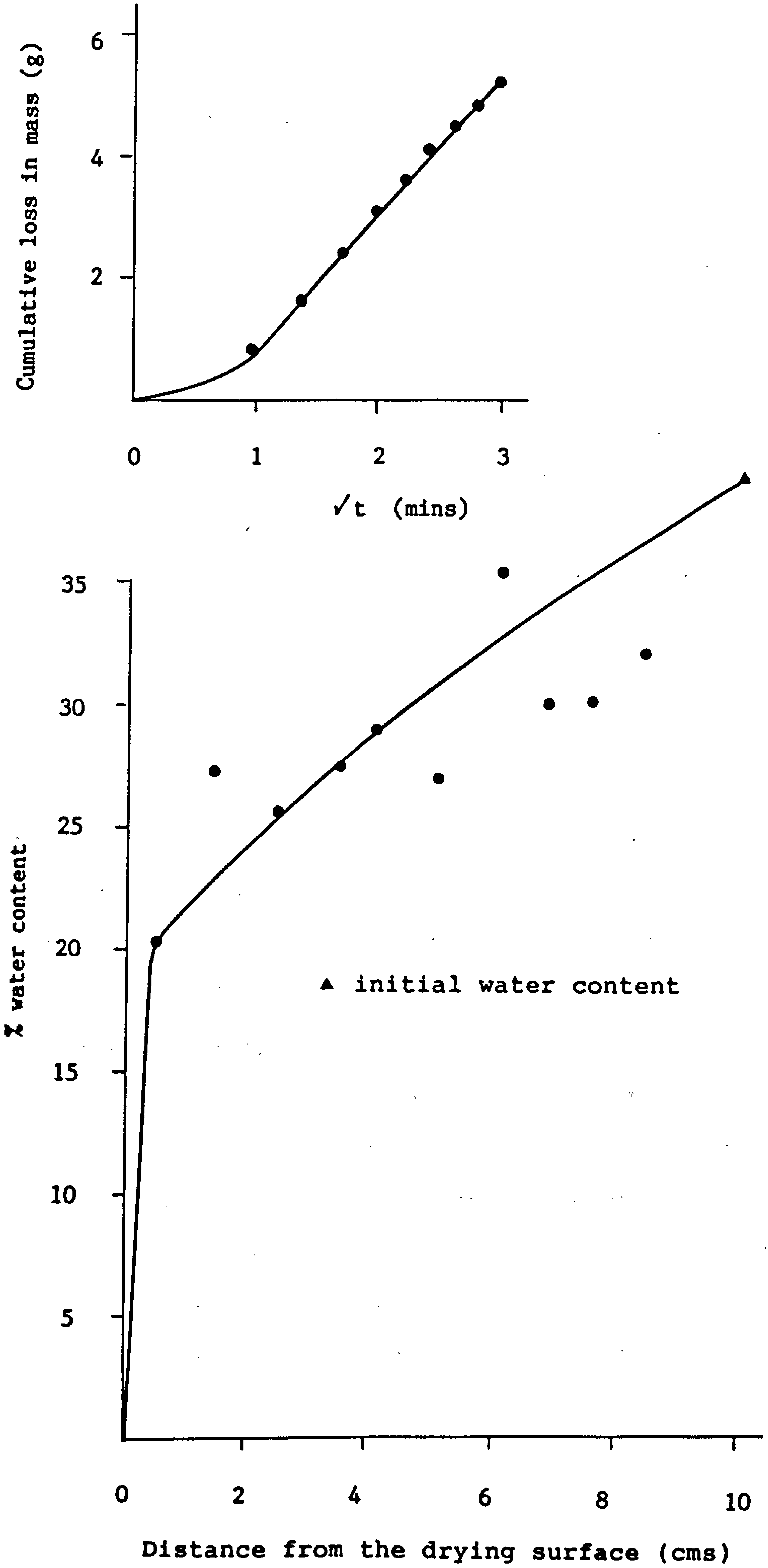


Figure 5.5 Drying pattern and water content distribution for In situ Clay



5.4 Modification Of The Equipment

A number of problems were encountered with the above procedures:

One of the main problems with calculating conductivity values from HAM is it is difficult to obtain replicate results. This is partly due to the heterogeneous nature of soil materials, and the difficulty in obtaining replicate samples.

The initial water content of samples frequently differs, and therefore the drying pattern and diffusivities of replicate columns can differ slightly.

Samples packed at high densities (i.e. the Gateshead Gravel), or samples with a large fine fraction (clays) proved to be very difficult to extrude and frequently took considerably longer (15 to 20 minutes) than was acceptable. It was felt that during this time some redistribution of soil moisture would occur in the column, leading to erroneous results.

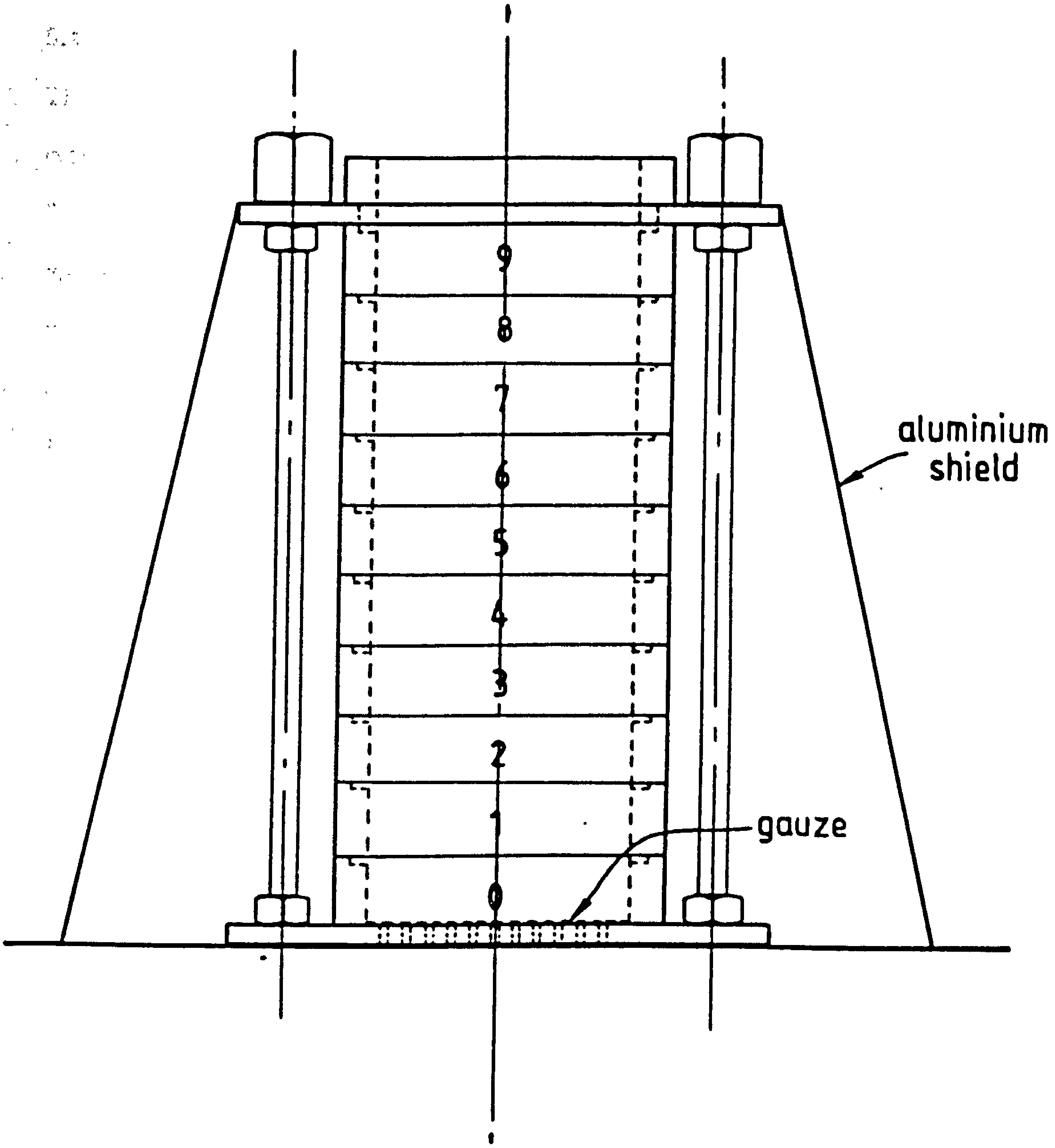
Quite a lot of force was required to extrude the sample. This appeared to force moisture from the base of the sample into subsequent layers, thus the base of the sample was often found to be below the initial water content, whilst subsequent slices had moisture contents in excess of that of the last slice.

The hot air current heated the side of the column and in some cases caused the soil to become warm (especially where drying times exceeded 15 minutes). This could produce thermal currents within the soil and so lead to erroneous results.
Where coarse sands or gritty materials were tested the surface materials were blown away by the force of the hot air current as the soil surface dried.

A modification of the sample tube was required to reduce errors incurred during the experiment.
A sample tube consisting of ten interlocking rings was developed. The rings were held together with an easily removable clamp (figure 5.6), during packing and testing. Upon completion of the test the clamp was quickly removed and the sample tube divided into its ten sections.

A further modification was to shield the sides of the column from the effects of the hot air generator by surrounding the column with an aluminium shield, thus preventing heating of the column sides and the soil within and therefore reducing thermal currents in the soil.
An extra ring was placed above the soil sample to prevent the surface materials being blown away by the force of the hot air current.
This new tube proved to be much more satisfactory, and

Figure 5.6 Modified apparatus for the hot air method



enabled extrusion and weighing time to be reduced to less than five minutes.

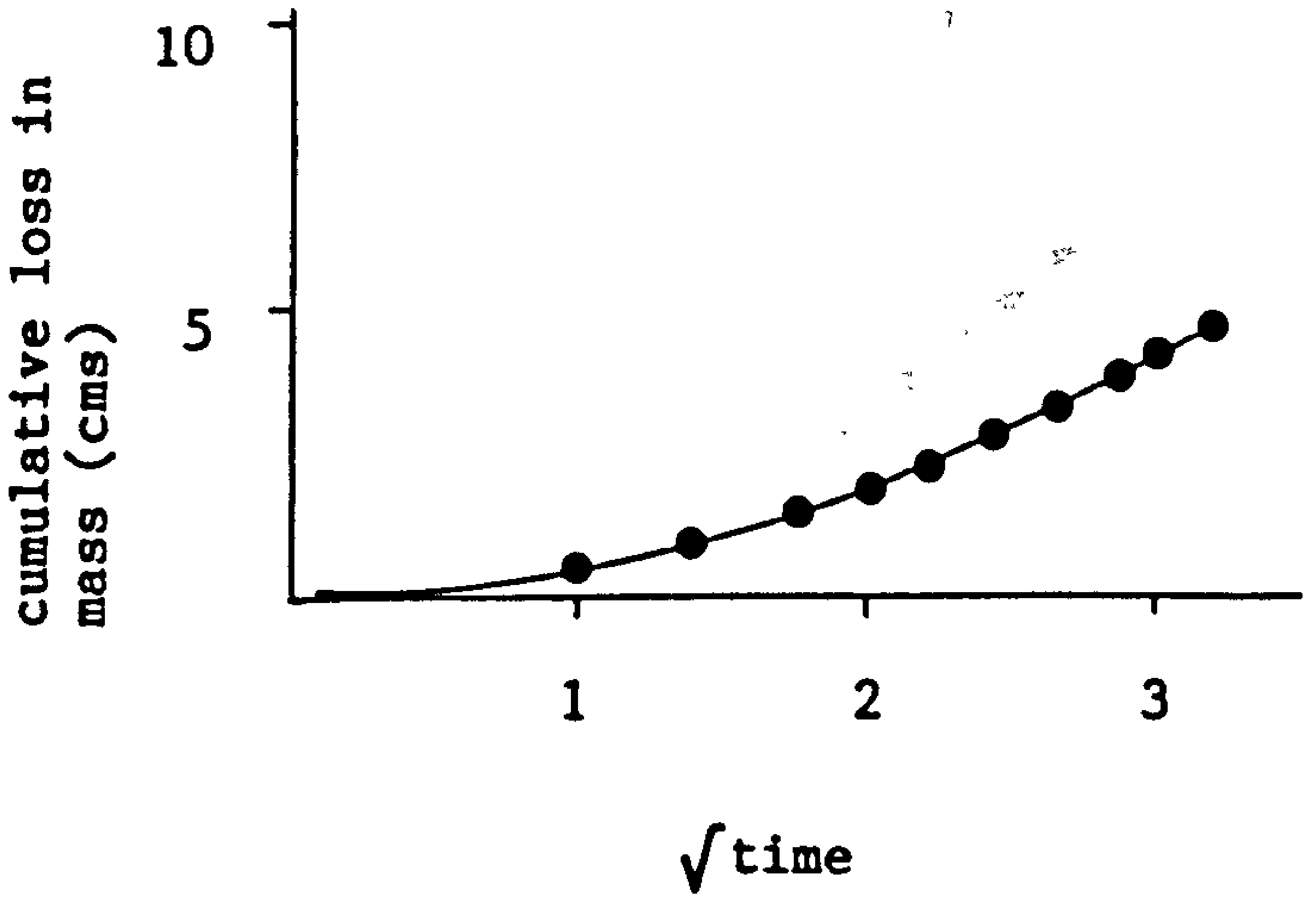
Replicate tests yielded much closer results and the arithmetic mean of each set was taken as the correct value.

5.4.2 The Results

The results obtained for each of the soils using the modified equipment are recorded in figures 5.7 to 5.10. Five replicate tests were conducted on each of the soil materials, these revealed that the water content distribution through each soil sample was accurate to + or - two percent (figure 5.11)

These results are much improved, and make the determination of the position of the curve d0/dh more obvious.

Figure 5.7 Drying pattern and water content distribution for Gateshead Gravel - improved procedure



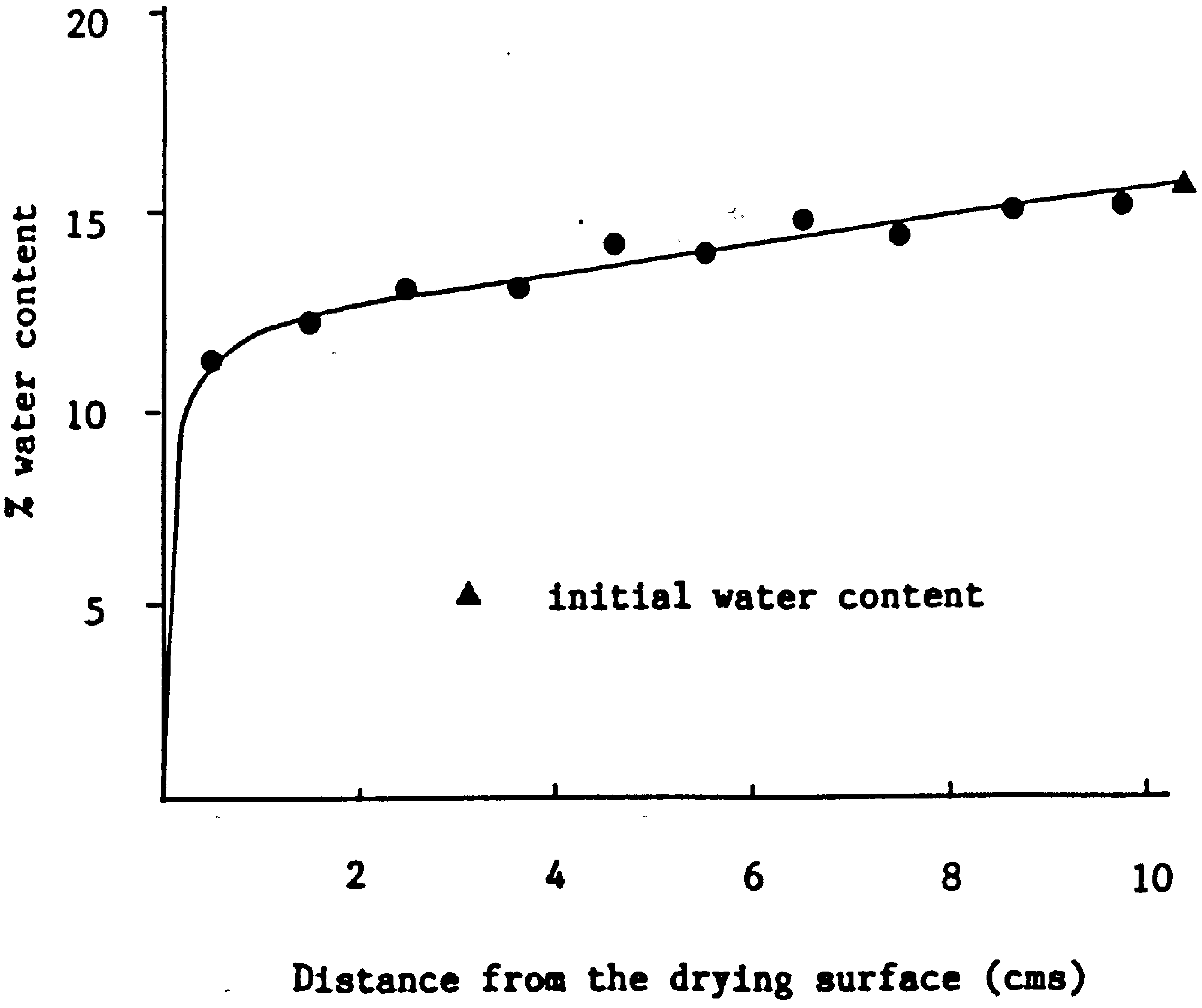


Figure 5.8 Drying pattern and water content distribution for Downhill Sand - improved procedure

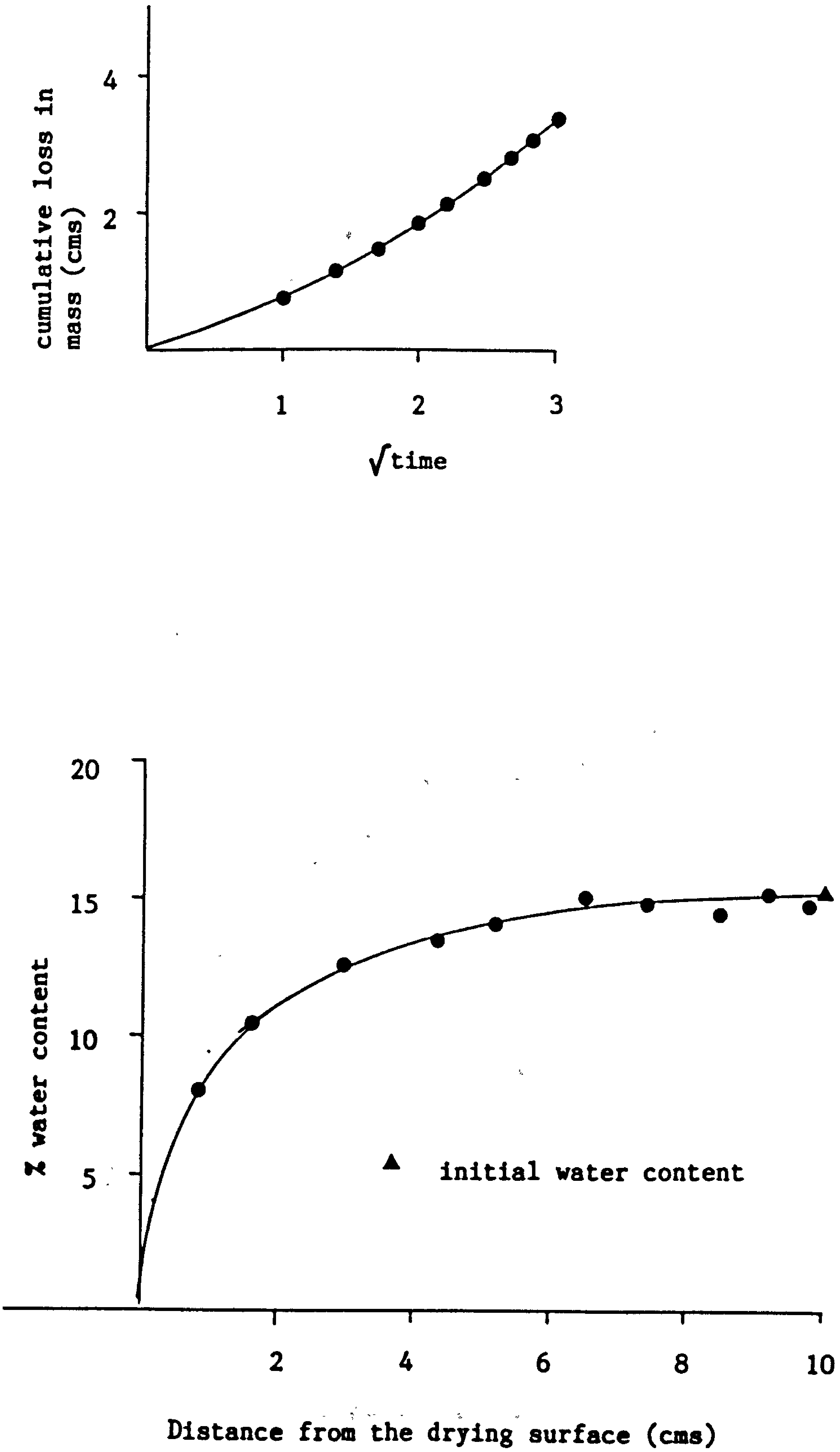


Figure 5.9 Drying pattern and water content distribution for Eighton Clay - improved procedure

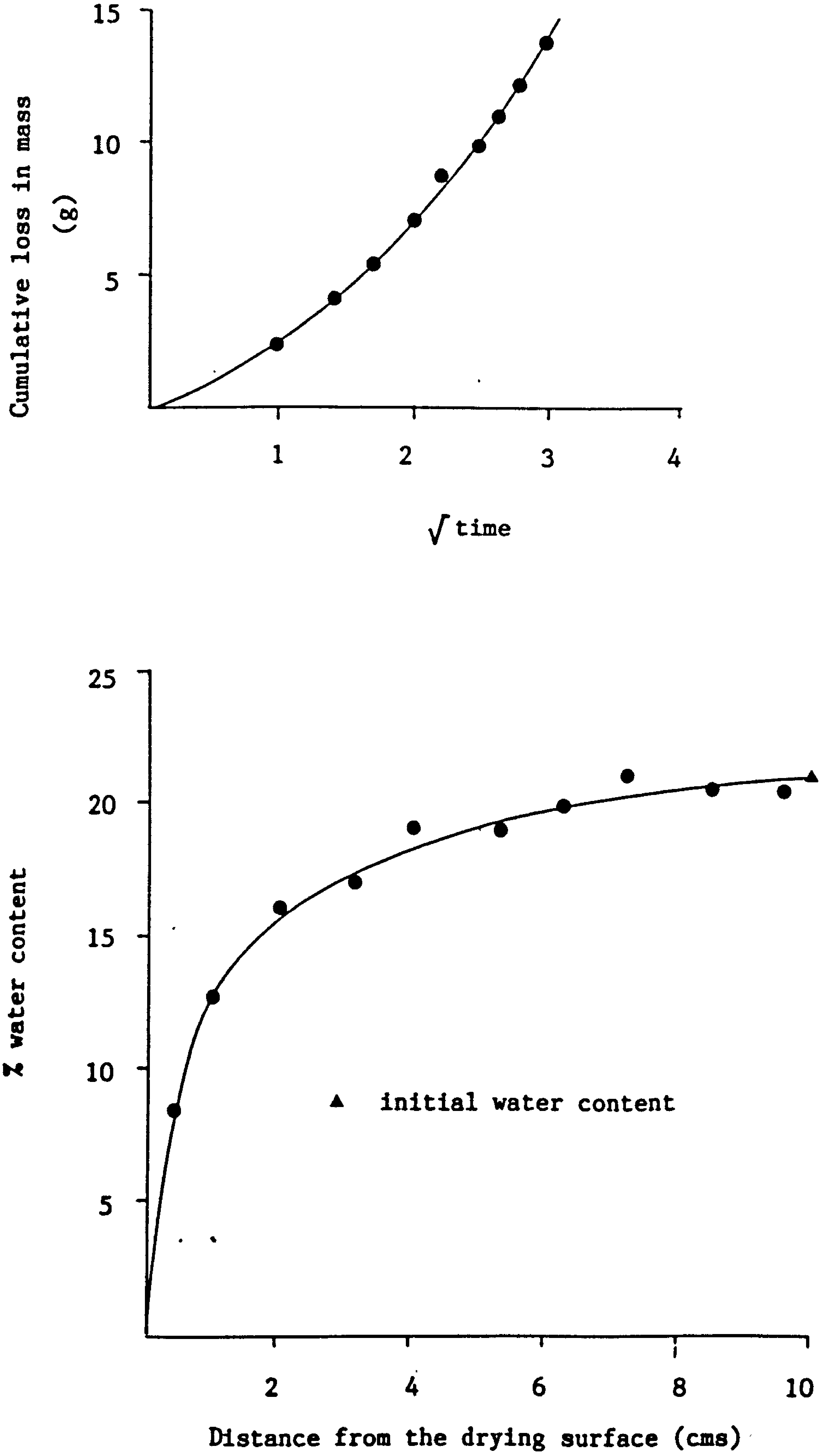


Figure 5.10 Drying pattern and water content distribution for Insitu Clay - improved procedure

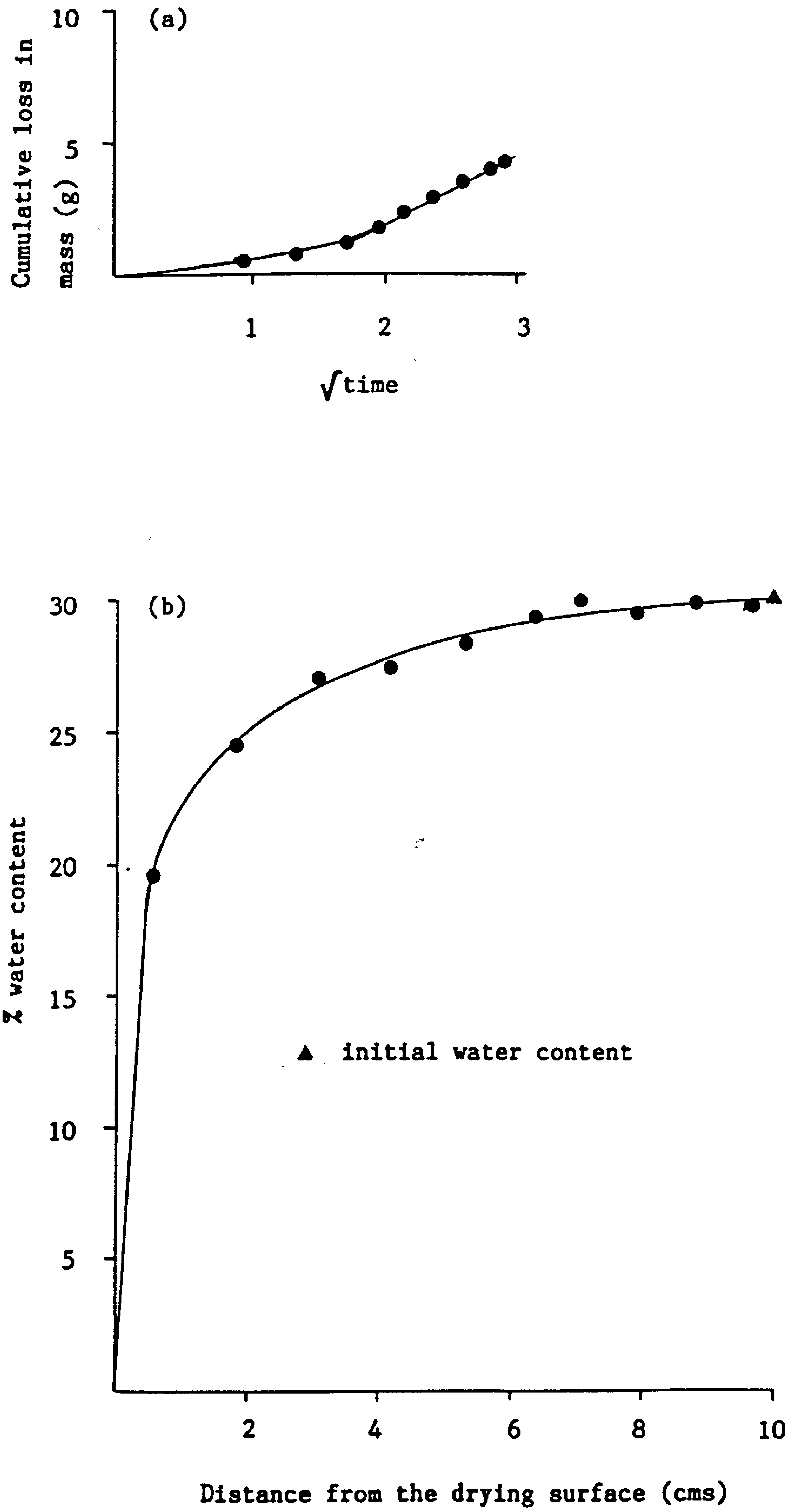
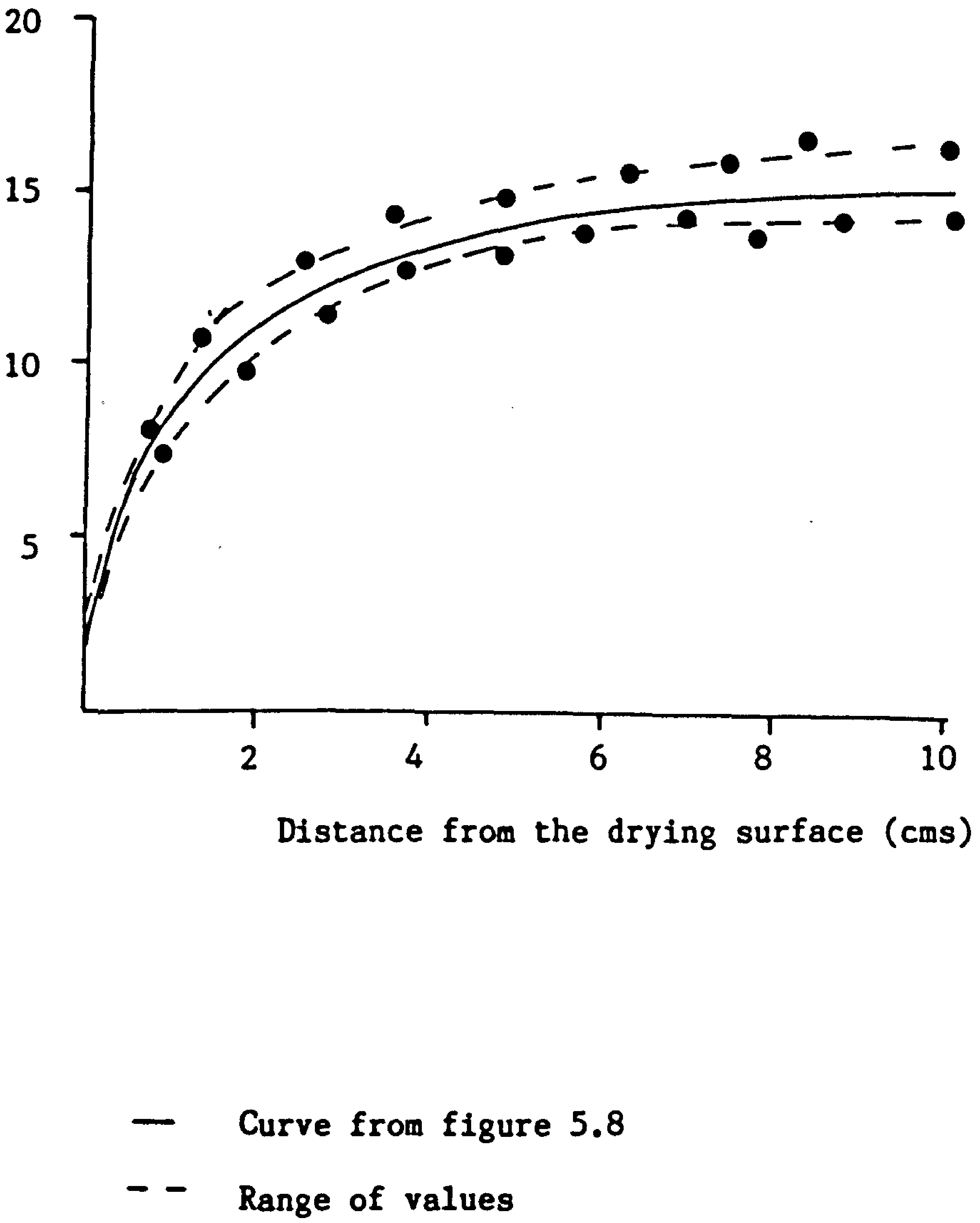


Figure 5.11 Repeatability of results (Downhill Sand)



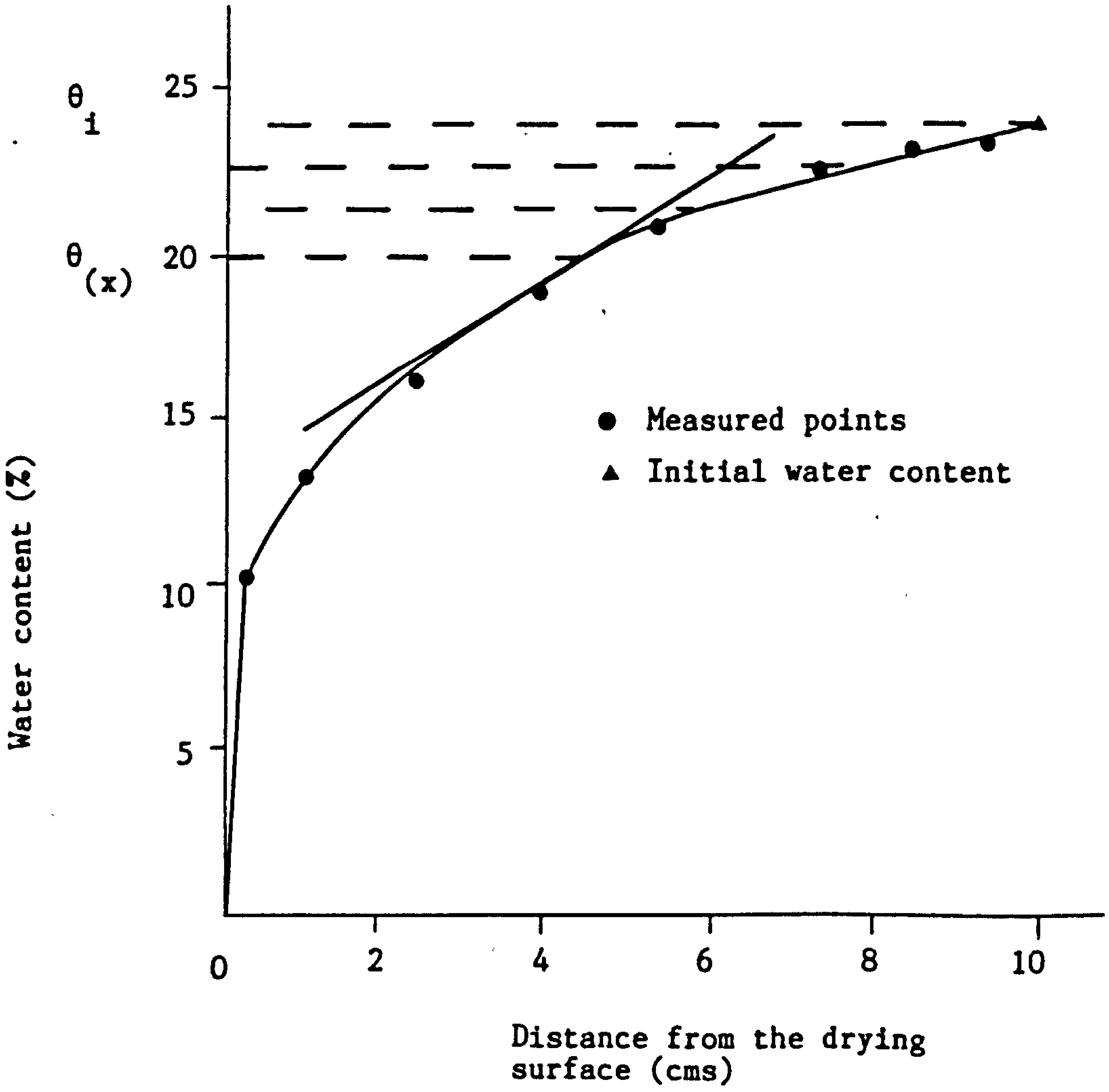
5.5 Calculation Of Diffusivity

From the graph of water content versus distance from the drying surface the term $dx/d\theta$ and the integral $xd\theta$ can be evaluated. where: $dx/d\theta$ is the gradient of the tangent to the curve at water content θ and $xd\theta$ is the area bounded by the curve and the 'Y' axis (figure 5.12).

Diffusivities were then calculated from equation 5.1 (where 't' is the length of time for which the soil column was heated) and converted to conductivity values using equation 5.2. (for suction water content data see Chapter 6).

The relationship between water content and hydraulic conductivity for each of the four soils are given in tables 5.2 to 5.5 for the four soils used in the soil column studies in Chapter 4.

Figure 5.12 Calculation of the terms $\int x \partial\theta$ and $\frac{\partial x}{\partial\theta}$ from the graph of diffusivity



The shaded area represents the integral of $\theta_{(x)}$ and θ_i

The tangent of the curve represents $\frac{\partial x}{\partial\theta}$

Table 5.2 Conductivity - Water content Relationship for Gateshead Gravel

Water Content (%)	Conductivity (cm/d)
2	4.49×10^{-5}
4	1.00×10^{-3}
6	4.32×10^{-3}
8	1.67×10^{-2}
10	1.48×10^{-1}
12	0.91

Table 5.3 Conductivity - Water content Relationship for Downhill Sand

Water Content (%)	Conductivity (cm/d)
2	3.75×10^{-3}
4	1.37 x 10-2
6	2.00×10^{-2}
8	0.467
10	0.882
12	3.97
14	5.48

Table 5.4 Conductivity - Water content Relationship for Eighton Clay

Water Content (%)	Conductivity (cm/d)
5	2.25×10^{-5}
10	5.60×10^{-4}
15	2.04×10^{-2}

Table 5.5 Conductivity - Water content Relationship for In-Situ Clay

Water Content (%)	Conductivity (cm/d)
5	1.00×10^{-6}
10	3.01×10^{-5}
15	2.56×10^{-4}
20	7.22×10^{-3}
25	1.25×10^{-1}
30	3.40

These values will be used in the following chapter to determine the suction - conductivity relationship of the soils.

5.6 Conclusion

No attempt was made to compare the results obtained from the hot air method with any other method for predicing unsaturated hydraulic conductivity. Bababe, (ref 5.10) however, compared the method with the One- step outflow method (ref. 5.6) showing that there was "reasonable alignment between the two methods..."

In conclusion one can sat that the hot air method (ref. 5.4) is a simple laboratory test which produces repeatable results, and is both rapid and inexpensive to run.

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Chapter Six: Determining Soil Suction For Input Into The CRISP Computer Model

6.1 Introduction

Soil suction is the ability of a drying soil to attract water molecules from wetter horizons in the soil profile.

Knowledge of the suction - water content relationship of a soil is necessary for calculating capillary rise of soil water.

A number of methods are available for determining this relationship, (table 6.1) however, many methods can only be applied to a limited suction range, some are difficult to set up, or are expensive and time consuming to operate, and are often not applicable to field situations.

The filter paper method does however overcome most of these limitations (ref 6.11), but, despite its simplicity the literature offers very few accounts of its use.

The filter paper method was first recorded in 1937 by Gardner (ref 6.4), who used a single filter paper sandwiched between two layers of soil to determine matrix potential.

The underlying assumption of the method is that as the filter paper and soil come into equilibrium their matrix potentials are equal. By obtaining a calibration curve for the filter paper of water content against matrix potential it is possible to determine the soils suction value.

Table 6.1 Methods available for determining soil suction

Method	Range (bars)	Reference
Hanging Water Column	0 - 1	6.1
Pressure Plate	0 - 1	6.2
Pressure Membrane	0 - 15	6.3
Filter Paper Method	0 - 1000	6.4
Tensiometer	0 - 1	6.5
Moisture Cell	0.3 - 20.38	6.6
Psychrometer	1 - 81.5	6.7
Salt Solutions	15 - 1000	6.8
Sand Box	0 - 0.5	6.9

Gardner, 1937, determined a calibration curve for Schleicher Schuell No. 589 White Ribbon filter papers using sulphuric acid in an evacuated chamber for low water potentials and centrifugal forces for high water potentials.

In 1968, Mc Queen and Miller (ref 6.10) obtained a more complete calibration curve (using a variety of techniques) for the filter papers which showed that part of Gardner's curve was incorrect.
They also modified the method, placing a filter paper on the soil surface, rather than sandwiching it between two layers of soil, and noted that a filter paper in good contact with the soil measures matrix potential, whilst a filter paper placed in a closed chamber with the soil, but not in contact with it measures both matrix and osmotic potential. All samples were held at a constant temperature of 20 °C, and left to equilibrate for one week. They concluded that their method gave results over the entire range from air dry to fully saturated.

The method was further investigated by Al Khafaf and Hanks, 1974, (ref 6.11) who showed that values for both matrix potential and osmotic potential could be obtained from the same sample. By placing one filter paper below the soil sample i.e. in good contact, and one paper suspended just above the soil surface, i.e. no contact.
All samples were held at a constant temperature and equilibration times reduced to two days.
Their work also showed that whilst absolute temperature was not important, temperature variations produced erratic results.

A different brand of filter papers, Whatman No. 42, were investigated by Fawcett and Collis-George, 1967, (ref 6.12), Hamblin, 1981, (ref 6.13) and Chandler and Gutierrez, 1986, (ref 6.14). Despite the variety of techniques used by these workers to calibrate the filter papers all three curves show good agreement.
A calibration curve for Whatman No. 42 filter papers was determined by workers at Liverpool Polytechnic using a number of methods including, pressure plate, pressure membrane, hanging water column apparatus and osmotic solutions. The curve obtained shows good agreement with those obtained by previous workers.

Prior to Hamblins' work in 1981 all filter papers had been treated with various substances to prevent microbial decomposition during the equilibrium period. Investigating the effect of treated and non treated filter papers on the calibration curve Hamblin concluded that treatment did not affect the calibration and was therefore not necessary where equilibrium times were short.

Chandler and Gutierrez critically reviewed the filter paper method suggesting that care must be taken not to compress the filter paper as this restricts water uptake and can result in overestimates of some 1000cms of water suction being produced, (ref 6.14). They also concluded that the method was only accurate between pF 2.8 and pF

4.8 (where pF is the negative log of cms of water head), however they acknowledge that this is still a much greater range than any other single technique.
This range is also adequate for the suctions likely to occur in the UK during drought/drying conditions.

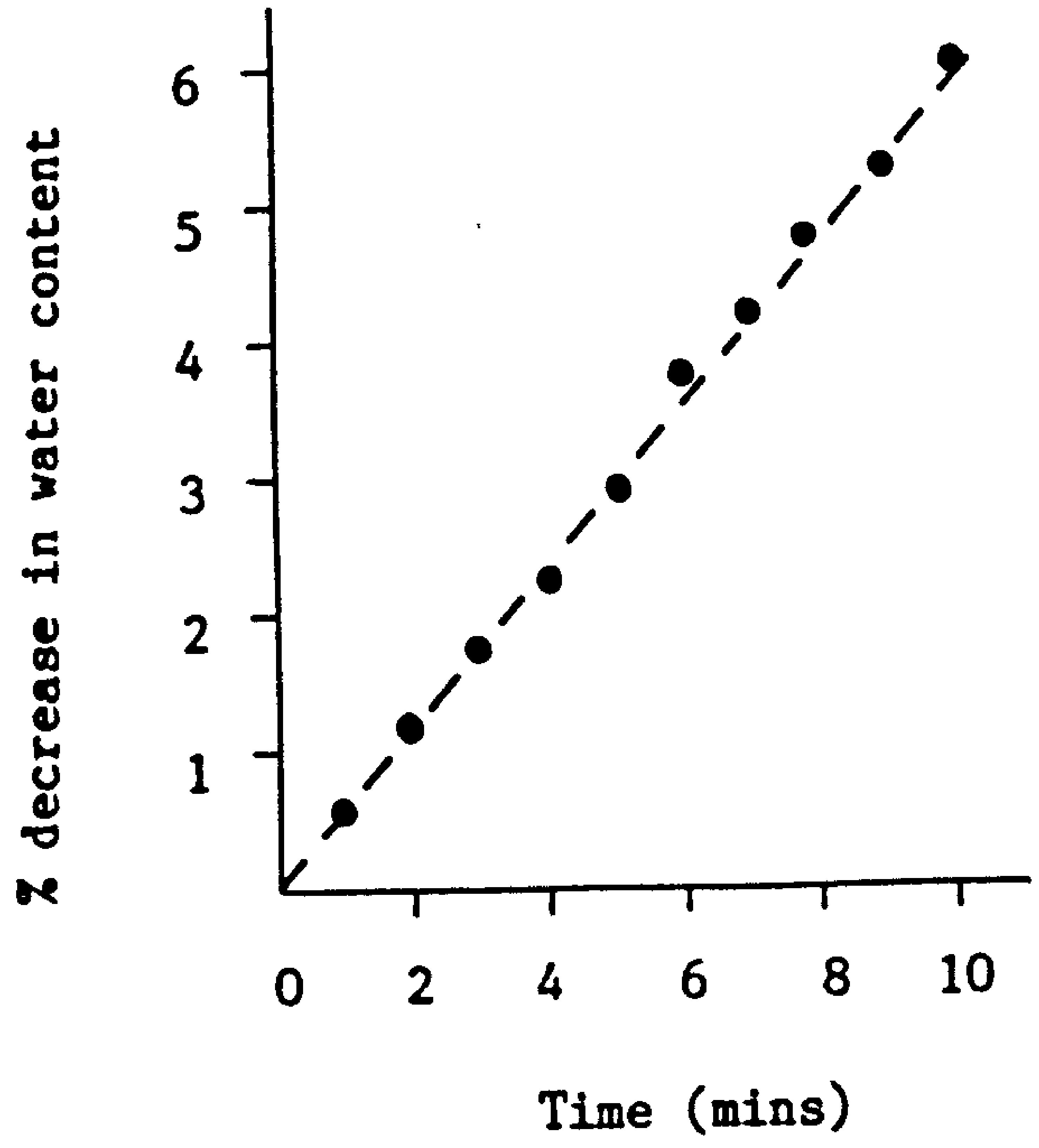
6.2 Materials and Method

A representative sample of soil at a known water content is packed into a soil water content tin (approx 100 mm diameter x 20 mm depth) at a given density. Three Whatman No. 42 filter papers are sandwiched in the centre of the sample (the two outer papers are used to prevent soil particles sticking to the central filter paper). The tin is sealed and placed in a constant temperature environment to equilibrate (5 to 7 days). After equilibration the tin is opened and the central filter paper removed with forceps, and accurately weighed to 0.001g, this stage is done as quickly as possible as evaporation from the filter paper occurs almost instantly (figure 6.1). The filter paper is then dried in the microwave oven and the water content determined.

A sample of soil is taken from each of the two soil layers and the average water content determined.
The soil suction corresponding to the water content of the filter paper is determined from the filter paper

calibration curve, and this is then plotted against the water content of the soil. By repeating the method for a range of soil water contents it is possible to construct the suction water content curve for the soil.

Figure 6.1 Evaporation from a filter paper left in the laboratory atmosphere



6.3 Results And Discussion

A suction water content curve was determined for each of the soils already discussed in chapter four. In order to ensure accuracy three to five replicate tests were conducted at each water content value. These results are recorded in figures 6.2 to 6.5, where no attempt is made to distinguish between results from individual filter paper tests, since the results produced proved to be remarkably consistent.

From the results it can be seen that the spread of points for all of the soils, except Downhill Sand, becomes quite variable at values less than pF 2 / pF 2.5 as suggested by Chandler and Gutierrez, however no such discrepancies occurred at values greater than pF 4.8. An alternative method was therefore required to accurately determine the lower suction values of the curve. The hanging water column experiment was chosen for this purpose because of its attractive simplicity and low cost.

Figure 6.2 Suction water content curve for Gateshead Gravel

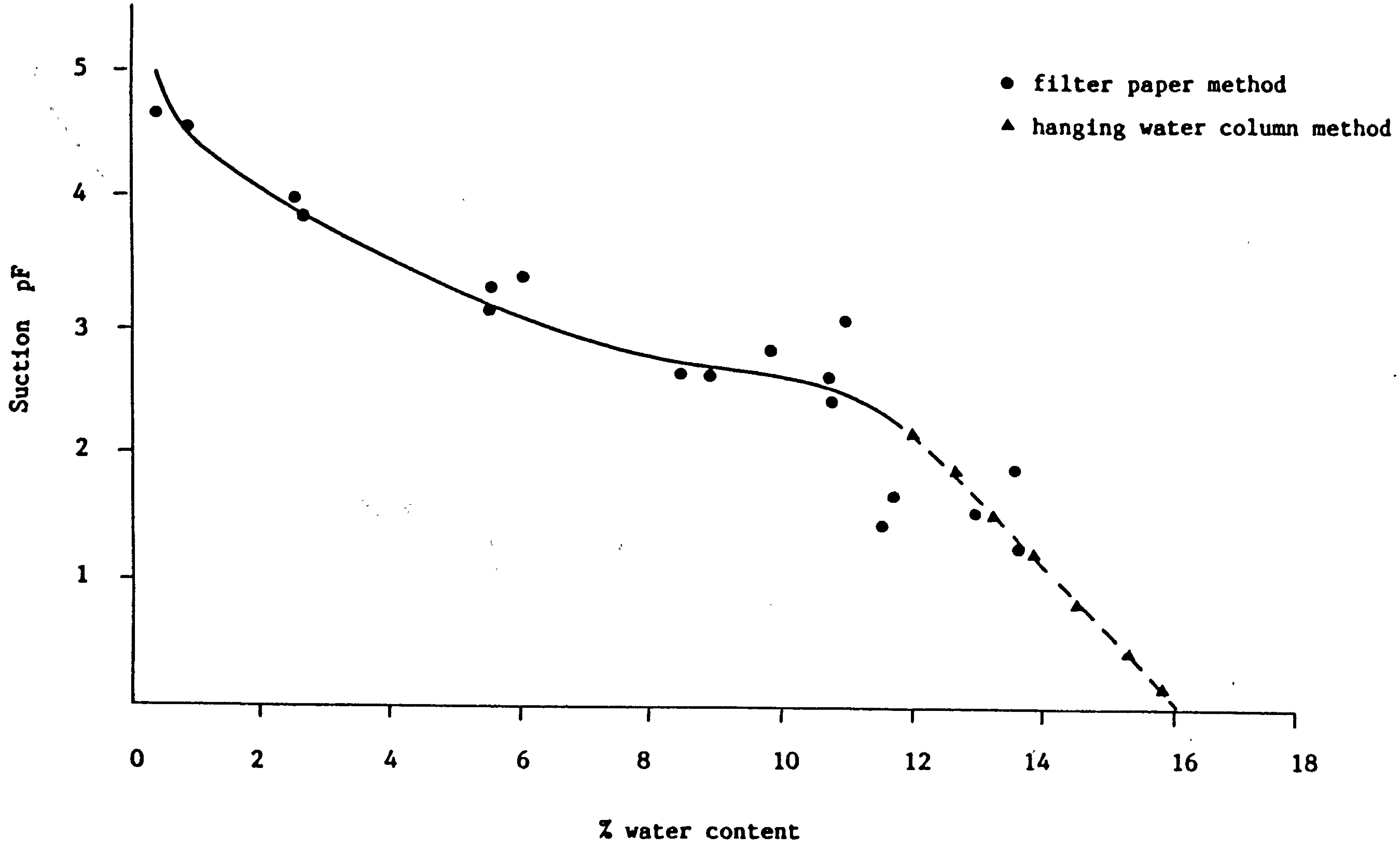


Figure 6.3 Suction water content curve for Downhill Sand

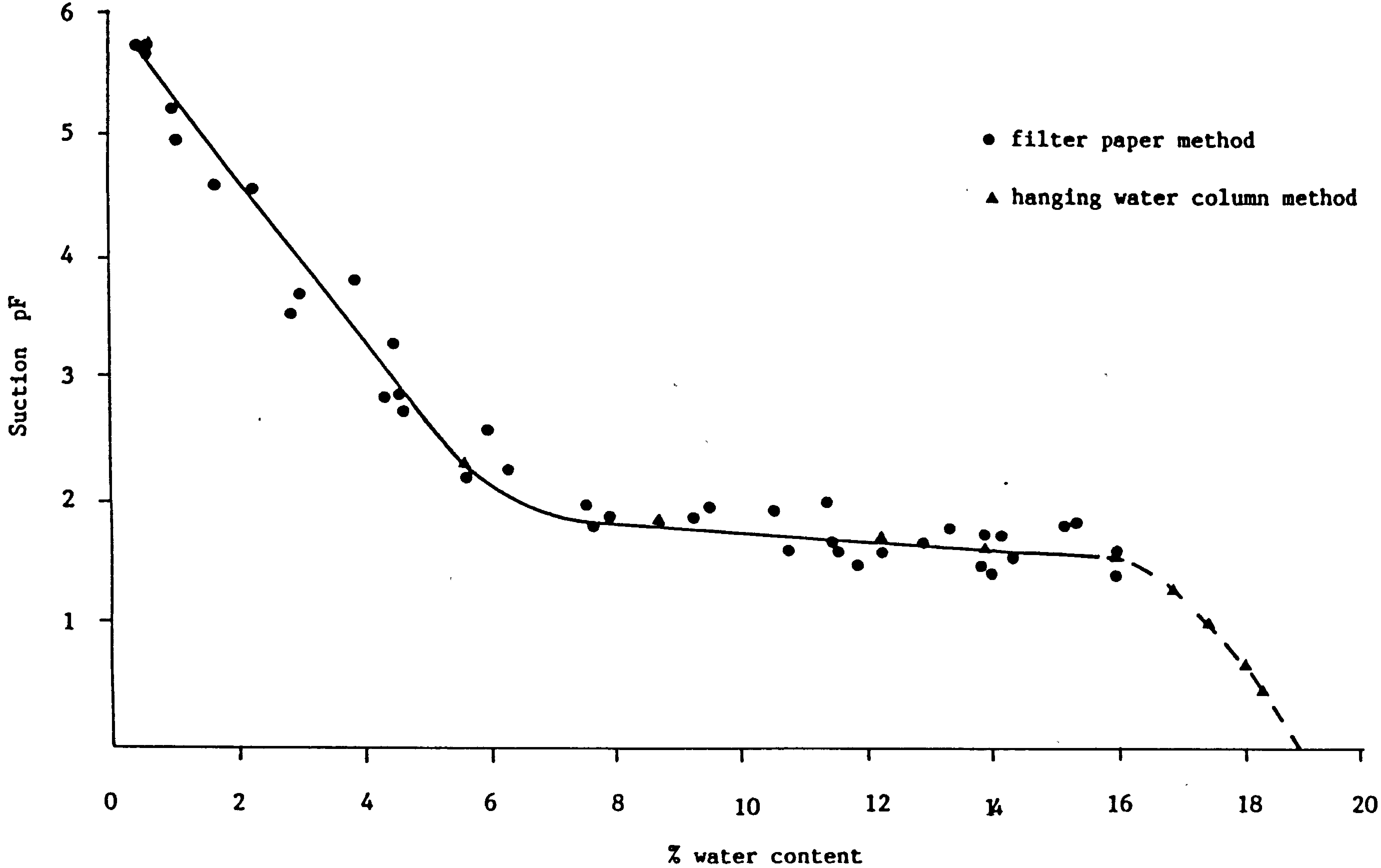


Figure 6.4 Suction water content curve for Eighton Clay

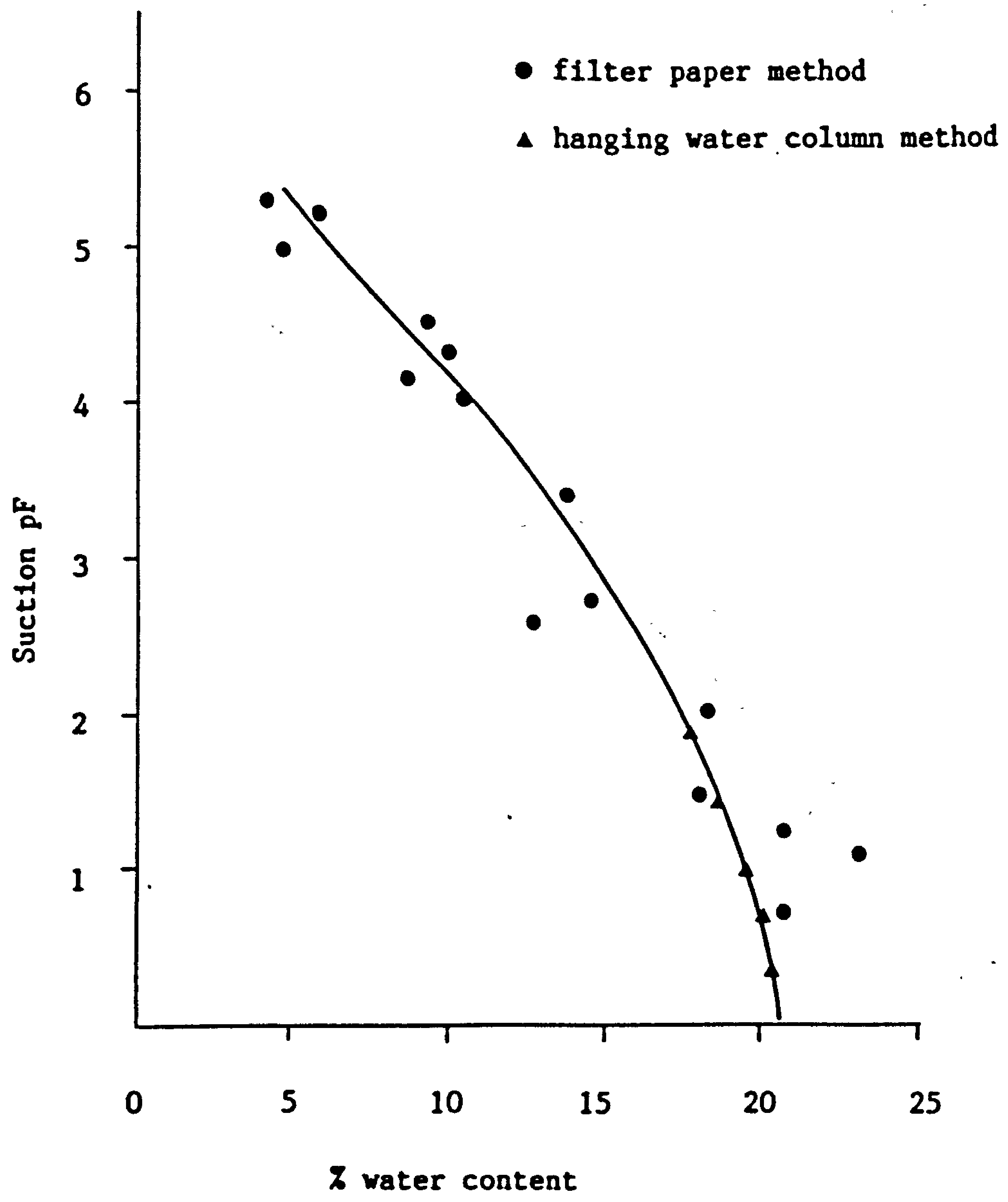
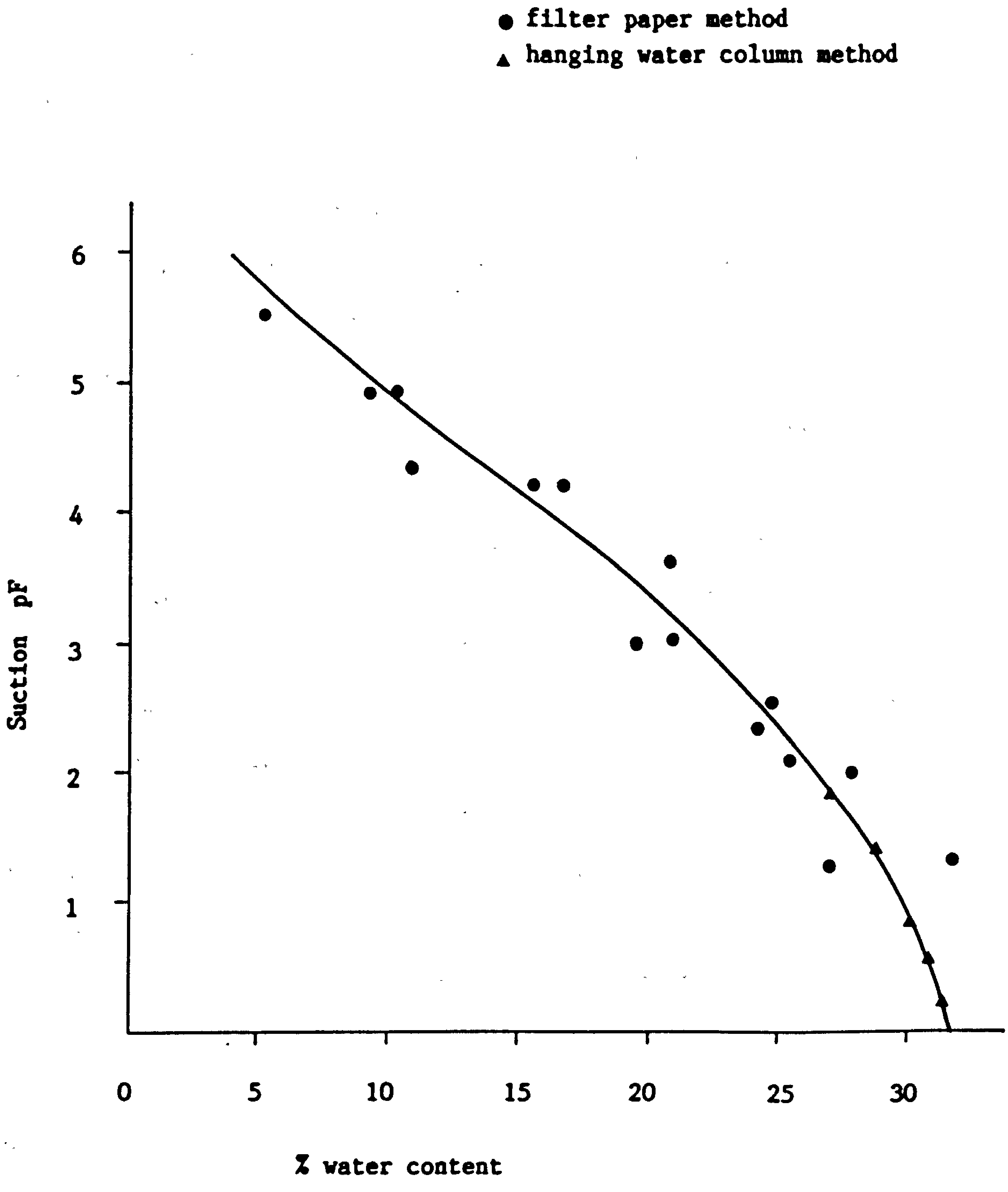


Figure 6.5 Suction water content curve for In-Situ Clay



6.4 The Hanging Water Column Method

The hanging water column method has been discussed by a number of authors, the most recent being Berliner _et al.,_ 1980, (ref 6.1), who describe a method whereby the water release curve can be determined gravimetrically from a single sample without removing the sample from the apparatus. In this way they achieved an accuracy of + or - 0.001g.

The available equipment precluded the use of the method of Berliner _et al.,_ it was therefore necessary to remove the soil sample from the apparatus for determination of gravimetric water content.

The method essentially uses a column of water to apply a suction to a soil sample which is placed on a tension plate (figure 6.6).

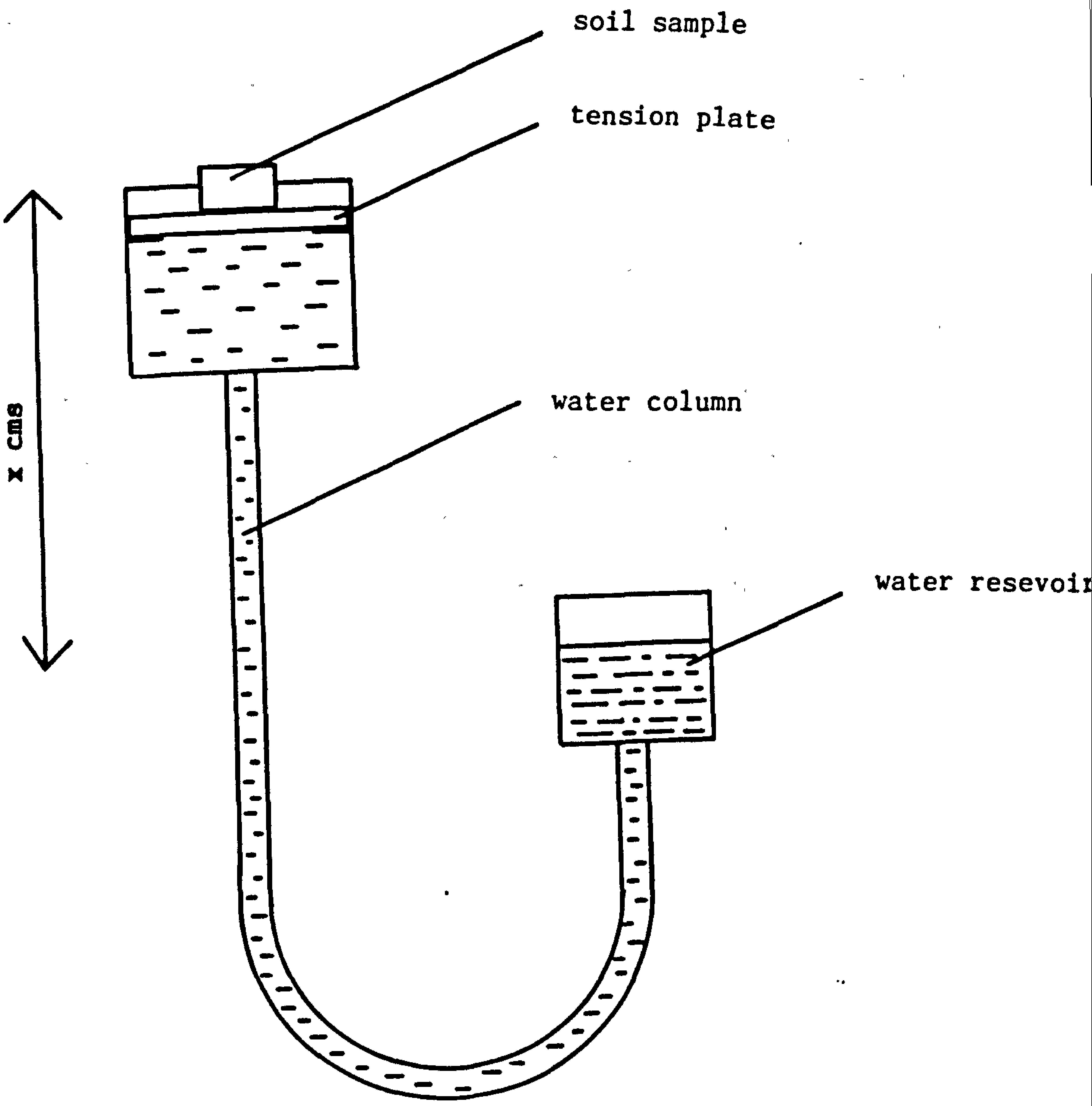
The suction applied will be equal to the vertical distance between the mid point of the soil sample and the water surface (X cms in figure 6.6)

Periodic weighing of the sample allows determination of the gravimetric water content of the soil for the given suction value.

The results obtained using this method are recorded in figures 6.2 to 6.5. These values enable the lower section of the suction - water content curve to be plotted more accurately, and the overlap of results from the two methods allows one to identify the accuracy of the results.

Obviously the hanging water column method is a useful, complementary experiment to the filter paper experiment.

Figure 6.6 Hanging water column apparatus



6.5 Obtaining the parameters for the computer

Having determined the unsaturated hydraulic conductivity (Chapter 5) and suction curves for each of the soils one can then determine the necessary parameters for the CRISP computer model.
By plotting conductivity against suction for corresponding water content values, (figures 6.7 to 6.10), the term 'n' in equation 2.2. can be determined as the gradient of the straight line section. ho is determined where the value of K(Θ) becomes negligibly small, at the intercept of the drying curve with the x axis. Where the drying curve approaches the measured value of 'Ks' the value of 'ha' can be read off the suction axis. However, the K(Θ)-h graphs shown in figures 6.7 to 6.10 do not extend as far as the measured values for Ks. Extrapolation of the graphs can lead to erroneous results being obtained, it was therefore necessary to calculate the value of ha (and therefore hw) from particle size data as detailed in section 2.3.3

Figure 6.7 Conductivity - suction relationship for Gateshead Gravel

Figure 6.8 Conductivity - suction relationship for Downhil Sand

Figure 6.9 Conductivity - suction relationship for Eighton Clay

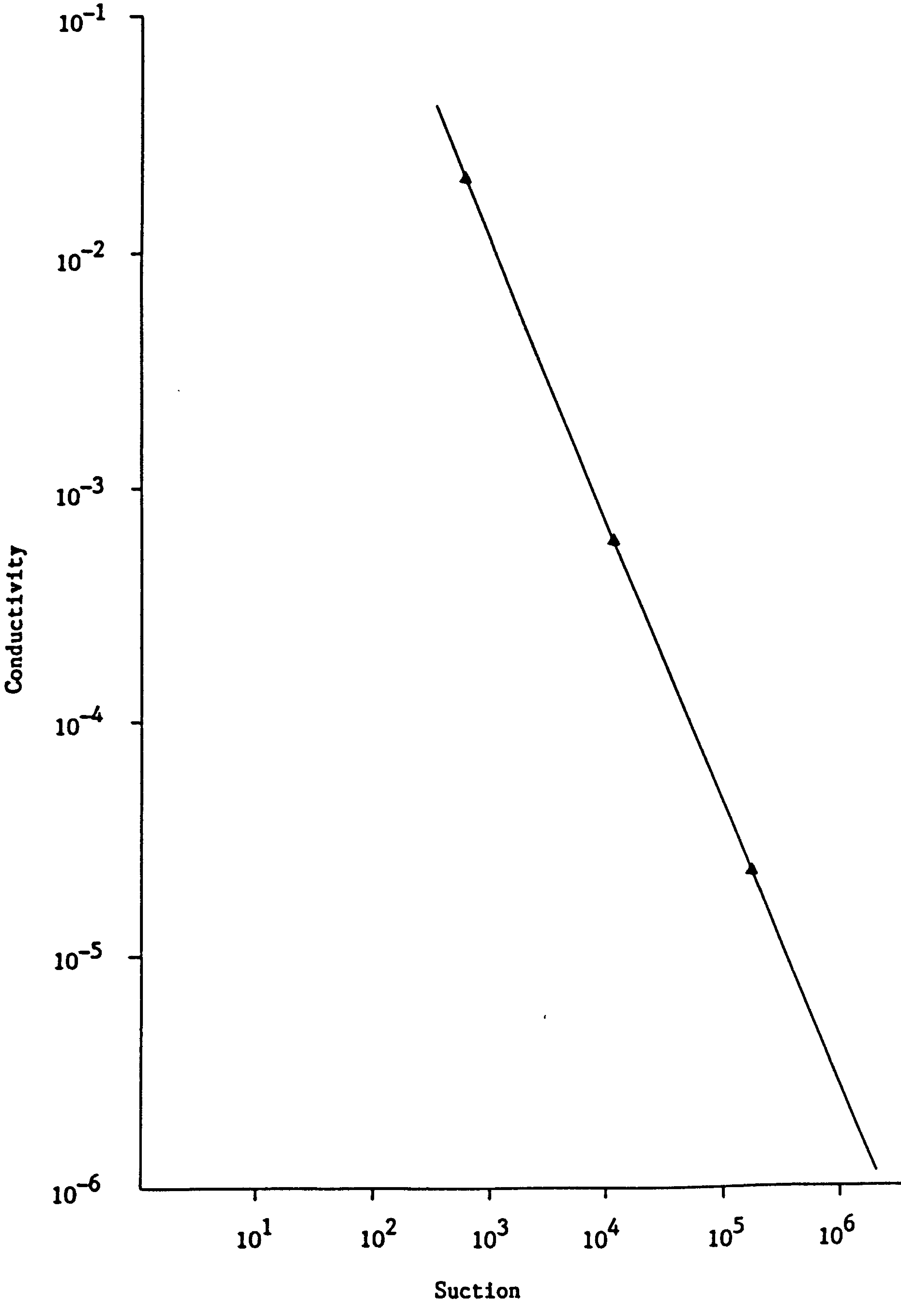


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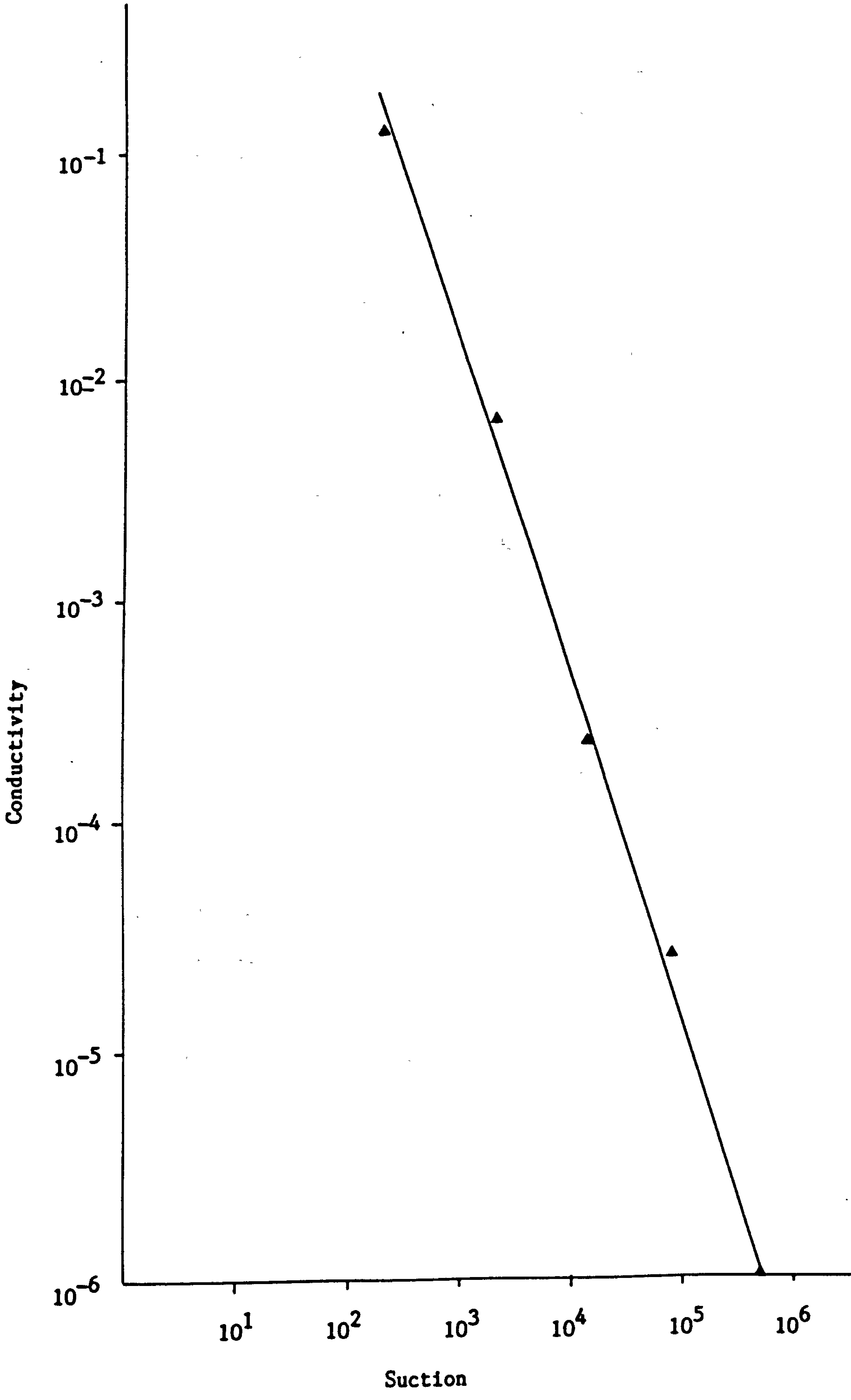
Figure 6.10 Conductivity - suction relationship for Insitu Clay



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Chapter Seven: Conclusion

Land which is chemically contaminated by past industrial uses is much more common in the U.K. (and other industrialised countries) than is generally recognised. Such land was once on the outskirts of the population centres but, is now usually surrounded by the urban sprawl of the last fifty years, and, obviously has existing access to roads, railways, water, gas and electricity, and so offers a real attraction to developers.

The political and social conditions in the U.K. differ from those in most other countries where such chemically contaminated land occurs. Here we have a government dedicated to the market economy, biased against the public sector, disinclined to allow any return to the controlled and legislated society that dominated until 1978, and eager to involve private money in a social and industrial improvements. Thus, the DoE / Welsh Office found it reasonable to issue a circular on the development of contaminated land (ref 7.1) that, whilst it fairly outlines the hazards of re-using such land, emphasises that the national policy is to risk such re-use and the developer, (not the planning officer), is the individual with the right to decide which reclamation work needs to be undertaken. Public safety is no longer as important as inner city renewal and the rapid removal of dereliction.

Whilst the above summary is political (and so, debateable), it is a fact that other countries, such as Holland, have spent vast sums of public money on developing various clean-up technologies that remove the hazards of contaminated land, whilst the U.K. has no such investment. The sole use of microbial reclamation methods in the U.K. (ref 7.2) was allowed only after BioTreatment had agreed to a performance bond that would cover the costs of excavation and removal of the Blackburn Gas works contaminants if the microbial technique failed to achieve its performance tarets. The contrast with the Dutch governments direct founding of many microbial reclamations is stark.

In the U.K., reclamation is now lead by private developers or by consortia of private and public organisations with limited government funding. Thus, the Gateshead (Redheugh and Norwood) reclamation was funded by the Government but only on the basis of the land being sold profitably to private developers after the 1990 Garden Festival.

It is, therefore, not unsurprising that the cheapest and most rapid reclamation method , i.e. the soil cover technique, dominates U.K. practice.
Cheapness, however, is not such a bad thing provided that the soil cover method is effective and provides the required public safety.

This thesis thus examines the soil cover method in the light of current U.K. conditions. Developers now insist on some guarantee of safety and success, and demand that consultants and designers carry professional liability insurance. These developers (and their insurers) obviously have greater confidence in reclamation methods which produce quantifiable safety margins.
Thus the soil cover method and its associated CRISP computer model fit in well with current U.K. practices.

The CRISP computer model does, in fact, perform remarkably well.It does over predict the amount of contamination that will rise up through a soil cover in a design drought, but this is not a bad thing, as it does include an additional factor of safety to the design.
Over prediction could perhaps have been reduced by including many intermediate values for surface suction, and mimicking the actual drying pattern within each soil column, however, because of the poor results obtained from the psychrometer probes this was not possible in this research and not practical for commercial designers to attempt, given the data at their disposal.

It was felt that having to predict the values of hw and ns from particle size data would inevitably introduce random errors to the CRISP output, this in fact did not occur despite two very different soil covers being evaluated.

On balance:

the CRISP model is easy to use,

determining the required hydraulic conductivity and suction values with both repeatability and accuracy is not unduly difficult,

the output results are reasonably accurate and safe (in that they are overpredictions if used without the refinements of intermediate surface suctions to mirror the gradual drying out of the soil surface in a design drought)

and, it is difficult to fault the method.

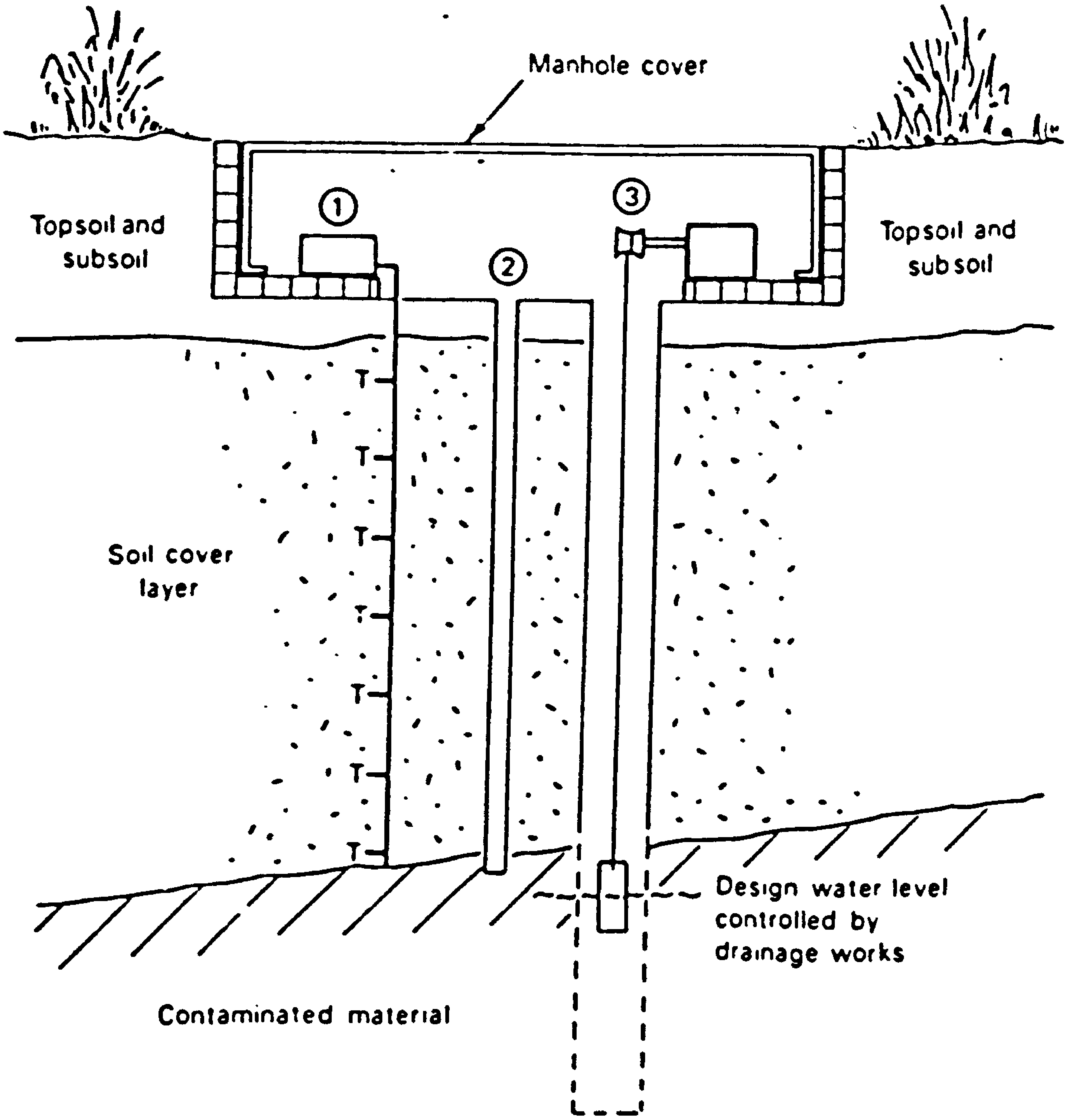
This supports the Government's view (ref 7.3) that checks show that past soil cover reclamations are proveably efficient and safe, and that introducing more expensive thermal, chemical and microbial methods is unnecessary.

The soil cover method and the CRISP based design technique satisfy the safety levels detailed in Chapter 2, at least for the period of the soil column tests.
A futher evaluation based on the actual monitoring of real soil covers would, of course, be an additional and

useful check, and, whilst it is possible to design suitable monitoring systems for such long term measurement (figure 7.1) so far no such long term monitoring systems have been installed on any U.K. reclamations to the author's knowledge, though such works are being included on the Norwood site in 1989. This is obviously the final stage of proving that the U.K. based soil cover method is adequately safe, provided that the reclamations are designed on rational grounds and on the basis of measured soil data and factual drought drying levels.

Figure 7.1 Monitoring system

1 Tensiometer array connected to data logger
2 Aluminium access tube for neutron probe, to obtain accurate soil water content data
3 water level observation borehole, with gas detection facilities if required



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