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UNIVERSITY OF NOTTINGHAM

DEPARTMENT OF MINING ENGINEERING

GROUNDWATER RECOVERY PROBLEMS ASSOCIATED WITH OPENCAST MINE BACKFILLS.

by

S. M. REED, B.Sc.

Thesis submitted to the University of Nottingham for the Degree

of

Doctor of Philosophy.

July 1986

AFFIRMATION

The work submitted in this thesis is my own, and has not been previously submitted for any other degree.

The following publications have been extracted from the present research.

S. A. Ngah, S. M. Reed and R. N. Singh.
Groundwater problems in surface mining in the United Kingdom.
International Journal of Mine Water, Vol. 3, No. 1, March 1984, pp1-12.

R. N. Singh, B. Denby and S. M. Reed.
The effect of groundwater re-establishment on the settlement of opencast mine backfills in the United Kingdom.
Second International Congress of the International Mine Water Association, Granada, Spain, September 1985. pp803-817.

R. N. Singh, S. M. Reed, B. Denby and D. B. Hughes.
An investigation into groundwater recovery and backfill consolidation in British surface coal mines.
Symposium on Surface Mining, Hydrology, Sedimentology and Reclamation, University of Kentucky, Lexington, Kentucky, U.S.A. December 1985. pp231-236

July 1986.

ABSTRACT

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The research outlined in this thesis is concerned with the environmental aspects of groundwater re-establishment as a consequence of surface mining. Two principal effects which have been identified as being detrimental to the restored land area are as follows;

i). The vertical and horizontal displacements of backfill materials following restoration, and

ii). The pollution of groundwater from contact with weathered rockfill materials.

The research into settlement has attempted to classify the types of movement which may occur within a backfill mass, in particular the differential movements which are of great importance to the stability of proposed structures or surface drainage. The field results from 10 opencast mine sites are presented, 3 of which were instrumented for detailed field investigations. It has been shown that backfill movements do not necessarily show similar trends under similar conditions, and reasons for this are proposed. A variety of instrumentation schemes have been devised to examine backfill displacements, both vertically and horizontally. Permeability testing has been conducted at different horizons the backfill mass in order to locate the zones of collapse settlement due to groundwater recovery.

A critical review of the instrumentation utilised in the investigations is presented, with suggestions for improvement.

Investigations into groundwater pollution have been devoted to examining the qualities of groundwater flowing into British surface mines and evaluating its likely reactions with fill materials. An insight into general groundwater pollution and treatment techniques is presented together with a critical analysis of their applicability to British conditions.

An investigation into water qualities in each of the six geographical regions of the opencast mining industry of Great Britain is detailed.

Finally some suggestions for future research areas are indicated.

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SUMMARY OF TERMS.

A1	Surface Levelling Station.
ANC	Acid Neutralizing Capacity, % $CaCO_3$.
A.O.D	Above Ordnance Datum.
A.S.D, a.s.d.	Above Site Datum.
B1	Surface Levelling Station.
C1	Surface Levelling Station.
D, d	Diameter of Test Compartment, Constant Head Test.
Day 200	200th day since the commencement of monitoring.
E1	Magnetic Extensometer/Standpipe Piezometer.
H	Water Pressure Head, (metres).
k	Coefficient of Permeability parallel to borehole.
kp	Coefficient of Permeability vertical to borehole.
l	Length of Test Cavity, Constant Head Test.
m	$(k/kp)^{1/2}$
MHD	Manhole Cover used for Surface Levelling.
MPP1	Multi-Point Piezometer.
O.C.C.S.	Open Cast Coal Site.
P	Pressure Head, p.s.i. measured in permeability test.
P1	Standpipe Piezometer.
PX	Borehole Casing Size, 133 mm.
q	Flow Rate measured in Constant Head Test.
S1	Surface Levelling Station.
SP1	Spider Magnet.
t	Time taken for Constant Head Test, (seconds).
TWE1	Tension-Wire Extensometer.
V	Volume of Water pumped during Constant Head Test.
α	Creep Settlement Rate Parameter.

CHAPTER 1.

INTRODUCTION.

CHAPTER 1. INTRODUCTION

1.1. A HISTORY OF OPENCAST PRODUCTION.

The mining of near surface coal deposits in the United Kingdom dates back to at least the time of Roman Occupation. In spite of this long history, opencast coal mining only began in earnest in 1941 when these deposits were urgently required to supplement coal production to meet wartime requirements. Until 1958, all opencast operations were subject to the Defence (General) Regulations 1939, which included aspects of prospecting, land requisition and authorisation. In 1952 all opencast workings were taken over by the National Coal Board, when the Opencast Executive was established.

Despite threats of running-down in the years 1949, 1958, and 1967, opencast mining has continued since the war to be of increasing importance as a supplement to the nation's deep mined output. Following the effects of the 1973 O.P.E.C decision to increase oil prices, the British Government, the National Coal Board and the Mining Unions came to an agreement aimed at securing the future of the coal industry. The agreement was published as "Plan for Coal" in 1974 including the raising of the opencast coal outputs to a sustained 15 million tonnes per year by 1980.

In the early years of opencast coal production, operations were restricted by the size of the excavating plant available.

In 1942 the maximum depths excavated were between 9 and 12 metres, attaining maximum overburden to coal ratios of 5:1. Today excavation on the Westfield Site in Scotland has approached 250 metres and depths of 80 metres and overburden to coal ratios of 25:1 are common. In 1945 production amounted to 8 million tonnes rising to 14 million tonnes by 1958. Output then slumped to only 6.5 million tonnes in 1967, but from the early 1970's opencast production increased as the deep mines found themselves unable to satisfy certain markets.

At present the production of opencast coal totals around 14 million tonnes. This indicates that in accounting for about 10 % of the total production of coal in Great Britain, opencast mining is still on a very small scale in world-wide terms. Justifications for these small scale operations include profitability and specialist market coals.

The Opencast Executive makes a considerable operating profit, (Table 1.1), helping considerably to offset the deep mines losses. Further to this a substantial proportion of the opencast output has special market characteristics such as coals in short supply (anthracite, coking coals), and coals with quality advantages suitable for sweetening the deep mined output.

The main obstacle facing the future of the surface mining coal industry in the United Kingdom is the growing concern of the environmentalist lobby. By their nature opencast mine sites are transient and for every new application to work, new people generally unaware of the techniques of opencast production and restoration, must be approached for consent.

	1983/4	1984/5
Saleable Output, (million tonnes)		
Deep Mines.	90.0	27.6
Opencast, Total	13.8	13.6
England and Wales	11.3	11.3
Scotland	2.5	2.3
Licensed Mines, tip coal.	1.5	1.5
Total Coal Production.	**105.3**	**42.7**
Profit/(Deficit), (£ millions)		
Deep Mines.	(595)	(1773)
Opencast, Total.	211	140
England and Wales.	171	124
Scotland.	40	16

1984/5 results affected by Industrial Dispute.

Scottish Opencast taken over by Deep Mines Division, 1.4.84

Table 1.1 Coal Production in the U.K. 1983/5.

The arguments against opencasting are mainly environmental and it is in this particular field that this thesis is ultimately concerned.

1.2. METHODS OF OPENCAST WORKING.

1.2.1. Initial Planning.

No opencast mine site may be worked by the Executive without the authorisation of the Secretary of State for Energy under the Opencast Coal Act 1958. When granting authorisation the Minister lays down conditions for both the working and the restoration of the land. Before the Executive receives authority to work a site, several years of investigation and preparation are necessary. The site must be first proven by exploratory borehole drilling and, if coal is located in sufficient quantity and quality, working and restoration plans are proposed.

Local Authorities and other statutory bodies as well as the landowners must be consulted in order to discuss the mining operations and proposed future land use. Once authorisation has been given to work then competitive tenders are invited from engineering contractors.

1.2.2. General Working Methods.

Opencast mining is the selective extraction of overburden, interburden and mineral used for the mining of near surface deposits. The layout of such an operation is largely determined by the type of excavating and loading equipment to be utilised at a mine. These themselves are determined by a number of certain site specific characteristics, (Young 1979).

a). The magnitude of operations.

b). Orientation, number and regularity of seams.

c). Thicknesses of overburden and interburden.

d). Diggability of the individual horizons.

e). Environmental constraints.

f). Economic constraints.

Many machines and systems exist for the operation of an opencast mine, (Atkinson, 1977). In the United Kingdom however, an operation can be described by one or a combination of the following;

a). Dragline Operations.

b). Truck and Shovel Operations.

c). Ripper and Scraper Operations.

A detailed discussion of each method would be out of context in this thesis and the reader is thus referred to Atkinson (1977), Young (1979) and Muftuoglu (1983).

As soon as the contractor is given possession of the site, he must complete preliminary works and take measures for the prevention of nuisance, e.g. the diversion of power lines, water courses, underground cables etc. before the main excavation is allowed to commence. Initially the topsoils and subsoils are stripped and stored in grassed mounds around the perimeter of the site, serving the dual purpose of storage and baffle mounds. If a deficiency exists in the quantities of soil available then drift materials may also be stored as soil-making materials. The choice of main excavating equipment is largely related to the geology of the site but above all it is the dragline which is preferred in British conditions. Where the economic depth of the dragline is exceeded, then large mining shovels of up to 10.5 m^3 capacity are used for advance overburden reduction, (figure 1.1). Large hydraulic shovels and backhoes have been introduced which are rather more flexible and faster in operation than the conventional diesel or electric rope crowd shovels. Servicing the shovels and hauling overburden within the site are generally dump trucks of varying capacities. Coal is produced at the individual seam faces which are successively bared by the main excavating machinery. The coal excavators themselves are much smaller rope or hydraulic crowd shovels of the order of 1 m^3 capacity. These load onto coal lorries at the face. As the coal is extracted then it is necessary to progressively or otherwise restore the mine void to reproduce an acceptable landscape.

1.2.3. Backfill Replacement Techniques.

Excavated overburden materials in the U.K. are generally replaced into the mine void by one or a combination of two

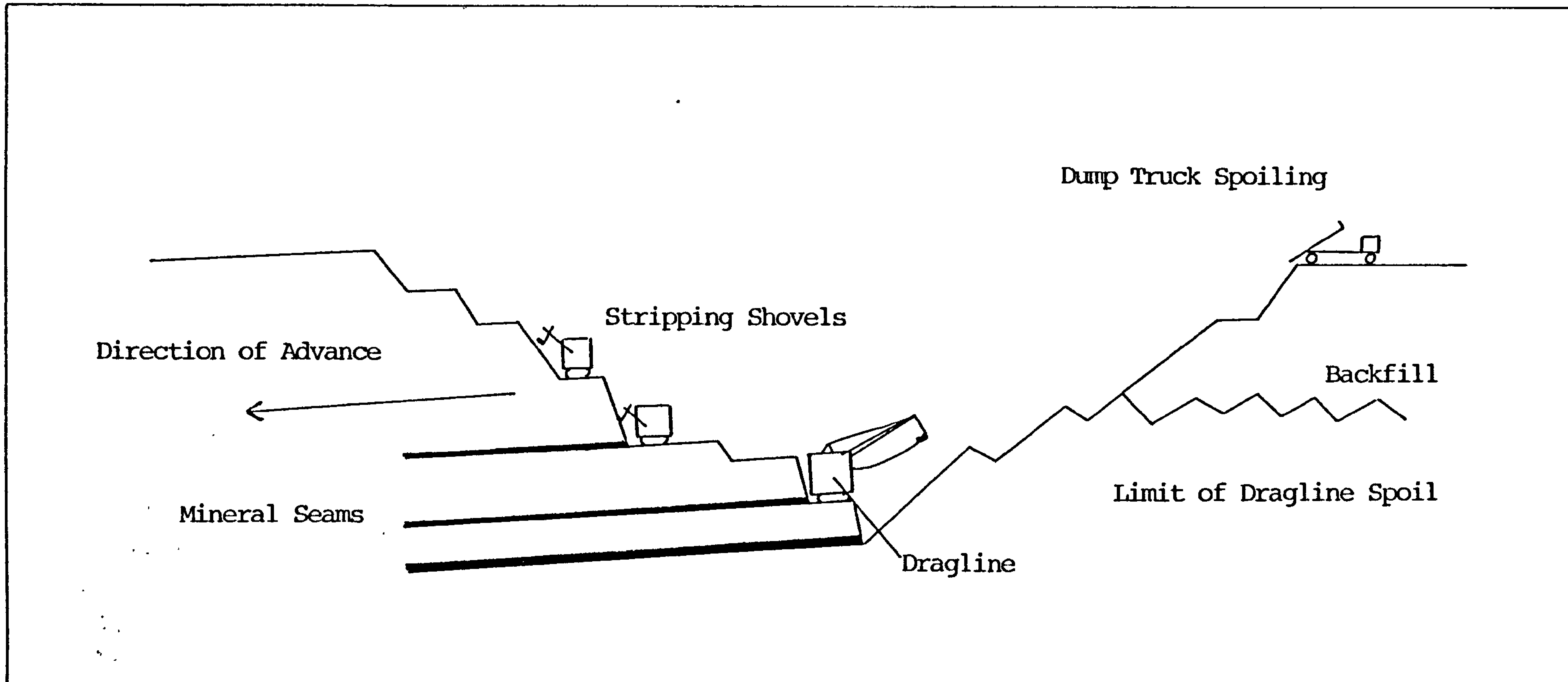

Figure 1.1 Typical Working Method using Advance Overburden Reduction, (Mck Guyan 1983)

PLATE 1.

DRAGLINE OPERATIONS IN THE NORTH-EAST OF ENGLAND.


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methods;

i). Dragline spoiling.

ii). Truck end-tipping

The dragline operation involves the stripping of overburden to expose the mineral seam, directly casting the spoil into the void left from the previous extraction. Final overburden levels are attained by dump trucks, scrapers and bulldozers. It is common for when the coaling ceases, to remove the dragline and replace its spoiling activities with dump trucks.

In the dump truck operation, spoil is loaded onto the trucks by a excavating shovel. It is then carried out of the excavation to be either stored in a temporary spoil heap, or end-tipped over the edge of the advancing loosewall.

Both systems result in a fill which would tend to have the larger boulders at the base of the vertical section, with smaller rocks nearer the restored surface, owing to the particle separation which will occur when tipping by gravity.

1.2.4 Soil Replacement and Surface Restoration.

The early restoration of 1940's was of a very low standard, much being of an experimental nature. Early practise was to preserve topsoil from one half of the excavated area and on completion respread this over the entire site. This produced a land on which the topsoil layer was inadequate to conceal the underlying overburden of intermixed boulders and rocks. The final product of opencast mining was a landscape far poorer in quality than that of the pre-mining one.

In 1951, the Ministry of Agriculture laid down an improved set of regulations regarding restoration. The important provisions of these regulations were as follows;

* The removal and separate storage and grassing of topsoil and subsoil.
* Five years post mining specialised agricultural maintenance.
* Adequate rehabilitation of woodlands.
* Installation of permanent water drainage with three years maintenance.
* Erection of hedges, fences etc.

Today the planning of restoration is considered long before the application has been submitted to the Secretary of State for the Environment. In the completed application all information for the complete restoration of the mine site and for a further five years are submitted for approval.

The topsoils and subsoils are replaced by scrapers and the final levels rooted to remove large stones, wire ropes etc. The production contract then terminates with the satisfactory replacement of the topsoils. From this stage onwards specialist contractors are employed on aspects such as fencing, ditching, drainage, planting and seeding. The Opencast Executive does not release the land until five years after the first seeding.

1.3. ENVIRONMENTAL ASPECTS OF OPENCAST MINING.

1.3.1. General Aspects.

The environmental controls imposed upon the surface mining industry in the United Kingdom place an obligation on the part of the industry to not only maintain strict control over inherent pollution during the mining operation but to recreate the excavated void into acceptable land. As surface mining machinery and techniques enable larger and deeper sites to be worked, so the effects on the environment are increasing.

The removal of overburden to exploit an underlying mineral deposit alters not only the state of nature of the near surface strata but also impinges on the entire ecological balance of the area. Environmental impacts as a result of surface mining may be classified into two categories:

* Impacts manifested during mining.
* Post-mining impacts.

The environmental problems encountered during mining are well appreciated by operators and are a major stumbling block in seeking authorisation to work a proposed site. Many control regulations exist, in particular regarding the following aspects.

* Land Degradation.
* Water Pollution.

* Air Pollution.
* Blasting Vibrations.
* Noise Pollution.

A detailed study of each of these topics was undertaken by the Department of the Environment, (H.M.S.O. 1981) to which the reader is referred.

This work is concerned with environmental aspects with respect to the behaviour of groundwater in a working site operating below the level of the natural water table with particular reference to the environmental effects following the completion of mining and the termination of pumping - the effects of groundwater recovery.

1.4. GROUNDWATER IN SURFACE MINING.

1.4.1. Sources of Inflow into a Surface Mine.

The sources of inflow to a surface mine excavation can be classified as follows, (Ngah, Reed and Singh 1984);

i) Inflow from atmospheric precipitation and percolation through the backfill which forms its own water table.
ii) Inflow from mineral beds and underground aquifers.
iii) Inflow through geological/structural features.
iv) Transmission via disused/abandoned mine workings.
v) Inflow via pit floor heave and/or piping.

Figure 1.2 illustrates these sources of groundwater and surface water inflow into a surface mine.

1.4.2. Hydrogeologic Modifications due to Surface Mining.

The main modifications which alter the nature of the local hydrogeology in a mining area consist of the following;

i). Changes in aquifer storage, recharge and permeability.
ii). Lowering of the groundwater table.
iii). Changes in groundwater quality.
iv). Creation of Hydrodynamic flow.

The storage offered by a flooded mine or quarry is so large compared with consolidated rocks, the local increase in storage will lower the local piezometric surface as groundwater flows into the surface void. The reduction in this level affects local water supplies, reducing the yield of water wells and decreasing the flow from springs.

When natural groundwater enters into a surface mine excavation, it becomes subject to a variety of chemical processes which are not active in the undisturbed aquifer. Degradation of minerals by various physio-/biochemical processes result in a change in the local groundwater geochemistry. These processes are discussed in great detail in chapters 7 and 8.

The creation of hydrodynamic flow occurs as seepage forces develop as a result of the resistance offered to the flow of

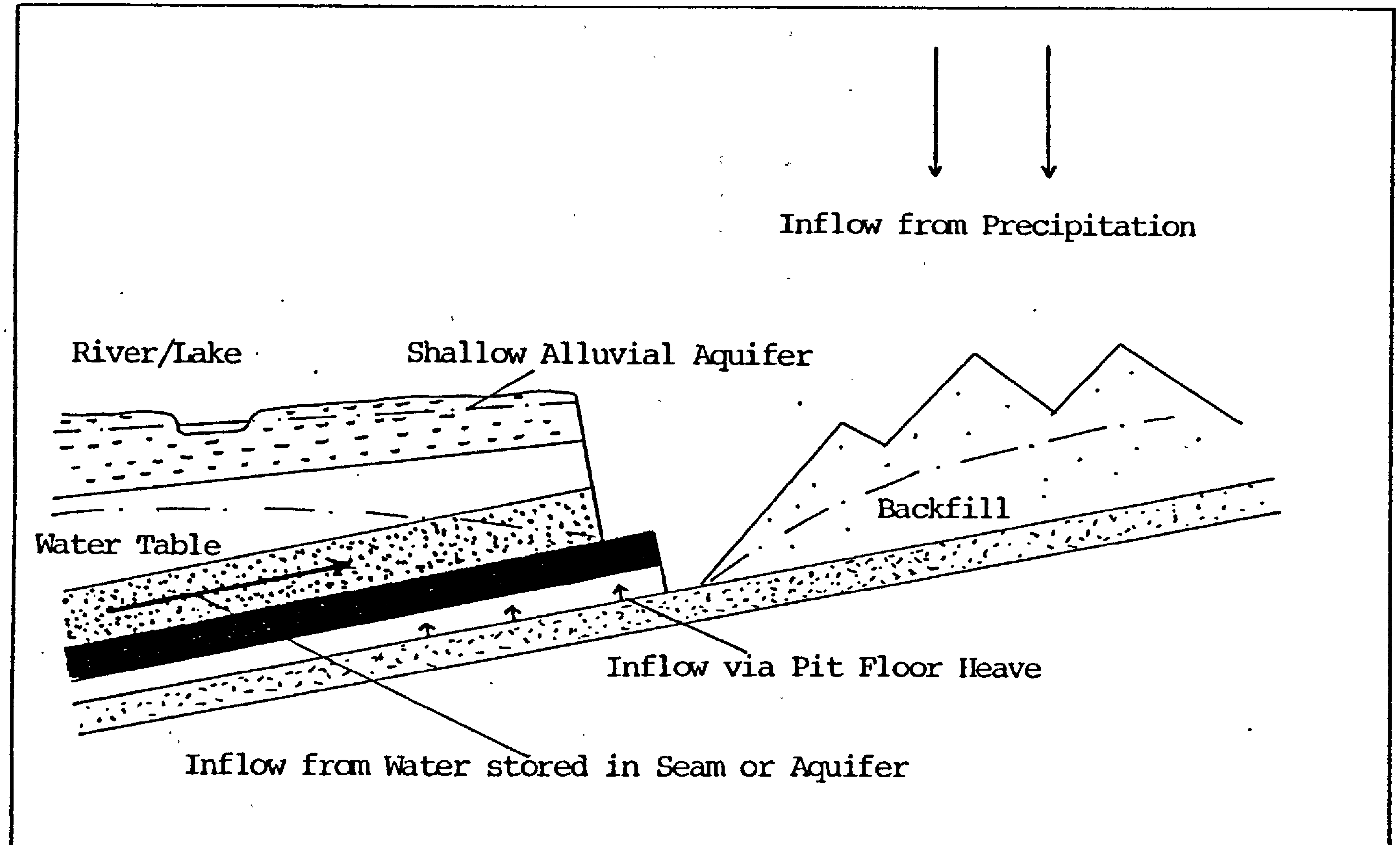


Figure 1.2 Sources of Water Inflow to a Surface Mine, (Ngah, Reed and Singh 1984).

water by the generally low permeability of rock slope material. Seepage forces can become very high which in turn increases the shear stress acting on the rock material, facilitating mine slope failure, (Brawner 1983).

1.4.3. Control of Groundwater in British Surface Mining.

a). Sump Pumping.

Until recently the sump pumping technique has been the most common method of dewatering in British surface coal mines, (Norton 1983). The technique involves the creation of a sump at the lowest point of excavation within the working area and allowing water to accumulate, Figure 1.3. Water levels within the sump are regulated by pumps to the discharge point. The main disadvantages of the method may be summarised as, a). increased slope stability, b) the restriction of vehicle movement within the mine and c). the pollution of clean groundwater which may enter the mine and be contaminated by chemical reactions occuring within the mine. The method has the further disadvantages in that the local water levels are only reduced to the levels of the sump, thus blastholes can still be wet and slopes may remain undewatered. The method is only suitable for sites pumping small volumes of water with no stability or water pollution problems.

b). Advance Dewatering.

The method of advance dewatering is illustrated in figure 1.4. The technique depresses the groundwater level to below the base of the excavation and thus has none of the disadvantages of the sump pumping method. The method can manage larger quantities of water, and owing to high initial capital costs is best used only in long term mines with high pumping requirements. The principal advantages of the method include, enhanced slope stability associated with dry slopes, lower blasting costs as the need for slurry explosives is eliminated, longer vehicle tyre life associated with dry road conditions and, the reduction of water pollution in the mine area.

c). Other techniques.

The sump pumping and advance dewatering techniques are the principal methods of surface mine dewatering in the United Kingdom. Other techniques used elsewhere include drainage ditches at the surface of the mine or at the bottom of the pit, horizontal drains bored into slope faces, and dewatering by shaft or gallery, (Straskraba 1979).

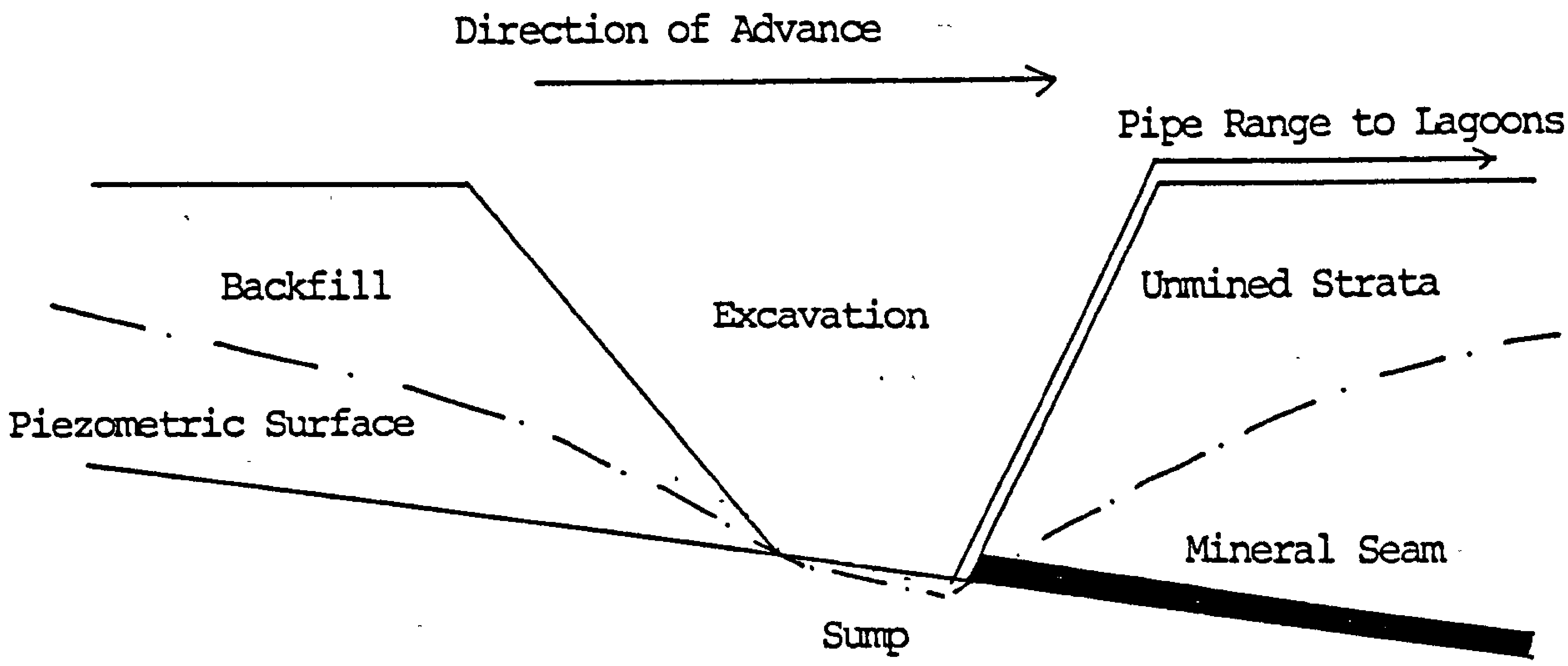


Figure 1.3 Surface Mine Dewatering - Sump Pumping.

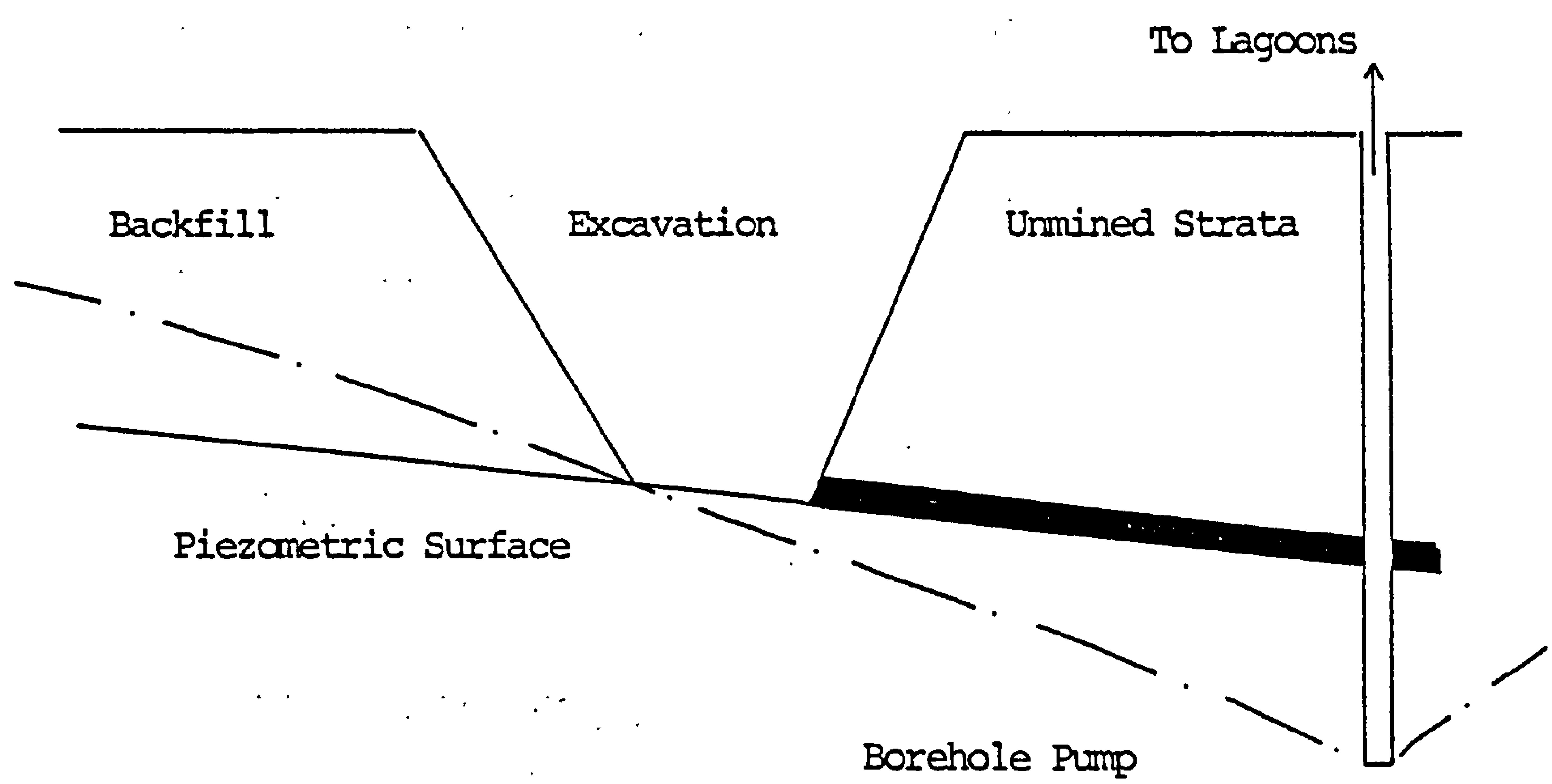


Figure 1.4 Surface Mine Dewatering - Advance Dewatering.

1.5 THE RE-ESTABLISHMENT OF GROUNDWATER EQUILIBRIUM.

1.5.I. The Sequence of Recovery.

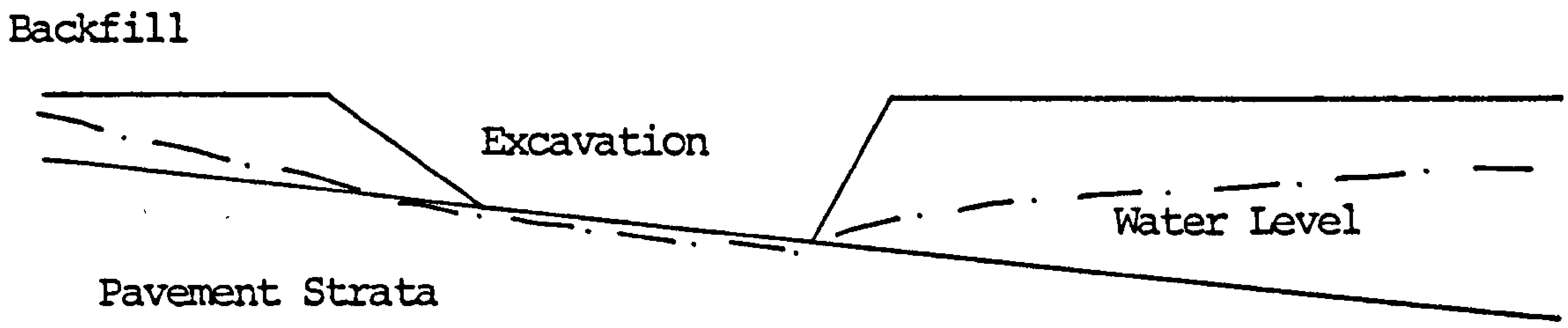
The sequence of groundwater recovery initiates on the cessation of pumping in a surface mine. The water levels by what ever means of pumping have been depressed during the mining operation and are now allowed to percolate upwards through fill material to attain an equilibrium position. The sequence is illustrated in figure 1.5.

1.5.2. Factors affecting Groundwater Recovery.

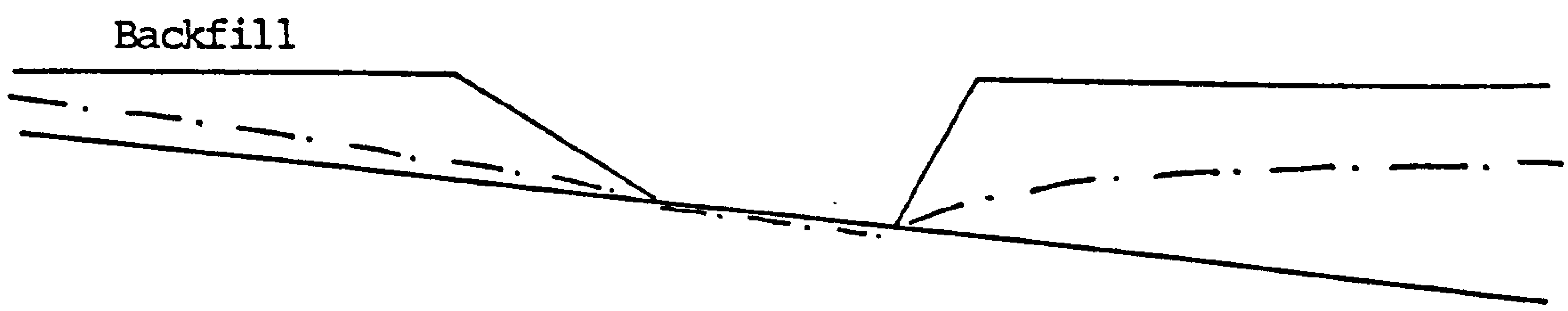
The process of mining and backfilling alters the state of nature of the mined strata from a condition of relative uniformity and competence to a disturbed, intermixed aquiferous formation. The rate of water recovery in this material and the level at which equilibrium occurs is depedent on a number of inter-related factors, (Herring 1977, Evangelow 1982).

a). The Post-Mining Hydrological Regime.

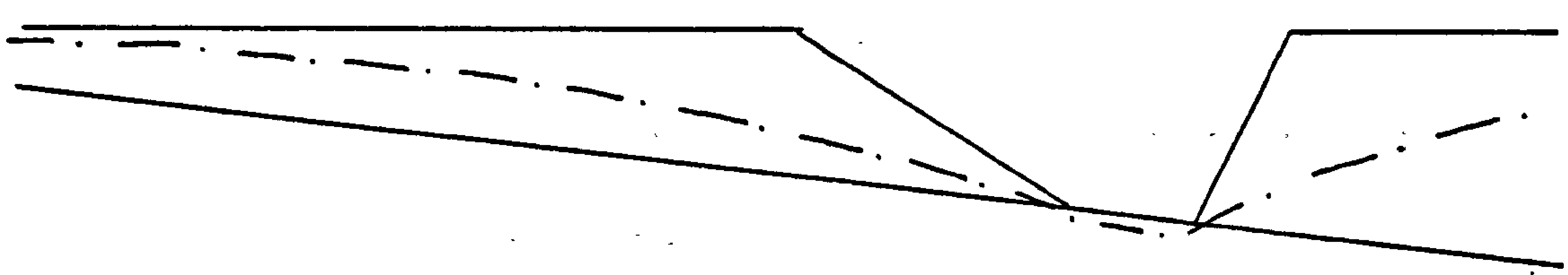
The hydrological regime will govern the degree of recharge to the backfill mass. Recharge may occur solely from surface infiltration or as a result of a direct contact between the fill and a subsurface aquifer. If the mine has intersected any old workings, then these may act as either a sump for the



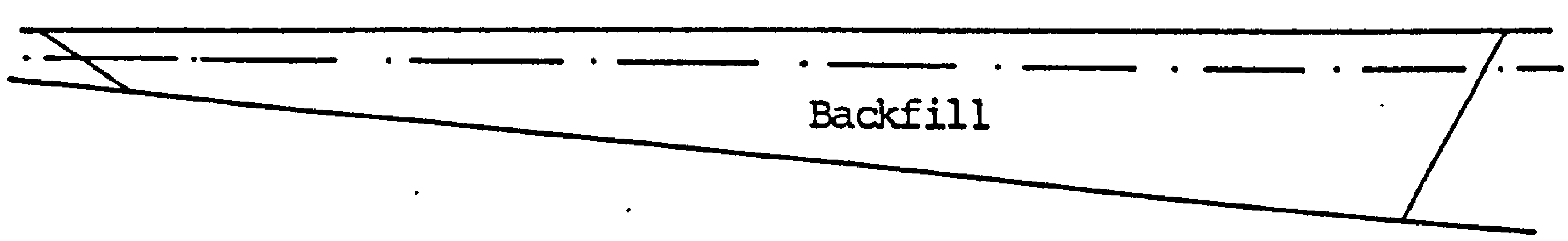
a). Advancing Down-Dip Surface Mine. Groundwater Depressed by Pumping.



b). As Mine Progresses, Water Recovers within the Spoil.



c). Mine Approaches Completion, Groundwater Rising through Spoil



d). On Completion, Groundwater Recovers to Equilibrium Level.

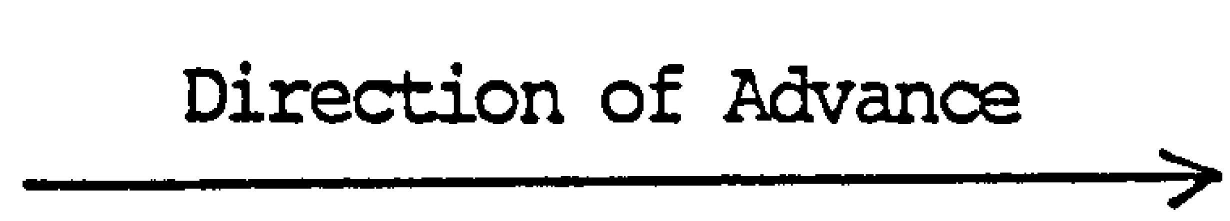


Figure 1.5. The Sequence of Groundwater Recovery.

infiltrating water or conversely as a source of water inflow.

b). The Nature of the Backfill.

The permeability of the backfill is largely dependent on the method of mining and restoration. Permeabilities of dragline spoils and spoil lain by dump trucks are much greater than those which have been subjected to an extra degree of compaction as in spoil which has been scraper lain. The type of material within the backfill is also of importance. A clayey backfill will be much more impermeable than one consisting of sandstone. The permeability of opencast mine backfills have been measured at between 10^{-4} and 10^{-8} m/s, depending on the argillaceous content of the particular fill. The type, thickness and extent of fill is also of importance and greatly affect the rate and manner with which water will percolate and re-establish to equilibrium.

c). Climate.

The climate of an area affects the rate of recharge within the near surface strata. In areas of high rainfall, the rate of recharge will be obviously higher than in lower rainfall areas. Effects are seasonal and at certain times of the year the groundwater may become static owing to ice and snow. In colder months the phenomenon of frost heave may occur resulting in an increased permeability of the near surface layers.

The period over which recovery takes place has been suggested as generally nine months, (Ferguson, 1984). For smaller sites in wet areas recovery would be expected to have been completed within one year of initiation. On larger sites in drier areas periods of years may be required. Part of this thesis is aimed at evaluating these periods.

1.5.3 The Effects of Groundwater Recovery.

The consequences of groundwater recovery in a backfilled surface mine site can be summarised into three categories;

i). The pollution of groundwater by contaminating wastes.
ii). The acceleration of backfill settlement rates.
iii). The creation of final void lakes or flooded areas.

The aims of this research are to evaluate the problems associated with groundwater recovery principally from the pollution and backfill settlement effects.

1.5.4. The Pollution of Groundwater By Contaminating backfill Wastes.

The rise of the watertable through the backfill mass on the cessation of pumping brings the groundwater into contact with highly weathered and broken backfill, and thus into any minerals within the fill which may react with the water to produce a polluting or toxic discharge. If such polluted waters leave the mine site and enter natural water courses then there are potentially drastic ecological effects.

1.5.5. The Settlement of Opencast Mine Backfill.

The action of water on the fill not only induces chemical changes but continues physical weathering processes. Settlement of fill materials is particularly important in cases of structural development, whether it be houses, roads or underground services. The research investigates the effect of groundwater on the rates of backfill settlements on a number of opencast mine sites in the United Kingdom. Aspects of backfill settlement are detailed in chapter 2. Field work is presented in Chapters 3, 4, 5 and 6.

1.5.6 Creation of Final Void lakes and Flooded Areas.

In the United Kingdom the creation of final void lakes, fig 1.8 are rare, a notable one being the Shipley Park recreation area in Derbyshire. In general they are always created with intent and thus are not a problem. The creation of flooded areas however can be a problem resulting from differential settlements of backfill producing ill-draining land. Alternatively they may be caused when a recoverying water table rebounds to surface. Such problems are normally avoided by the introduction of subsurface drainage in the latter years of the 5 year post-mining maintenance period.

1.6. RESEARCH OBJECTIVES.

1.6.1 Research into Water Pollution and Groundwater Recovery.

Research into groundwater pollution as a consequence of recovery in opencast mine fills consists of analysing mine water samples for polluting constituents. The objectives of the research are three fold.

a). To estimate the potential pollution loads which may be expected to generate from an opencast mine backfill material.

b). To observe polluting effects on local groundwater geochemistry.

c). To discuss methods of combatting a pollution problem.

Chapter 7 details an introduction to water pollution whilst chapter 8 presents the results of a geochemical survey conducted upon opencast mine waters in the United Kingdom. The research attempts to correlate the following;

a). Local groundwater geochemistry.

b). Levels of water within fill materials.

c). Material facets of Fill materials.

d). Ages of backfill.

1.6.2 Research into Backfill Settlements and Groundwater Recovery.

Field work consists of the instrumentation of selected opencast mine sites. Chapter 2 gives an introduction to aspects of backfill settlement, whilst chapters 3, 4 and 5 present the detailed instrumentation programmes and results from three opencast mine sites. Chapter 6 reviews backfill settlement and groundwater information on a number of sites for which past data has become available.

Correlations are drawn between groundwater recovery and backfill settlements with particular regard to the following criteria.

a). Properties of Fills, types, thicknesses and extents.

b). Degree of Compaction, in relation to mining method.

c). Water recovery and recharge rates.

d). Backfill ages and permeabilities.

The effect of differential settlements on land drainage and a discussion on lateral movements in opencast fills are also discussed.

CHAPTER 2.

THE STABILITY OF BACKFILL MASSES.

CHAPTER 2. THE STABILITY OF RESTORED BACKFILL MASSES.

2.1 INTRODUCTION.

The extraction of one tonne of coal may typically entail the removal of 20 m^3 of overburden under British conditions, (Charles et al 1977) and as a consequence of the backfilling operation, opencast mining leaves areas where the depth of loose backfill materials can be considerable. These unconsolidated materials have the capability to undergo significant settlement, with the degree and timescale of such movements being of extreme importance in cases where workings are required for surface development such as the construction of buildings, roads, railways or subsurface services.

This Chapter reviews the many interrelated factors which affect the nature of backfill stability and presents a brief review of previous studies in this field. Instrumentation for monitoring backfill movements are detailed and finally the process of site selection for instrumentation is presented.

2.2 THE BULKAGE OF BACKFILL MATERIALS.

Broken rock strata when used as a backfilling material can exhibit considerable volume changes as compared with the original intact material. Silts and plastic clays will soften and expand considerably when excavated wet, whilst soft organic materials such as peat can compress on dumping. On a normal surface mine site, despite the fact that 4-10% of the excavated strata is removed as coal, the overall bulkage of the backfill will usually result in the final landscape being at least the level of the original, if not even higher. Examples of recorded backfill bulkages for completed sites are presented in table 2.1. The range can be seen to be -3 to +12.2% with The lower figures being attributable to peaty sites, (Ferguson 1984).

Table 2.1

Bulkage of Completed Sites.

(Ferguson 1984).

Site Name	Bulkage%	Coal%	Remarks.
Auchingilsie	12.2	5.6	40% hard rock.
Shannockhill	10.9	7.2	27% hard rock.
Threeprig	10.3	5.5	38% hard rock, some peat.
N. Remiltoun	10.1	3.7	33% hard rock.
Waterhead	7.6	5.5	Small, shallow Site.
Fauldheads	1.3	4.4	26% hard rock, Peaty.
West Moss	-3.0	6.9	12% Peat.

2.3 SETTLEMENT OF FILL MATERIALS.

2.3.1 Effect of Mining Method.

In general the plant which operates on surface mine sites is large, cumbersome and heavy, giving complimentary compaction to the backfill mass. Strip mining operations using draglines, or tipping by truck and shovel operations result in a limited amount of layering with effective compaction at bench level, whilst at the other end of the scale, spoil handled by motorised box scrapers is given the most efficient system of compaction and consolidation excepting cases where some deliberate form of compacting machinery is used, (e.g. sheeps-foot roller).

Typical opencast mine backfills are left reasonably dense on the completion of operations, even those deposited by draglines, and it is the initial bulkage of the fill material which affects the total degree of settlement which the mass will undergo in time. The initial bulkage is in turn related to initial particle size. The larger the particle sizes within the fill than the greater the degree of size breakdown that can occur and consequently the greater the degree of settlement which will arise.

Figure 2.1 shows the settlement-time curves obtained from an investigation conducted by Knipe, (1981). In general both scrapers and dump trucks were used to lay the fill, but in some areas spoil was left loose-dumped resulting in a relatively unconsolidated fill mass. The curves illustrate well the differing degrees of settlement which can occur on a single site as a result of different backfilling techniques.

2.3.2. The Physical Weathering of Coal Measure Rocks.

The stresses exerted by the action of water may have a great effect on the backfill particles owing to the ability of

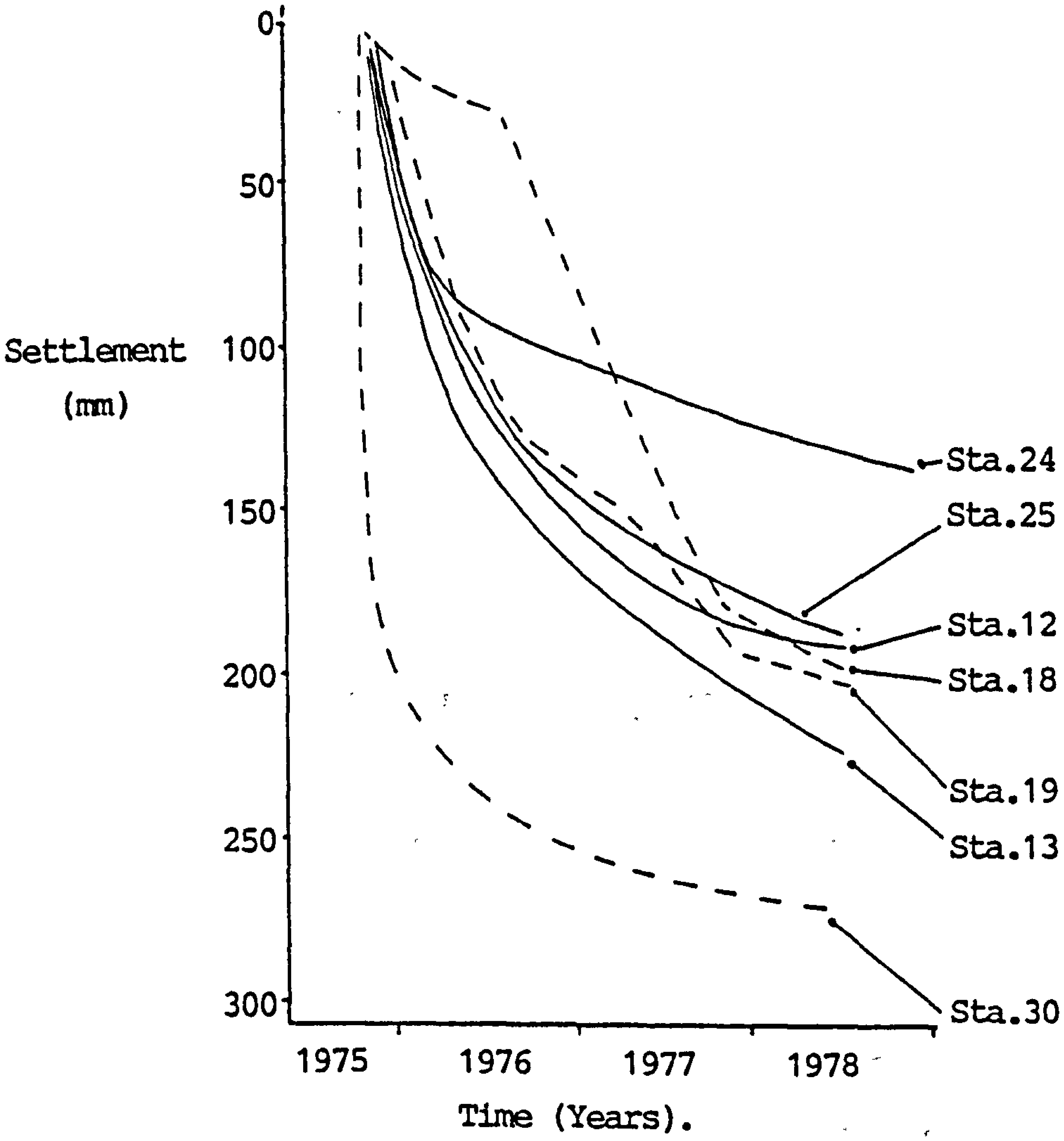


Fig. 2.1 Clockfields Site:- Settlement Observations. (Knipe 1981).

Stations 18, 19 and 30	:- Uncompacted Fill.
Stations 25, 12 and 13	:- Scraper Lain and End Tipped.
Station 24	:- Compacted Fill

water to weaken rock strength. The strength of a rock is proportional to its surface energy, and thus when the surface of the rock is wet then the surface energy is reduced resulting in a reduction in its compressive strength.

The physical weathering of rocks by water can be divided into four groups, (Huggins 1975).

a). Scouring Action of Particles.

b). Swelling.

c). Air Breakage.

d). Freeze Thaw.

a). The Scouring Action of Particles.

This phenomenon is confined almost completely to the surface of the spoil, during and immediately after heavy rain. Scouring may also occur during the percolation of water through the backfill. Weathering within a mine fill can be a combination of two effects working together, firstly the presence of water a secondly the crushing of the backfill under its own weight.

b). Swelling.

Many coal measure rocks, notably mudstones contain laminated layers of clay minerals which swell on contact with water. This swelling is a result of water being taken into the inter-layer structural sites, ie grain spaces. Swelling of rock particles within a fill can induce additional compressive stress on the rock resulting in increased crushing effects.

c). <u>Air Breakage.</u>

The mechanism of air breakage can be attributed to capillary action. When the rock mass is wet, large pressures build up in the pores as a result of the air which compresses as water enters the capillary spaces. This may give rise to literally an explosive phenomena. Several cycles of wetting and drying are required before disintegration will occur.

d). <u>Freeze-Thaw.</u>

Freeze-thaw is a process entirely restricted to the winter months, and is a result of water in the cracks of the rocks freezing and consequently expanding, exerting large pressures on the rock which impart when the ice thaws. The larger (near surface) portions of the backfill are particularly vulnerable and these can break down into smaller particles. Settlement thus proceeds by virtue of the reduction in size of the larger void spaces within the fill as smaller particles are compressed by self weighting effects.

Overall the breakdown of backfill materials by both chemical and physical weathering will result in the consolidation of the fill mass as the larger particles within the fill are broken down.

2.3.3. Consolidation Settlements of Backfill Materials.

In deep fills self-weight is often the principal source of settlement, (Charles, 1984), this primarily occuring on the immediate placement of the fill. (Along with compactive effects from mining machinery). Collapse settlements may then occur in the presence of groundwater. Following these effects significant movements can still occur under conditions of constant effective stress and moisture content - this being termed creep settlement. Creep settlements have been observed to follow the logarithmic decay such as was indicated by Kilkenny (1968) in his work on assessing the suitability of restored opencast sites for structural development. Charles defines a parameter α which is defined as the percentage vertical compression of a fill in a log cycle of time. Typical values of α are given in table 2.2.

Table 2.2

Creep Settlement Rate Parameter .(Charles 1984).

Fill Type.	Typical Value α	Reference.
Well compacted Sandstone Rockfill.	0.2%	Charles (1973)
Uncompacted opencast mine backfill.	0.5 - 1.0%	Charles (1977) Kilkenny (1968) Knipe (1979) Leigh and Rainbow (1979)
Domestic Refuse.	2 - 10%	Merz and Stone (1962) Rao et al (1977) Sowers (1973)

2.3.4. The Effect of Groundwater Recovery.

A recovering water table will have the effect of accelerating the processes of physical and chemical weathering as the water level rises through the fill, (Charles et al 1977, 1984). Results from a unique experiment on the Horsley opencast mine site in Northumberland have shown a significant influence on settlement induced by groundwater.

The Horsley opencast coal site had been worked between 1961 and 1970, winning approximately 37,000 tonnes of coal whilst excavating to a maximum depth of 63 m. The site was backfilled and restored in 1970 and intermmitent pumping continued until 1974, when settlement and water level gauges were installed. These instruments known as combined magnetic extensometers/ piezometers could directly relate the position of the groundwater table with zones of backfill settlement throughout the vertical section of the backfill. These instruments are discussed in detail in section 2.5. The instrumentation layout on the Horsley site investigated five predominant features on the site which could influence the degree and nature of backfill settlements, namely;

i). Oldest Fill.

ii). Deepest Fill.

iii). Fill in the vicinity of lagoons.

iv). Fill previously overlain by a spoil heap.

v). Most recent fill.

The instrumentation scheme is illustrated in figure 2.2. An example of the results are presented in figure 2.3 which illustrates the trend of groundwater recovery and backfill settlement for the instrument situated in the deepest fill on the site. The figure shows a close correlation between settlement and recovery rates and in general the results showed that the position of the water table was the most significant influence on the settlement of the backfill mass.

Water levels over the site recovered 20 metres in the first year and 9 m in the second with total recovery being completed within five years. The total recovery amounted to about 34 m.

The most important results from the Horsley experiment were as follows:

a). Settlement characteristics were heavily influenced by such features as lagoons - which can presaturate the fill resulting in ultimately less settlement, and by spoil heaps - which act as fill surcharges. On the removal of an overburden heap on the Horsley site, small heaving movements were observed resulting from overconsolidation of the underlying fill.

b). A significant proportion of the measured settlement was found to be due to compression in the upper 10 m of fill which had not actually being saturated by the water table. This indicates that groundwater may well serve to only accelerate settlement rates rather than increase total settlement magnitudes.

Several cases of destructive damage to structures constructed on opencast mine sites have been recorded. Leigh

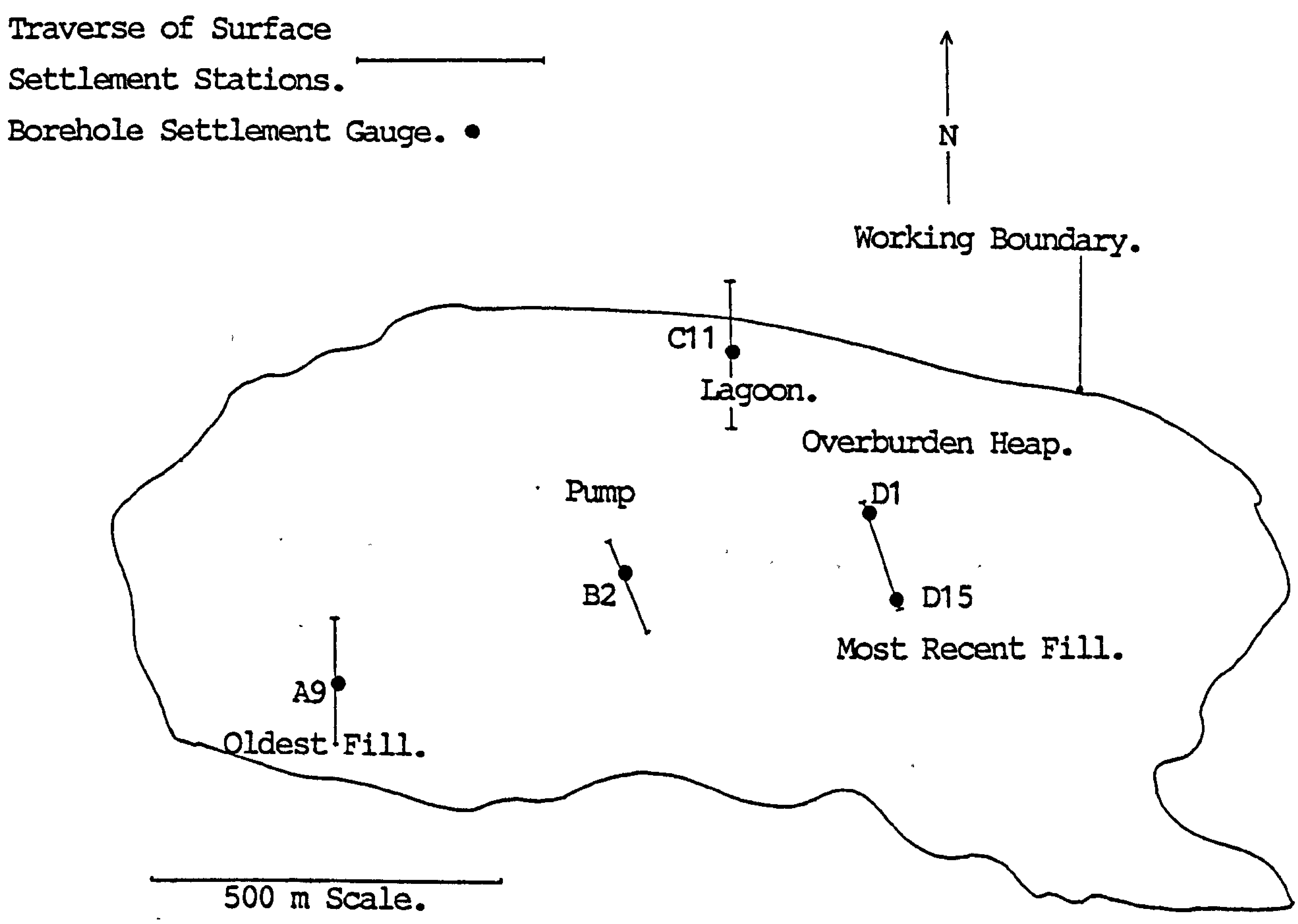


Fig 2.2 Plan of Horsley Site showing positions of Instruments.

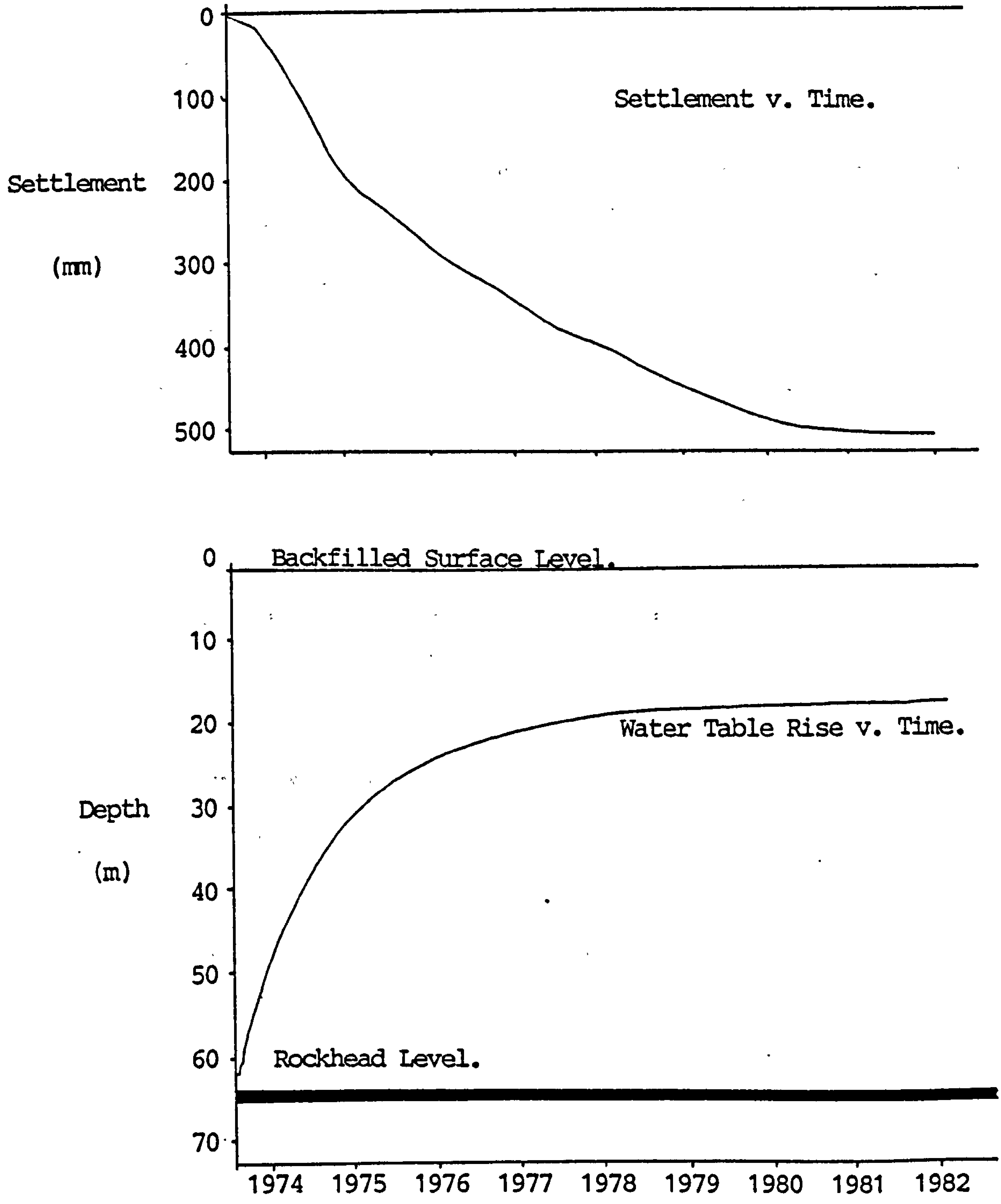


Fig 2.3 Settlement of Backfill and Rise of Water Table at Horsley O.C.C.S. (Charles 1984).

and Rainbow, (1979) report on a factory built in 1971 on fill which restored in 1953, leaving a fill 18 m deep. Substantial damage to the factory occured in 1977. Pumping in the area from underground mining had ceased by 1972, initiating the re-establishment of groundwater levels. Following damage, a site investigation revealed that the lower portions of the fill had been saturated resulting in a compression of 4.5% of the fill depth.

Guest, (1975) reported damage inflicted on a block of terrace houses constructed in 1973 on fill of 10 m thickness and 13 years old. Structural damage was reported in 1973. Investigations showed that drain trenches had filled with water indicating that saturation had been a major influence on the degree of differential settlement.

2.4 FURTHER OBSERVATIONS ON BACKFILL SETTLEMENTS IN THE UNITED KINGDOM.

Knipe (1981) presented results of backfill settlements on five opencast mine sites in the West Midlands. The project studied backfill settlements on sites on similar fill characteristics and thus attempted to evaluate principally the effect of mining method. An example of these results have already been presented in figure 2.1. The work inferred but did not evaluate the effect of groundwater on backfill settlements.

Recent studies of backfill settlements have been conducted by Smyth-Osbourne, (1984) who examined the settlement of a factory and damage induced by siting the structure partially on opencast backfill material, i.e. over a highwall. Additionally, Buist, (1984) studied deformations in a motorway carriageway which had been constructed on a restored backfill surface. Both researchers reported that changes in groundwater levels may have had effects on backfill settlements.

2.5 INSTRUMENTATION TO MONITOR GROUNDWATER RECOVERY AND BACKFILL SETTLEMENTS ON SURFACE MINE SITES.

2.5.1 Introduction.

This section describes instrumentation for the monitoring of groundwater recovery and backfill settlements. These instruments have all been used in this study. At this point only a description of their function will be given. Modifications and actual instrumentation procedures are given in full in chapters 3, 4, 5 and 6 which deal with specific site monitoring.

2.5.2. The Magnetic Extensometer/ Standpipe Piezometer.

This instrument is a method designed to relate groundwater levels within a soil or rockfill mass to the settlements which occur at various horizons within that mass. Settlement and heaving movements are assessed by monitoring the location of magnetic targets positioned in the fill over a vertical access tubing, (figure 2.4). Location of the targets is accomplished

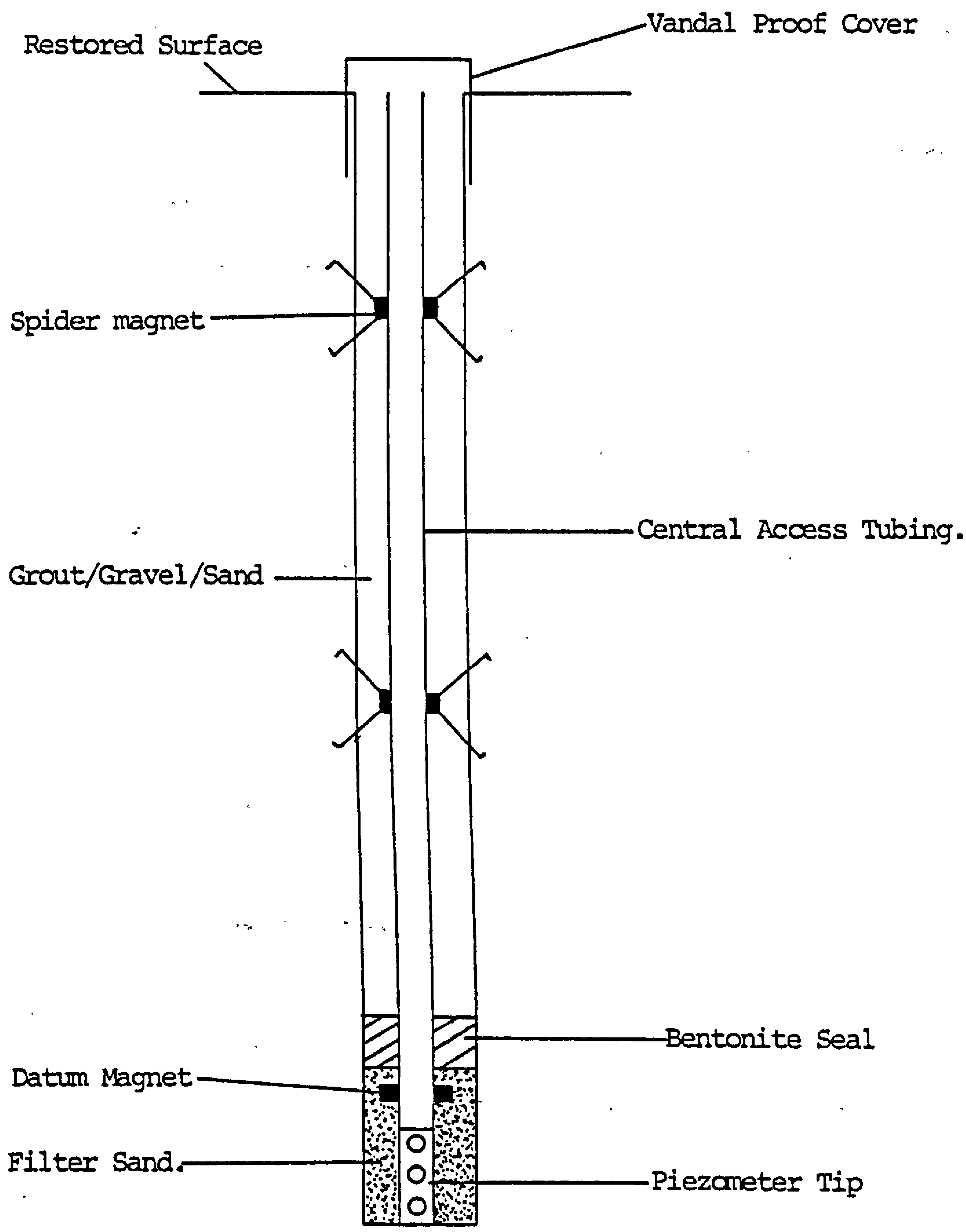


Figure 2.4. The Combined Magnetic Extensometer/Standpipe Piezometer.

from surface by passing a Reed Switch Probe down the hollow access tubing. When the probe enters the magnetic field generated by a target an audible signal is emitted at surface. A steel tape from which the probe is suspended is then used to read off the depth of the magnet from the top of the access tube. All measurements are referred to a datum ring magnet which is installed at the base of the hole beneath the level of the fill. Magnet movements can thus be evaluated by assuming that no movement occurs below the base of the fill in the bedrock. The magnets contain a well defined null point so that accurate repeatable results may be obtained.

A standard piezometer tip at the bottom of the access tubing enables the instrument to serve the dual purpose of a standpipe piezometer thus measuring water levels within the fill with a conventional dip meter.

The components of the system can be detailed as follows;

a). Flush Coupled Access Tube.

The 23 mm diameter tubing which is supplied in 3 m lengths serves a two fold purpose; to act as an access tubing for Reed Switch and Dip meter probes and to act as a "runner" along the outside of which the magnetic targets are free to move with the fill.

b). Magnetic Targets.

All installations have a circular ring magnet at the bottom of the access tubing to act as a datum. The moving magnets come in two forms which depend on installation method. They consist of a circular central magnet to which either three or six metallic strips are attached in a spiders legs arrangement, which form the contact with the fill.

c). Piezometer Tip.

At the base of the hole is a standard Casagrande type B piezometer tip, the coupling being slightly modified to fit the 23 mm diameter tubes. Normal piezometer tubing being 19 mm diameter. In the borehole the tip is surrounded by filter sand and a bentonite plug is placed on top of this to form an effective seal.

d). Flexible Outer Sleeving.

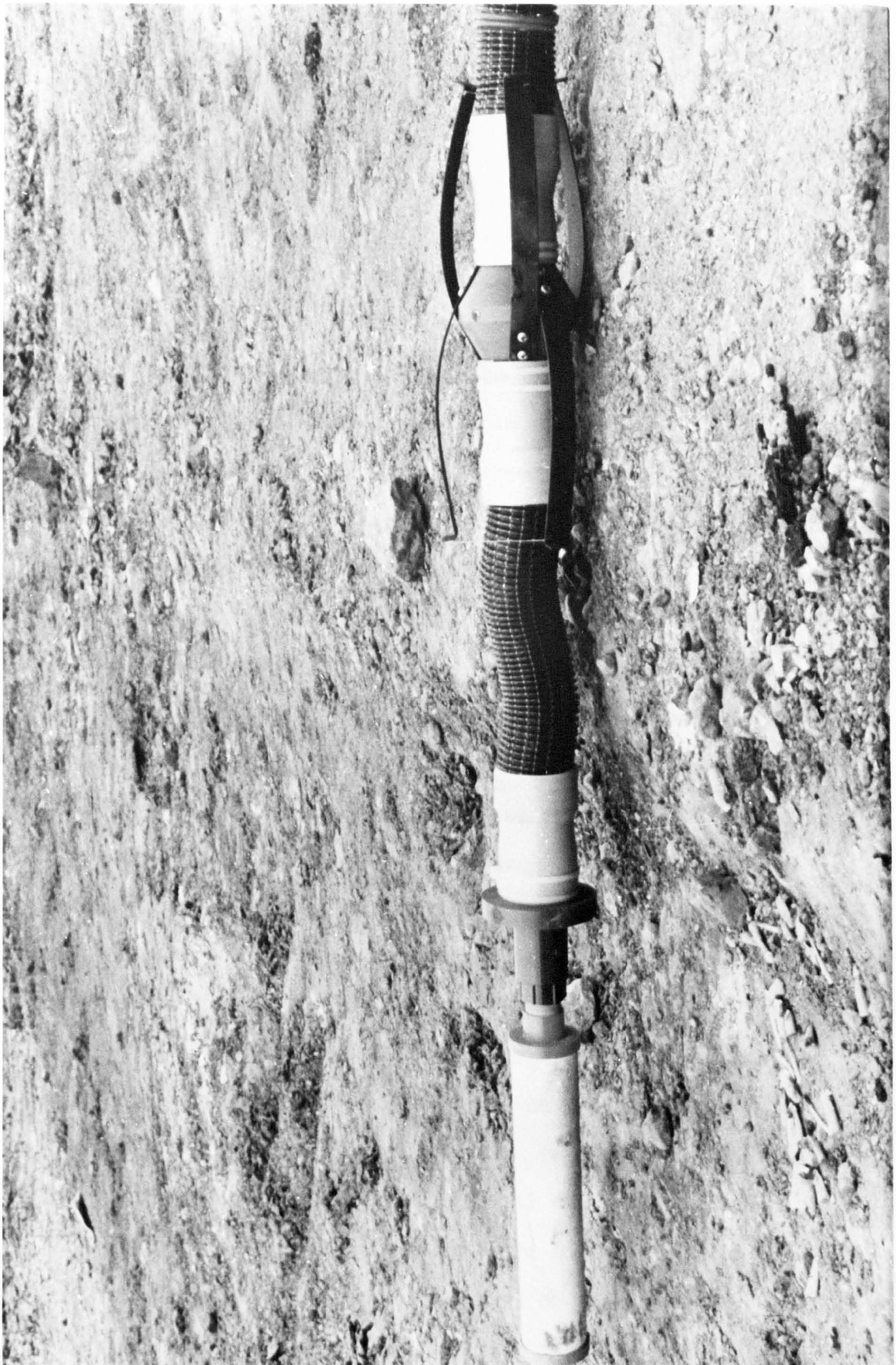
A flexible outer sleeve fits over the access tubing and physically connects each magnet to each other. The magnets are connected to the sleeving by a special thread moulded into the PVC material of the sleeve and the magnet. The aim of the flexible sleeve is to prevent any particles whether spoil or grout from preventing the magnets sliding down the access tubing freely.

PLATE 2.

COMPONENTS OF THE MAGNETIC EXTENSOMETER/

STANDPIPE PIEZOMETER INSTRUMENT.

Plate illustrates Piezometer Tip, Datum Magnet,
Flexible Sleeving and Spider Magnet.



2.5.3. The Tension-Wire Extensometer.

a). The Basic Instrument.

The Tension-Wire Extensometer Instrument consists of three basic components:-

a). Firm anchorages in the borehole to form a contact with the fill, from which measurements may be taken.

b). A tensioned mechanical linkage between the individual anchors and the surface.

c). A means of assessing any length change that the mechanical linkages may be subjected to.

The Multi-Wire system has the advantage that once installed nothing has to travel the hole in order to make measurements. The sources of error in the instrument can be broadly summarised as the avoidance of excessive temperature fluctuations and the avoidance of excessive friction in the system. Constant tension systems have been shown to eliminate many sources of error, and have shown that errors are independent of strain wire length, (Hedley, 1969).

Fig. 2.5 details the basic instrument and illustrates how consolidation and shear movements may be determined. As with the probe type of instrument a datum is required in the bedrock beneath the fill. As the fill undergoes settlement then the wires in the hole linking the anchor points to the tensioning device on the surface appear to come out of the borehole. If shear movements take place then the wires appear to enter the hole. Both movements can be measured on the

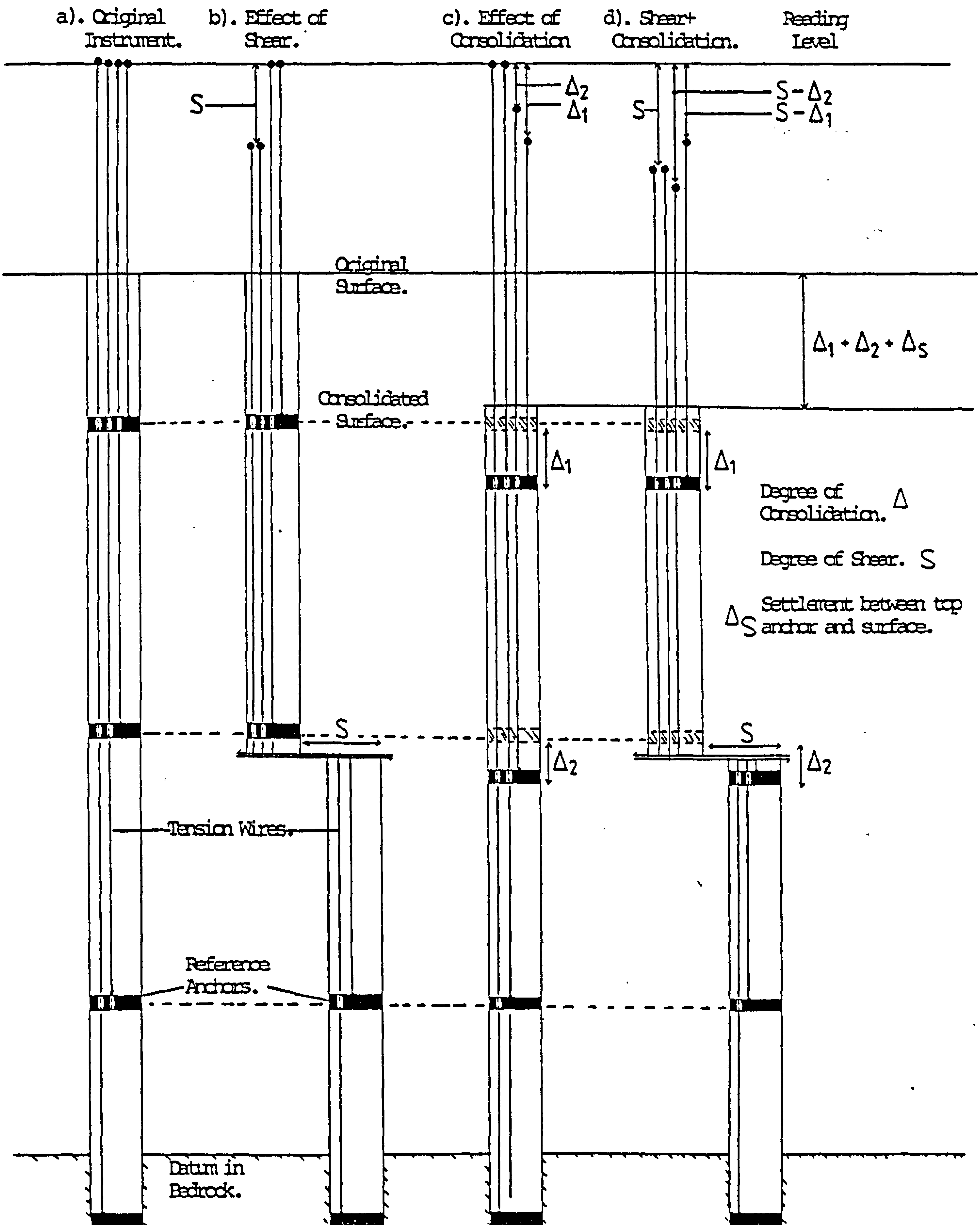


Figure 2.5 Measurement of Consolidation and Shear by Tension-Wire Extensometers.

surface and thus the degrees of settlement and shear may be evaluated and referred to anchor locations/horizons.

Conventionally the mechanical linkages are in the form of rods, tapes or wires. Using rods it is possible to achieve an instrumental accuracy of $\pm$0.01mm, but this form of linkage is usually associated with single point extensometers of only 10 m length/depth.

Tapes increase monitored lengths by up to 200 m but again there is difficulty in installing more than one anchor point, a difficulty which is overcome by the use of steel wires as the mechanical linkages transmitting the borehole strains.

In order reproduce repeatable readings the strain wires must be subjected to a set tension whilst measuring is taking place. Although the best method is to keep the wires in tension at all times it is still reasonable to apply temporary tension during readings.

To maintain constant tension at all times an extensometer head as illustrated in fig 2.6 can be used. For each anchor in the instrument a tensioning weight is require and readings are taken on the extensometer head with a depth gauge micrometer. Any change in the measured distance is a reflection of the displacement of the anchor with respect to the head of the extensometer.

One distinct advantage of this instrument is that its reading range is effectively limitless for practical purposes. Each of the strain wires can be cut so that a free length of 2 - 3 m of of wire protrudes beyond the base of the tensioning weight. If the tensioning weight drops or is raised to the

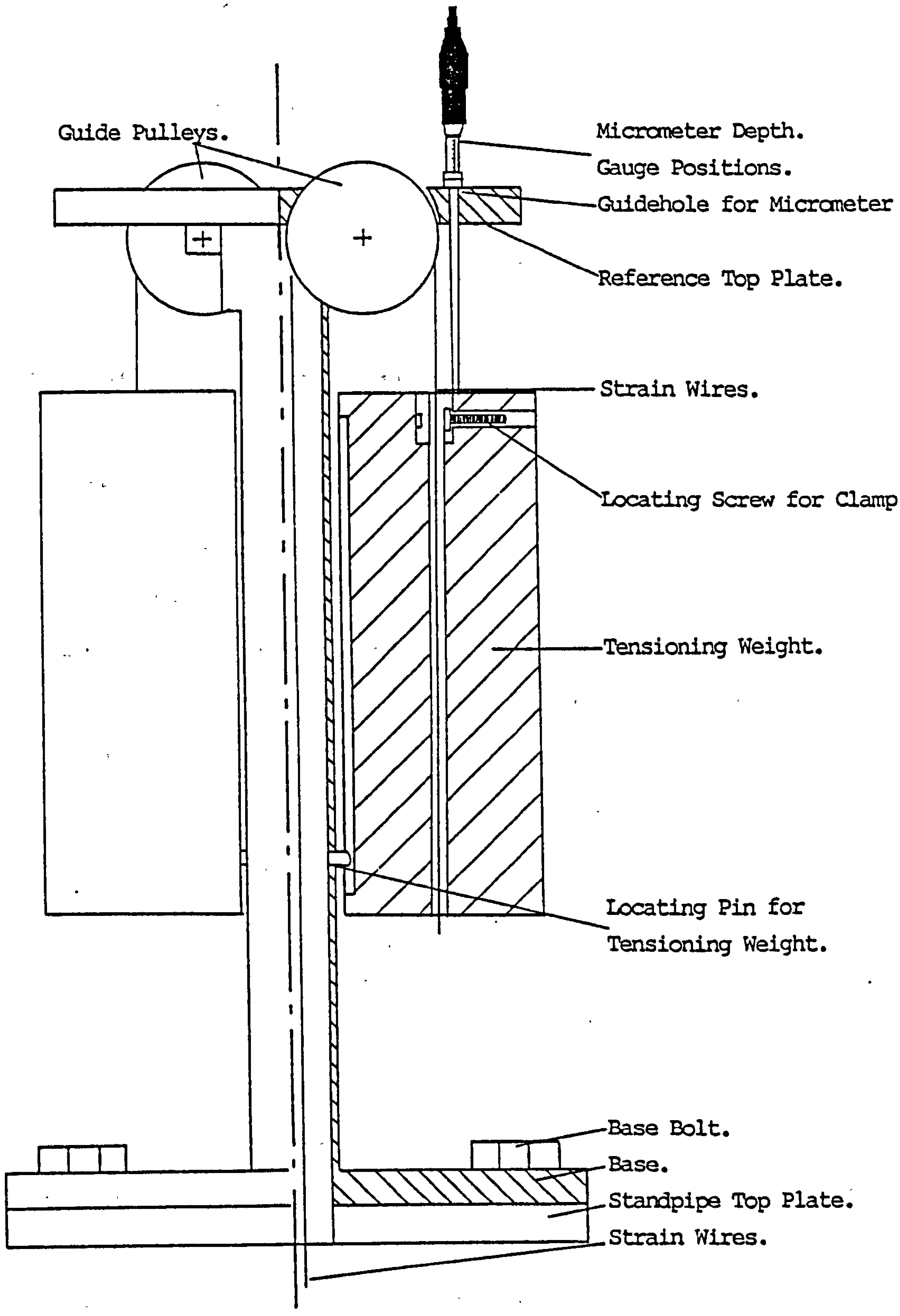


Figure 2.6 The Extensometer Head.
(after Whittaker and Woodrow, 1977)

limit of its travel, the reference depth is measured using the micrometer, and the position of the weight on the strain wire is adjusted by loosening the strain wire clamp and reclamping it at a suitable point. The reference depth is re-read and the subsequent data is adjusted accordingly.

b). <u>Modifications for Permeability Testing.</u>

The above instrument may be modified by the inclusion of test compartments to enable the conduction of permeability tests. Fig. 2.7 illustrates a typical installation with four seals. An individual seal is detailed in fig 2.8. The strain wires are contained within 12 mm continuous tubes as supplied by Celtite Selfix Ltd, Alfreton, Nottingham and these tubes allow the pumping of water into the borehole to the various testing compartments.

The principle of the pumping-in test as conducted using this instrument is to pump water at pressure into each individual compartment. When the compartment fills with water, steady-state conditions are obtained and inflowing water quantities and pressures are measured. From these values permeability values may be calculated for each compartment. In this way an attempt can be made to monitor consolidation by changes in permeability. A special end-piece must be attached to the instrument to enable a pressure seal to be constructed around the tension wire, (figure 2.9). The mathematical relationships are illustrated in figure 2.10. The arrangement for the conduction of a pumping test is presented

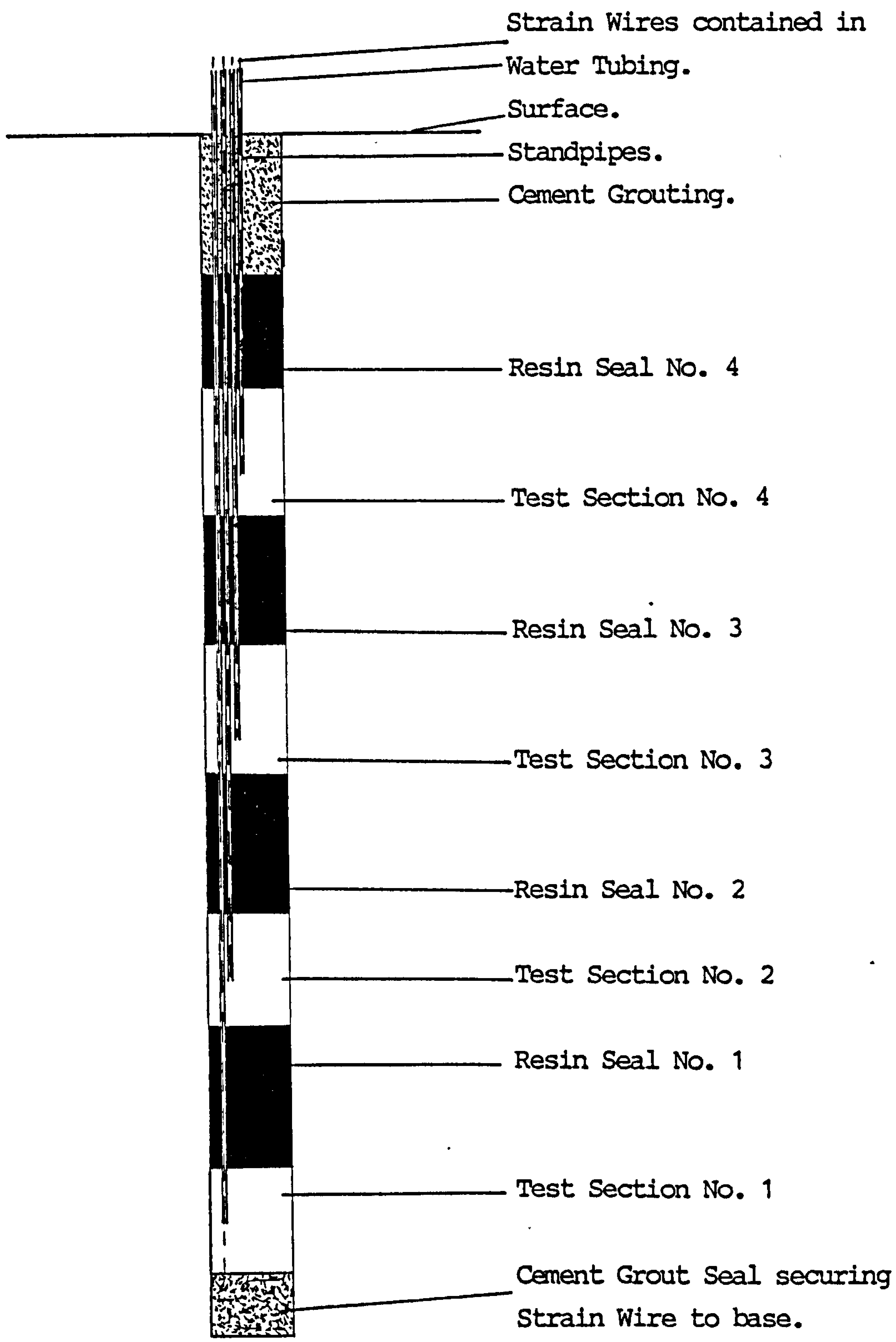


Fig 2.7 Basic Design of Tension-Wire Extensometer modified for Permeability Testing, (Whittaker et al, 1979).

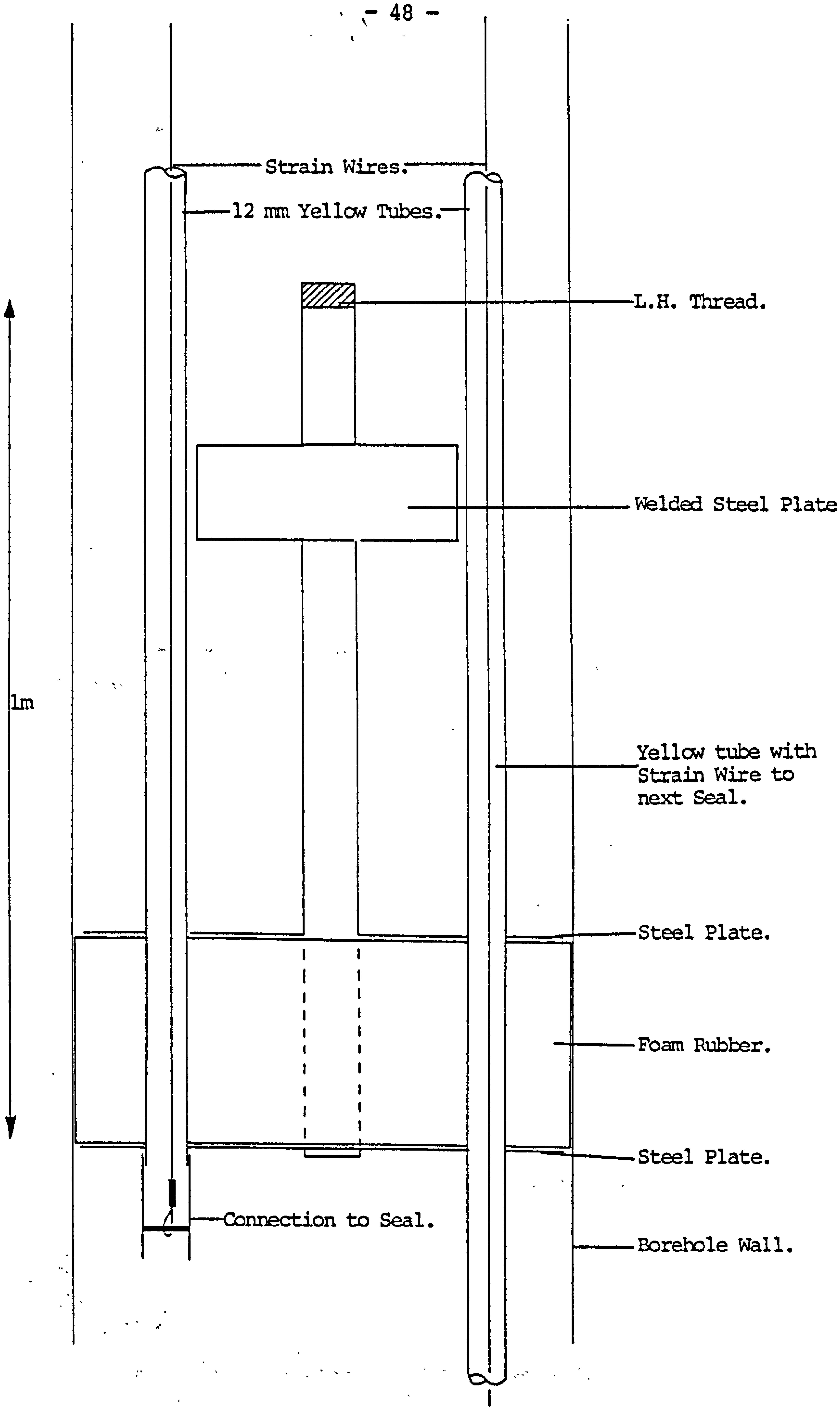


Figure 2.8 The Design of Mechanical Seals.

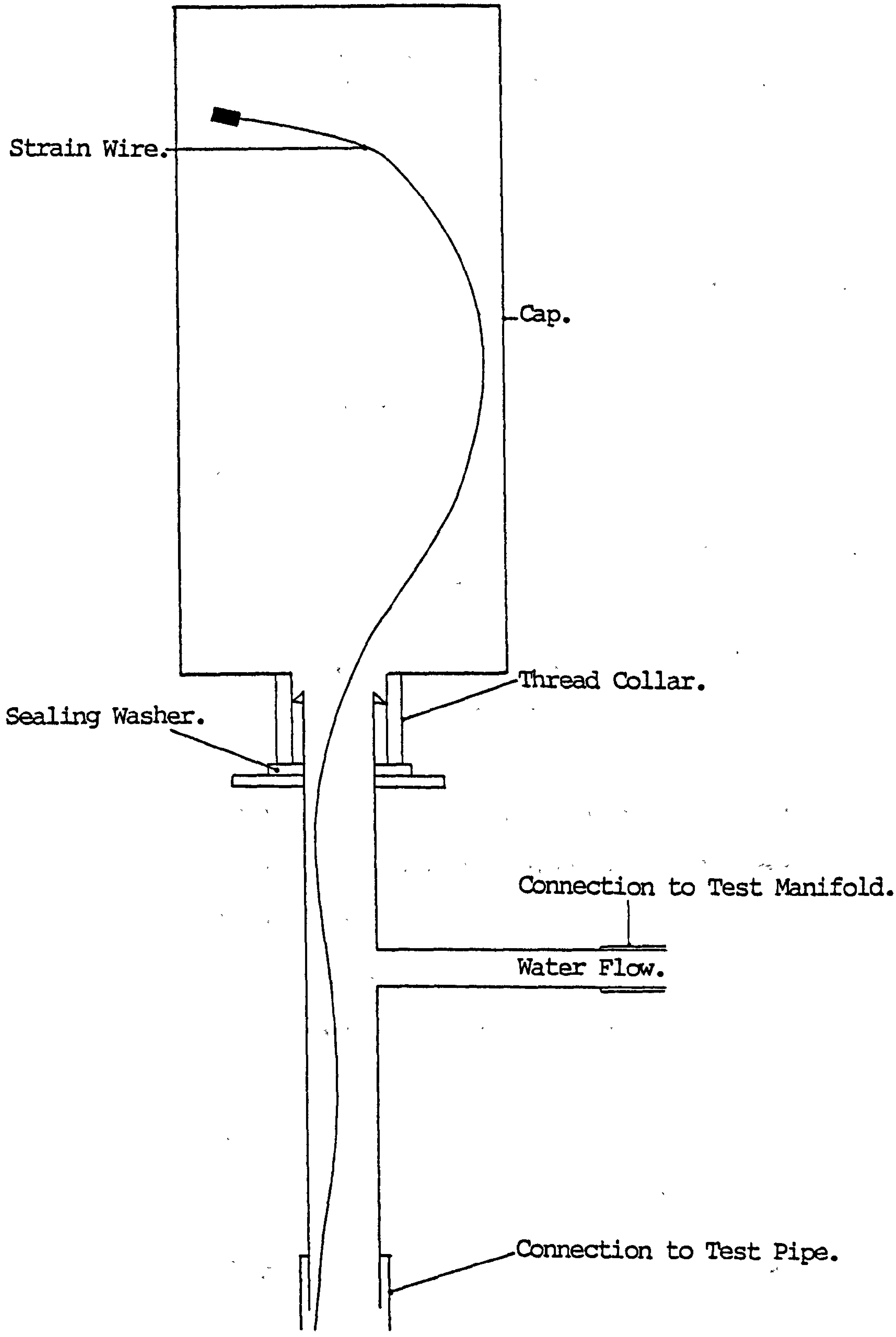
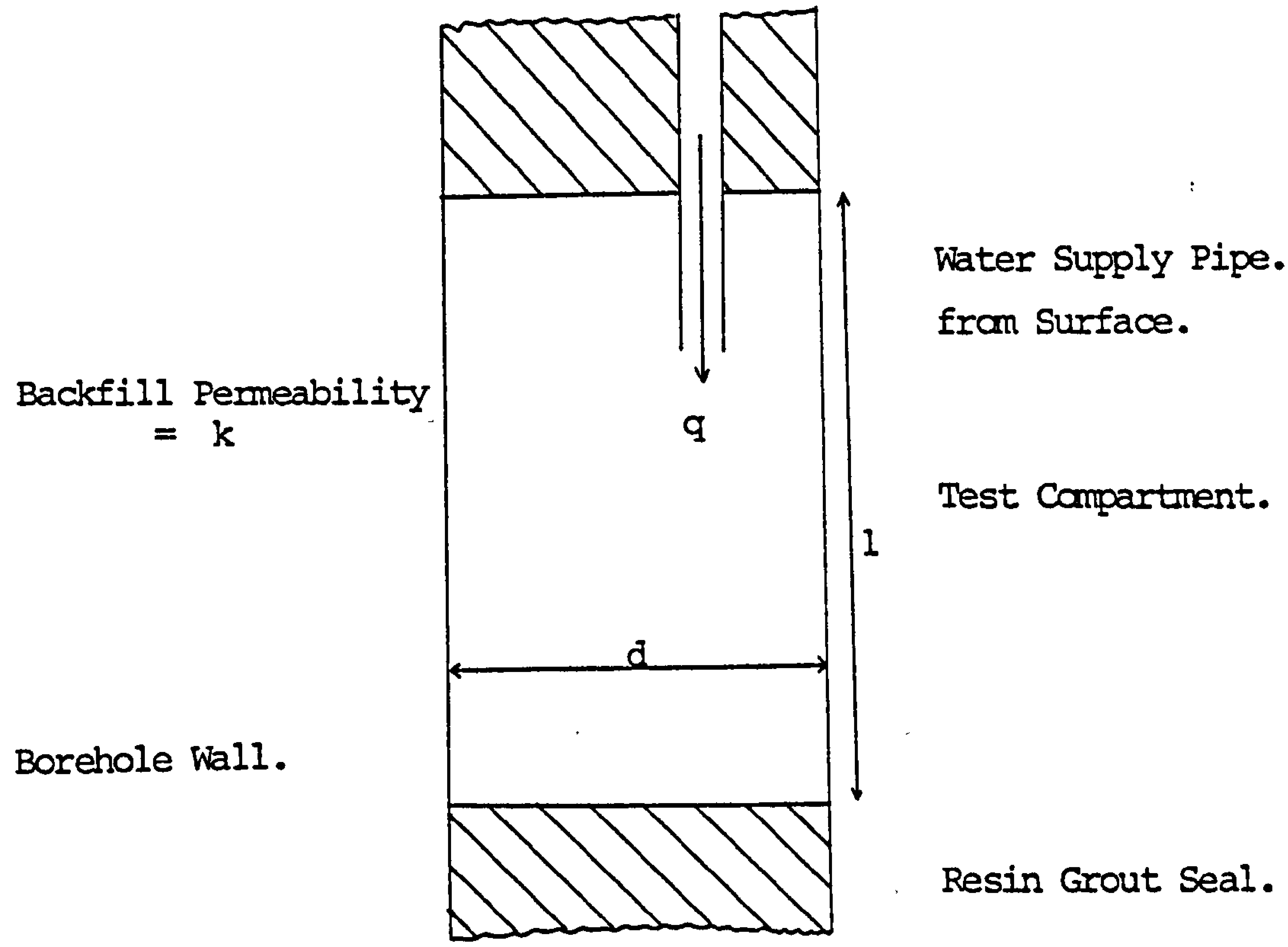


Figure 2.9 Tension-Wire Extensometer End-Piece (required for conduction of permeability tests).



$$k = \frac{q.\ln(2.m.l/d)}{2.\pi.l.H}$$

k = Coefficient of Permeability normal to the compartment, m/s.

k_p = Coefficient of Permeability parallel to the compartment, m/s.

q = Flow Rate, m^3/s

l = Length of Test Cavity, m.

D = Borehole diameter in Test Cavity, m.

m $= (k/k_p)^{1/2}$

H = Constant Pressure Head of Water applied during test, (above any original groundwater value), m.

Figure 2.10 Determination of Permeability from Pumping Test Data.

in figure 2.11. Appendix 1 details an example of a permeability calculation.

2.5.4 Single and Multi-Point Piezometers

a). Single Point.

The single point piezometer is an extremely simple instrument for monitoring water levels in rock strata. The instrument consists of a porous tip which is installed in the base of the borehole, linked to the surface by a 19 mm diameter hollow PVC access tube. An electrical dip meter is lowered down the access tube and gives an audible sound when water is encountered. The water levels in the tubing directly give the water levels in the rock.

b). Multi-Point.

The multi-point piezometer is an extention of the single point instrument by having more than one piezometer tip in the hole, ie piezometers are installed to different depths within the borehole, figure 2.12 illustrates the principle. Bentonite seals isolate each of the tips from each other and ensure that the instrument does not act as a surface drain.

The objective of the instrument is to indicate by differences in water level, difference in water pressue within a vertical section. The instrument can also indicate the presence of perched water tables.

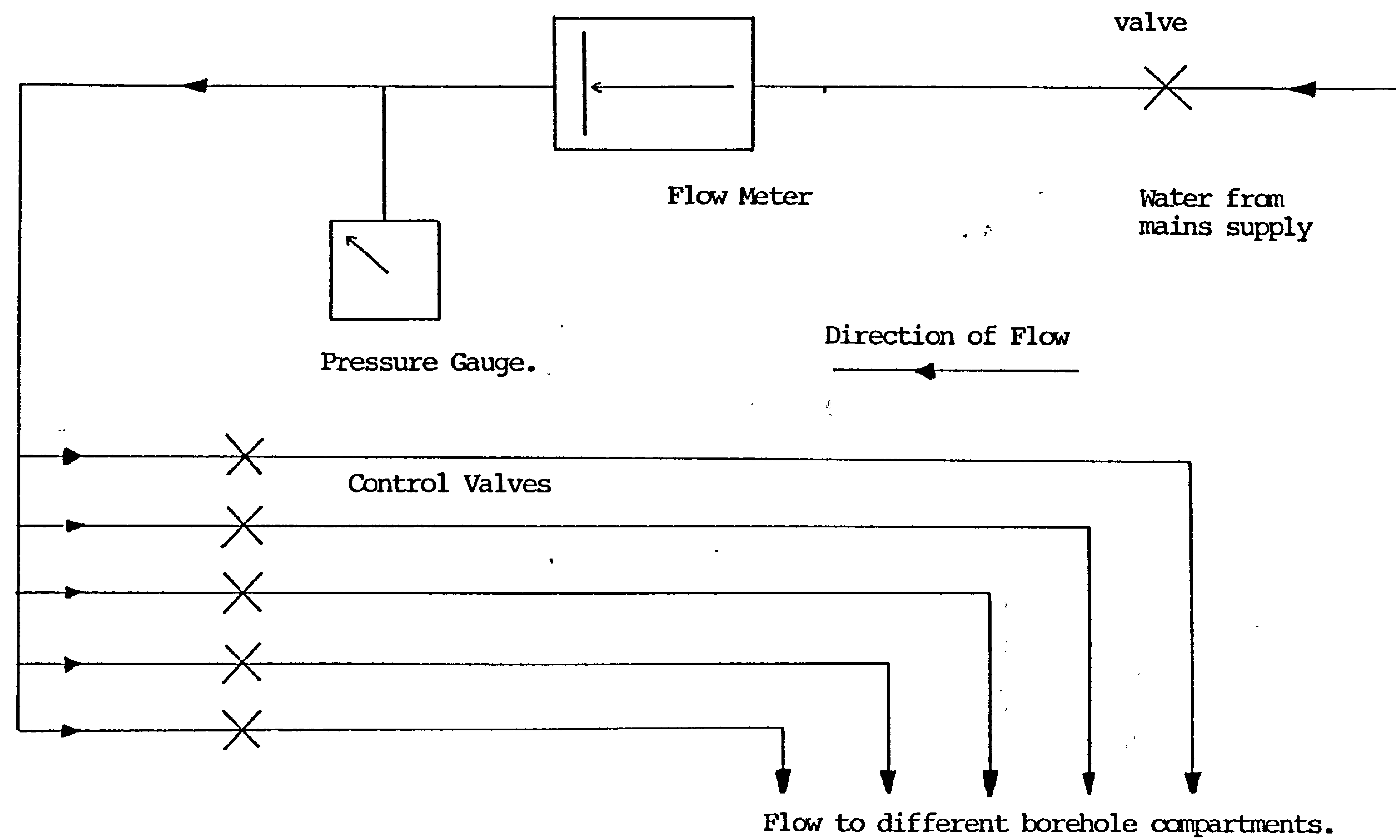


Figure 2.11 Schematic Diagram of Constant Head Testing Manifold.

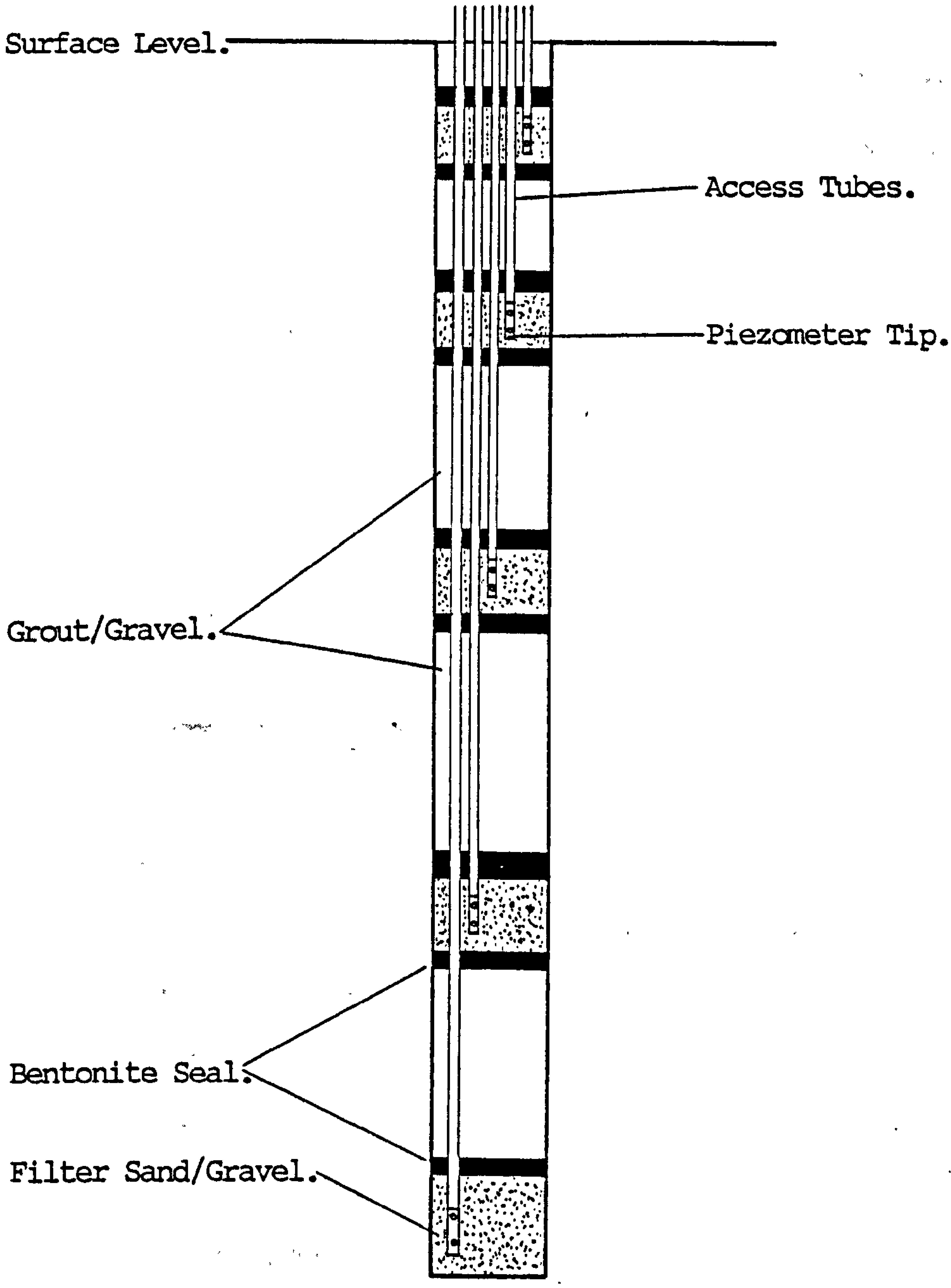


Figure 2.12 The Multi-Point Piezometer Instrument

2.5.5 Surface Levelling Stations.

A typical surface levelling station is illustrated in figure 2.13. These are used to supplement the information gleaned from the more expensive borehole instruments. When precisely surveyed, the instrument can provide the total vertical settlement of the fill beneath it along with a measurement of the lateral movement which has occurred at that point.

2.6 SITE INVESTIGATION PROCEDURE.

2.6.1 Preliminary Investigations.

Owing to the necessity to install instrumentation on opencast mine sites, a programme of site selection for settlement monitoring purposes was initiated. Selected sites would be ones nearing completion, with either the final void infilled or approaching this point. Instruments were planned to be installed on any selected opencast mine site once the final overburden levels had been achieved. This is necessary so that a minimum of settlement and groundwater recovery would be missed by delayed instrumentation. The chosen sites had obviously to be working and pumping beneath the level of the natural water table.

Several meetings were held with members of the Opencast Executive in all of the geographical regions, (Scotland, North-East, North-West, Central East, Central West and South

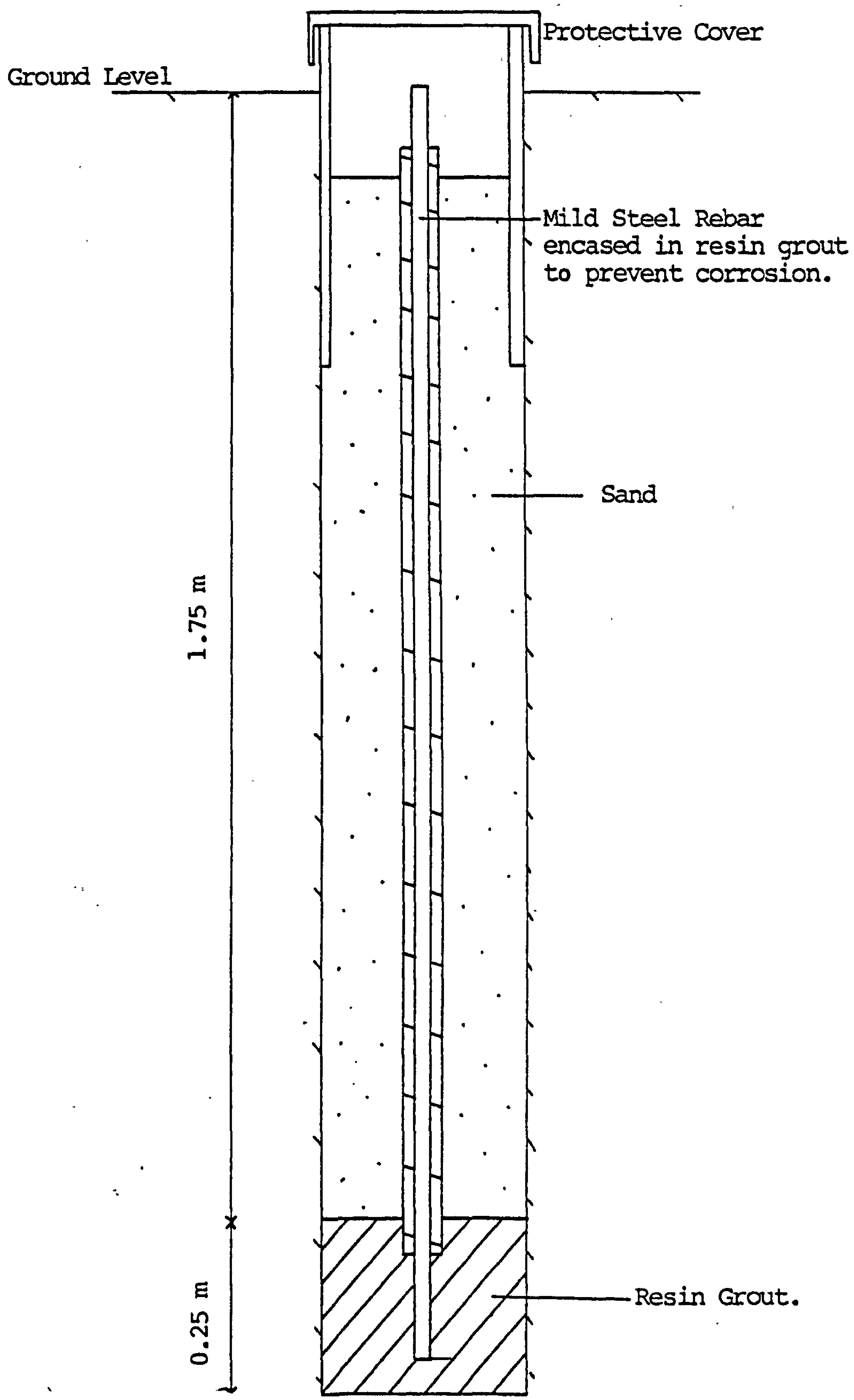


Figure 2.13 Surface Levelling Station.

Wales). Site visits were then made on the basis of the results of these meetings. In total about 20 opencast mine sites were considered. A proposed monitoring scheme was initially postulated and is illustrated in figure 2.14. The scheme aimed at monitoring two profiles of recovery and settlement across the mine site. The layout would change depending upon site restrictions, features and availability and suitability of instrumentation.

The site selection procedure led to initially two sites being selected for instrumentation. These were then supplemented by a site instrumentation project given to the University by the Scottish Region of British Coal. The selected sites can be summarised as follows:

2.6.2 Summary of Selected Sites.

a). Site A.

This site which was worked by truck and shovel methods is situated in the East Midlands area, close to Nottingham. The site itself was very small working an average depth of 17 metres. The fill consists of predominantly mudstones. Monitoring commenced in October 1984.

b). Site B.

Depths of up to 80 metres were excavated on this dragline site in the North-East of England. Monitoring commenced

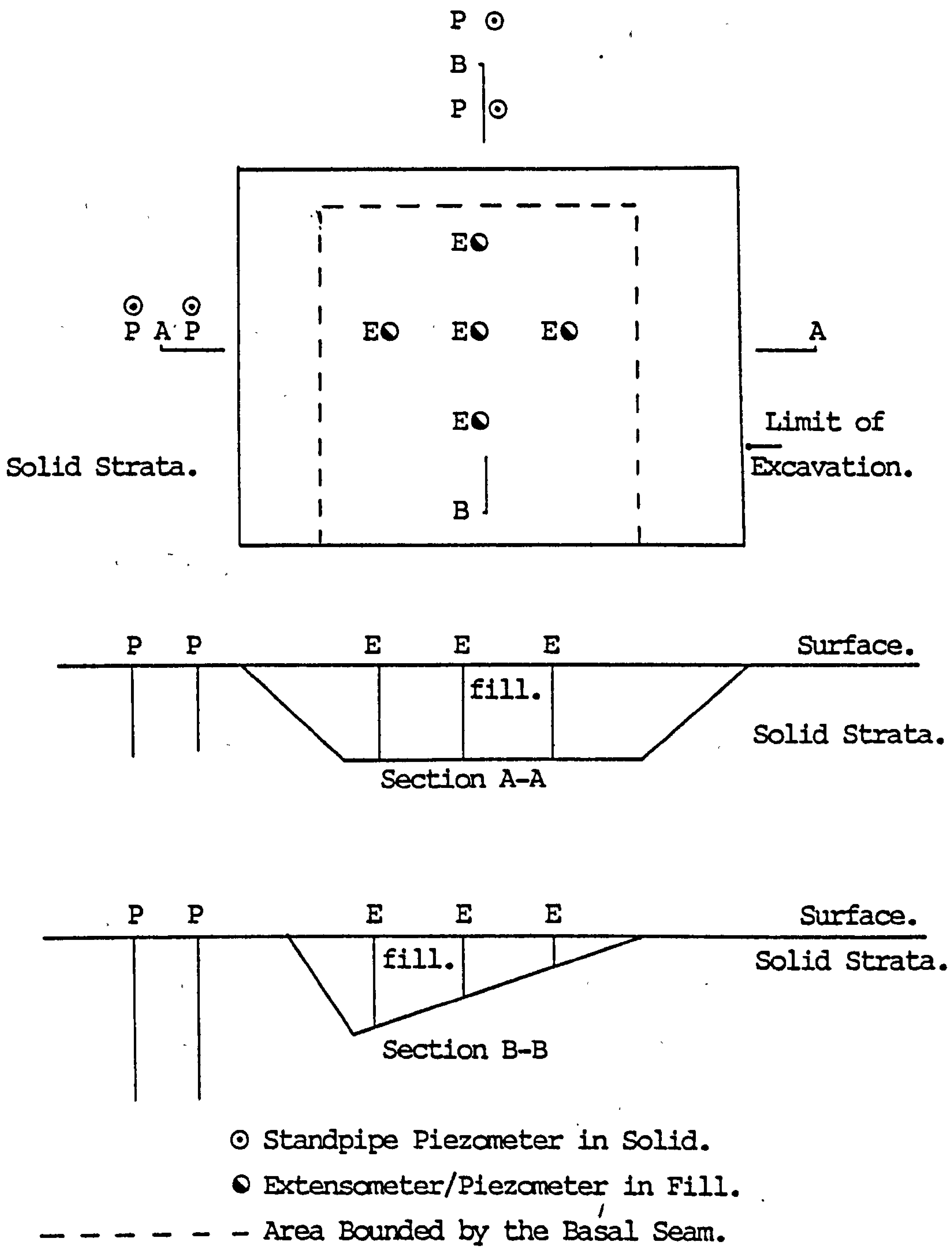


Figure 2.14 Idealised Instrumentation Layout for a Hypothetical Site.

December 1984. Fill had also been end-tipped by dump truck in addition to the dragline operation.

c). <u>Site C.</u>

Monitoring consists of observing deformations in a road constructed upon variable thickness, (30-70 metres), backfill material. The site was worked by Truck and Shovel methods.

2.7 CONCLUSIONS.

This chapter has reviewed the factors affecting backfill settlements together with the field instrumentation required to evaluate magnitudes and trends of both backfill settlement and groundwater recovery.

Chapters 3, 4 and 5 concern the detailed field instrumentation programmes initiated on the above selected sites. Chapter 6 presents some groundwater and settlement data fpr a number of opencast coal mines the analysis of which has been part of this work.

CHAPTER 3

SETTLEMENT AND GROUNDWATER OBSERVATIONS ON A SHALLOW, BACKFILLED SITE.

CHAPTER 3. SETTLEMENT AND GROUNDWATER OBSERVATIONS ON A SHALLOW, BACKFILLED SITE.

3.1 INTRODUCTION.

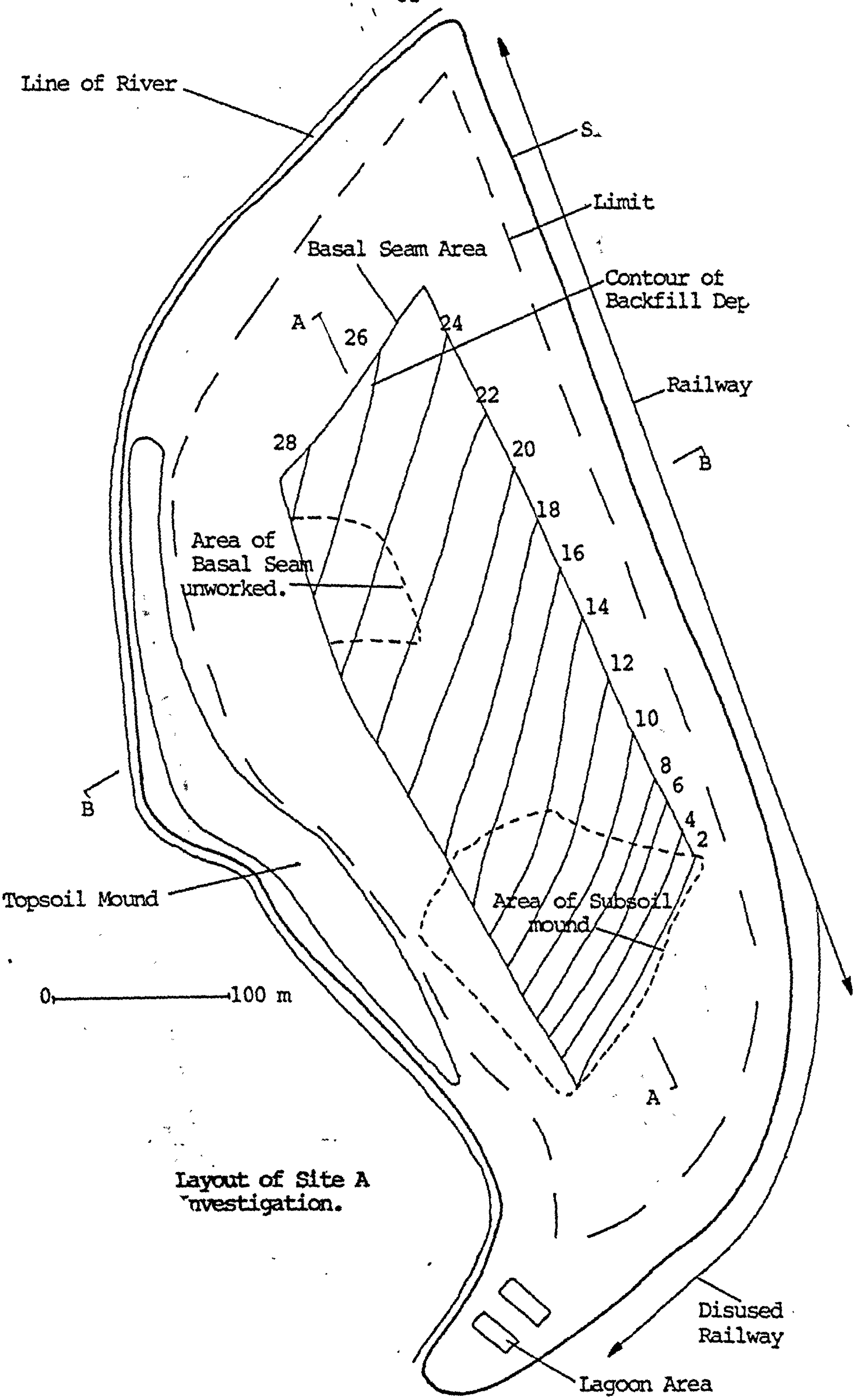
This chapter examines groundwater recovery and backfill settlements which were recorded on a shallow, mudstone backfilled site in the East Midlands area. For the purposes of this work the site will be designated as Truck Shovel Site A. The site itself was one of the smallest worked by the Opencast Executive by present day standards, the take comprising of 0.9 hectares, 6 seams, at an overburden to coal ratio of 10:1. The mine operations extended down-dip from the coal outcrop to a maximum depth of 31 metres, the average depth of excavation on site being 17 m. The mine was worked over a period of 2 years by truck and shovel methods. In-filling of the void area with spoil was performed by dump trucks tipping over the edge of the loosewall. Scrapers were used to finalise overburden levels and to replace soils. The mine produced an average of 1000 tonnes of coal per week.

3.2 SITE TOPOGRAPHY, GEOLOGY AND NATURE OF BACKFILL.

The original land surface was essentially flat, lying at a level of 46 to 47 m above Ordnance Datum (A.O.D.). The area of the site served as the flood plain for a river which flows down the northern and western edges of the site. Prior to mining the ground had been very marshy with standing water covering several areas of the site for most of the year. The site is bounded on the eastern and southern sides by railway lines.

Figure 3.1 indicates the layout of the site with respect to boundaries, areas of excavation and depths of fill over the restored area. Figures 3.2a and 3.2b illustrate pre-mining geological profiles.

A typical geological section of the excavated material over the site is presented in figure 3.3. From this the characteristics of the backfill may be deduced. Overburden and interburden strata consisted of mainly mudstone rocks together with occasional bands of silty or sandy material. Five seams were taken in total although only four were worked substantially. Alluvial deposits covered the entire area of the site to a depth of approximately 3 to 4 m, which increased to 9 m in the north-western part where a buried river channel lay. These deposits generally consisted of 0 to 2 metres of sands and gravels overlain by clay layers. Old deep mine workings in the two lower seams were encountered during excavation and occasionally during the working of the site old mine shafts were excavated resulting in substantial water



Layout of Site A
'nvestigation.

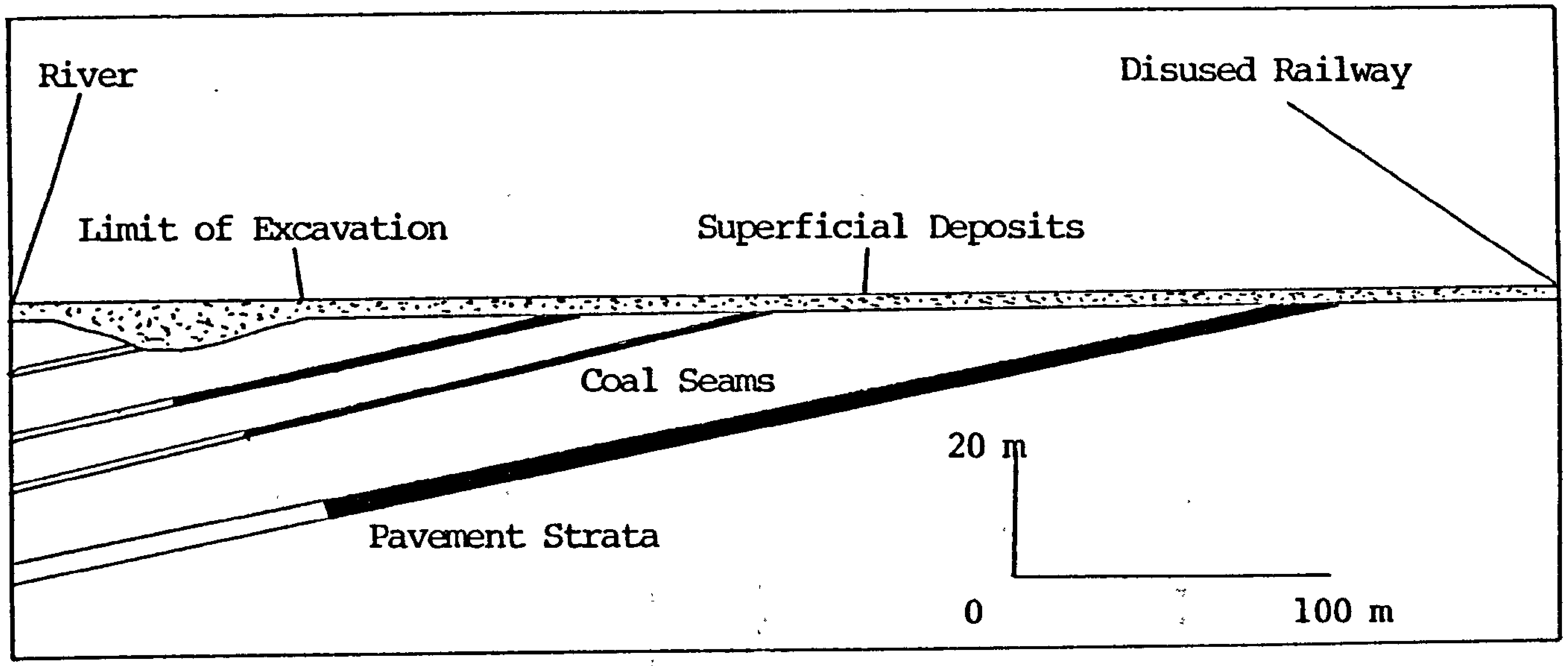


Figure 3.2a Section A-A´, Site A.

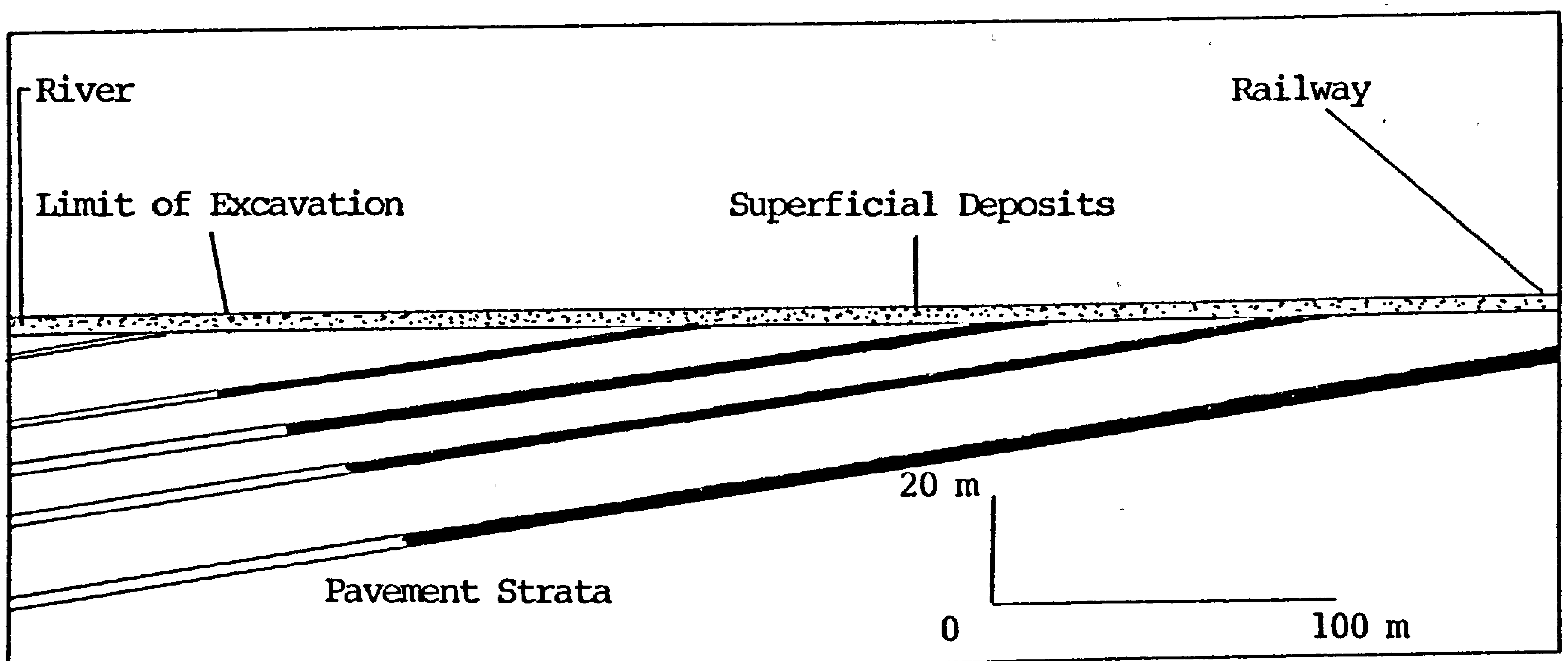
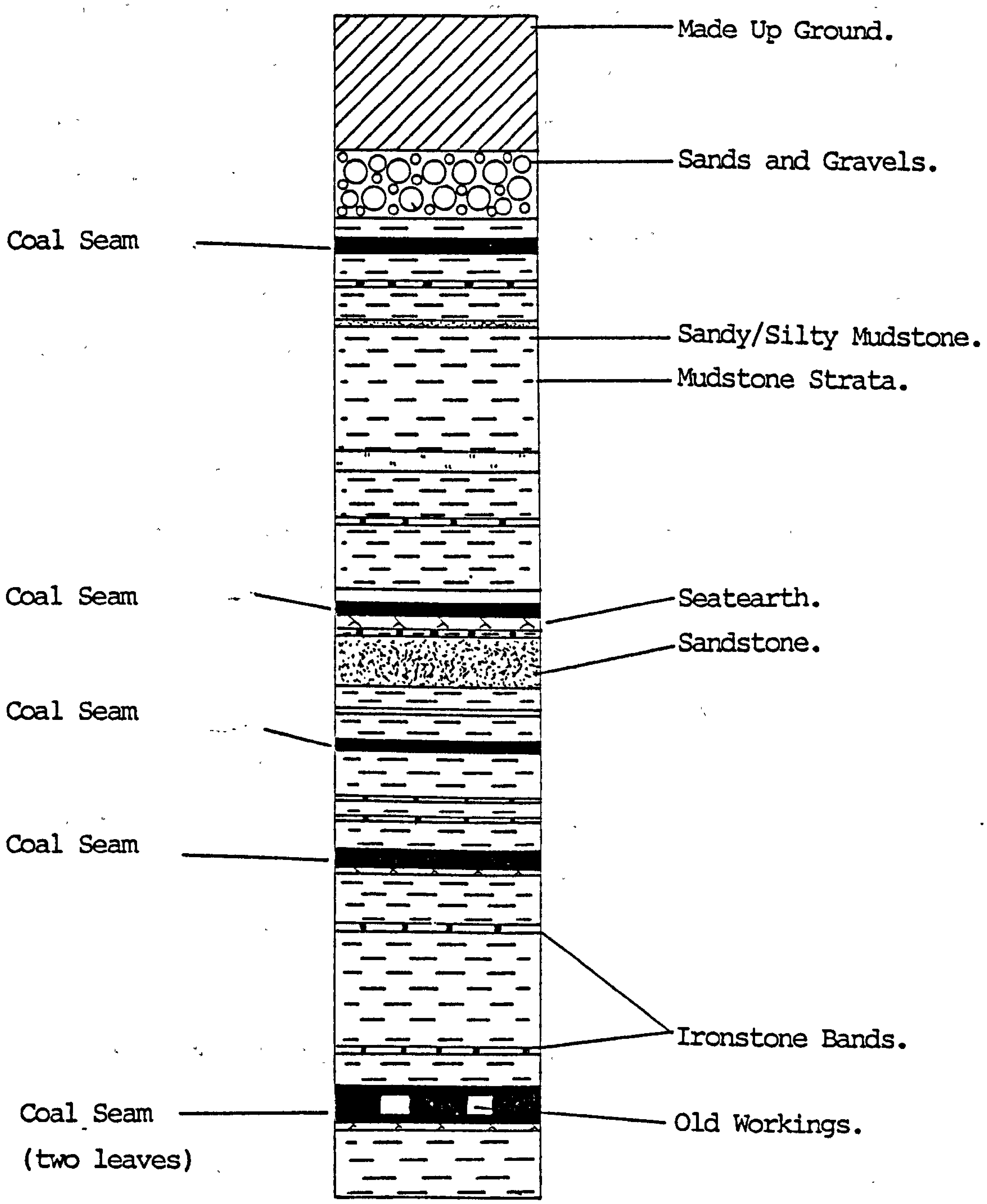


Figure 3.2b Section B-B´, Site A.



Total Depth of Section = 44 m

Figure 3.3 Typical Geological Section, Truck-Shovel Site A.

inflows into the mine. On one occasion such a inrush resulted in a major loosewall instability which required a three week period of rectification before coaling could recommence. Over the life of the mine 2,200 litres per minute were pumped out of the void using sump pumping techniques.

The backfill is known to be of uniform composition over the area of the site. The fill is predominantly mudstone, (70%), with alluvial deposits comprising 12%. The remainder of the spoil consists of sandstones, siltstones and seatearths. The expected bulkage of the site, (i.e. the increase in volume of the spoil material resulting from rock breakage during excavation) was around 10 to 12% - and thus would compensate adequately for the excavated coal mineral. However, presumabley due to the wet conditions on the site, a bulkage of only 7% was realised. The alluvial deposits which had been previously kept aside as potential soil making materials were used to raise overburden levels to the required level over the north-eastern part of the site. The depth of this material over the standard backfill varied from 1 to 3 metres.

3.3 PREDICTION OF GROUNDWATER RECOVERY.

As the site lay in the flood plain of a river and had been frequently covered with standing water together with the fact that deep mine workings had been discharging into the mine excavation it was concluded that groundwater levels would rise to meet the restored surface level of the mine. The measurable degree of recovery can thus be calculated from knowledge of the basal seam contours. These values are presented in figure 3.4.

3.4 INSTRUMENTATION SCHEME.

3.4.1. General Details.

The date for instrumentation was set to commence as soon as the overburden had been restored to its final level, (prior to the replacement of the soils). This was done so that instrumentation could be installed as soon as possible following the cessation of pumping but at such a time that there would be a minimum of interference both to and from mobile plant.

The Instrumentation plan was to install five magnetic extensometers/ piezometers in two profiles across the mine, and to install four piezometers in the solid ground, two at one end of each profile to monitor water levels in the solid strata monitoring rates of recharge. Details of the individual instruments have previously been discussed in chapter 2. All boreholes were backfilled on installation with a weak bentonite grout.

The layout of the site on instrumentation is illustrated in figure 3.5. The two profiles of instruments are also shown, one along the strike of the mine, one down-dip. Table 3.1 gives the initial surface levels and depths of each instrument and details the individual magnet positions. Figures 3.6a and 3.6b show the instrumentation scheme in the form of

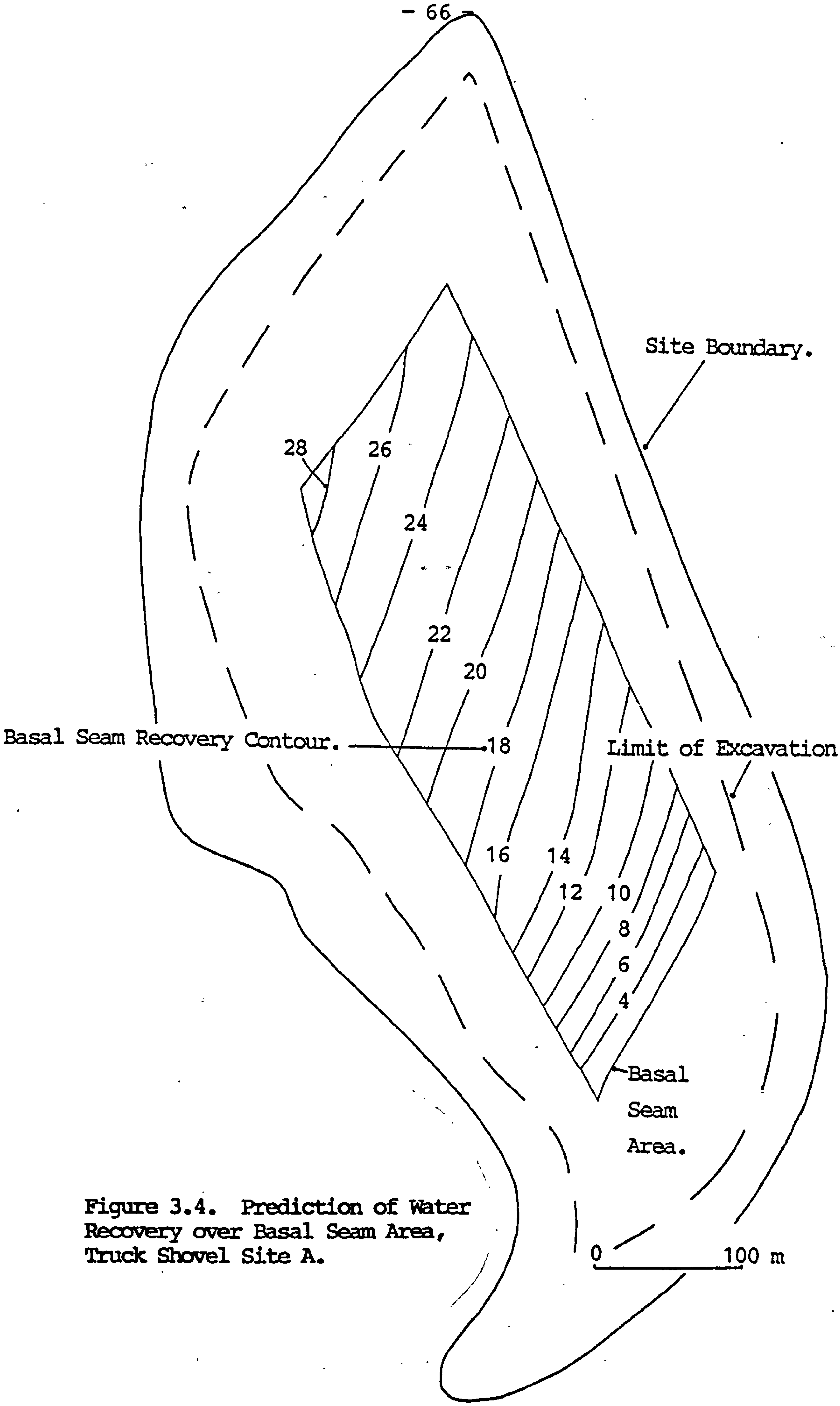


Figure 3.4. Prediction of Water Recovery over Basal Seam Area, Truck Shovel Site A.

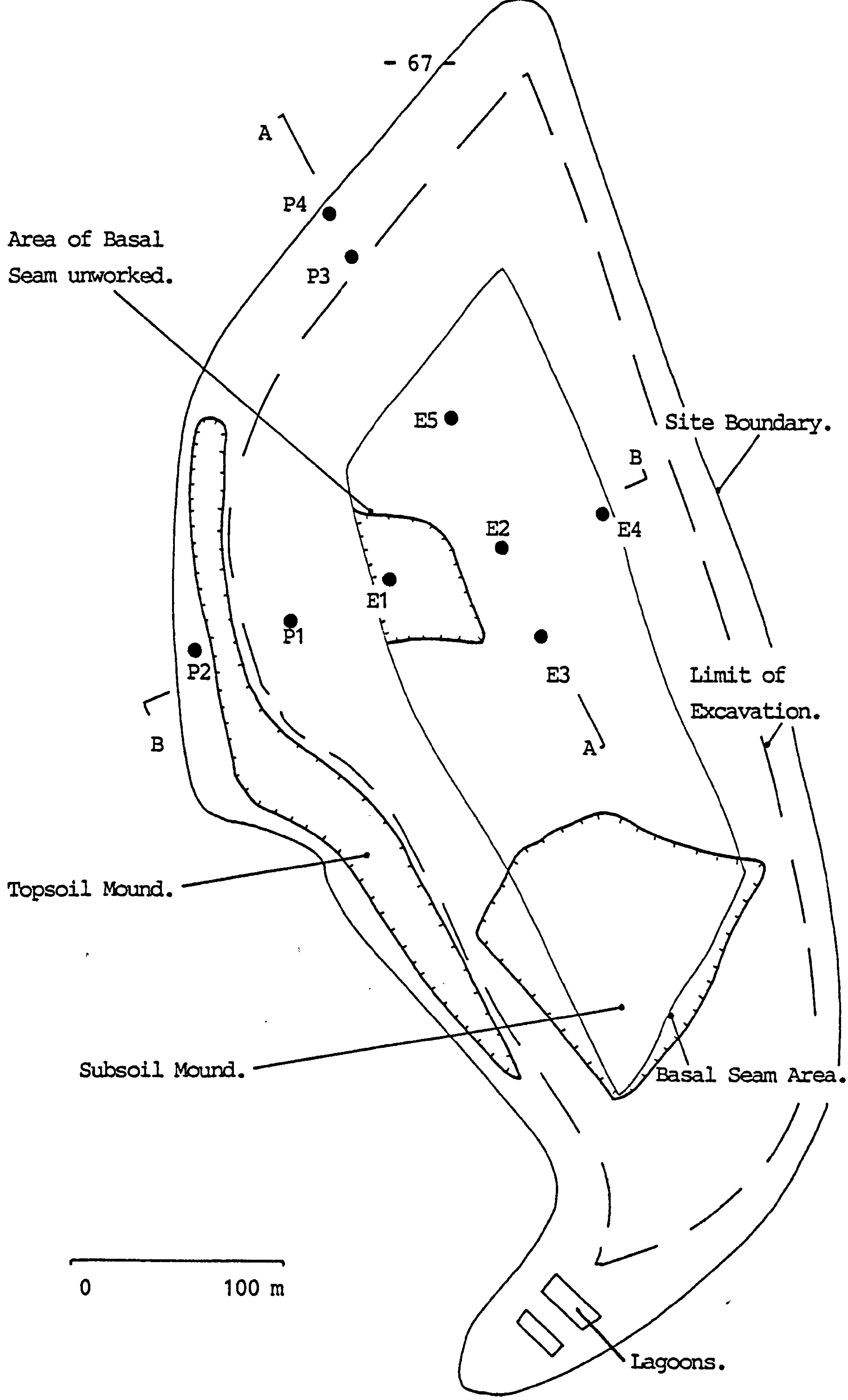


Fig. 3.5 Instrument Positions and Site Characteristics.
Site A.

Table 3.1.

Instrumentation Details, Truck Shovel Site A

Extensometer	Fill Depth (m)	Surface Level (m A.O.D)	Magnet Positions (Depth metres)					
E1	20.56	45.48	20.5	17.5	13.8	8.7	3.8	1.9
E2	23.90	44.98	23.3	22.7	18.5	13.4	7.8	2.7
E3	22.70	45.67	21.9	17.8	15.3	11.7	7.5	2.8
E4	21.40	45.04	20.4	16.9	13.0	10.3	6.4	2.5
E5	25.40	45.40	24.7	19.4	15.7	10.8	6.0	2.2

Piezometers.	Depth	
P1	33.60	45.51
P2	33.60	47.22
P3	33.60	48.94
P4	33.20	48.27

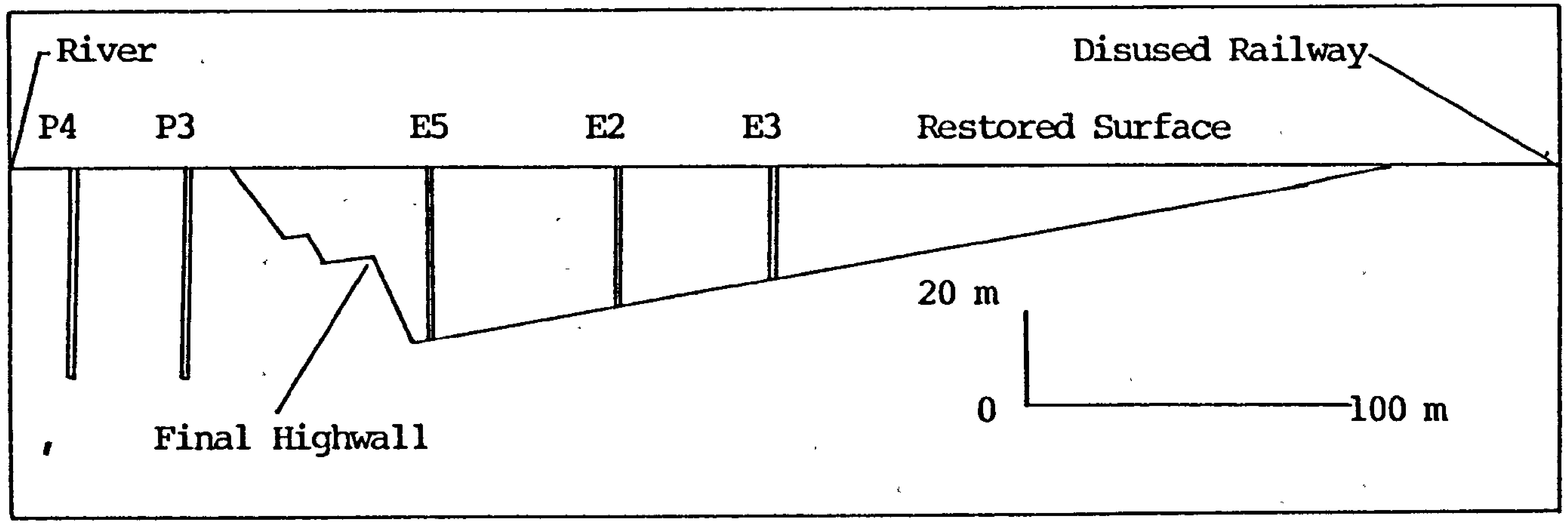


Figure 3.6a Instrumentation Scheme Section A-A′, Site A.

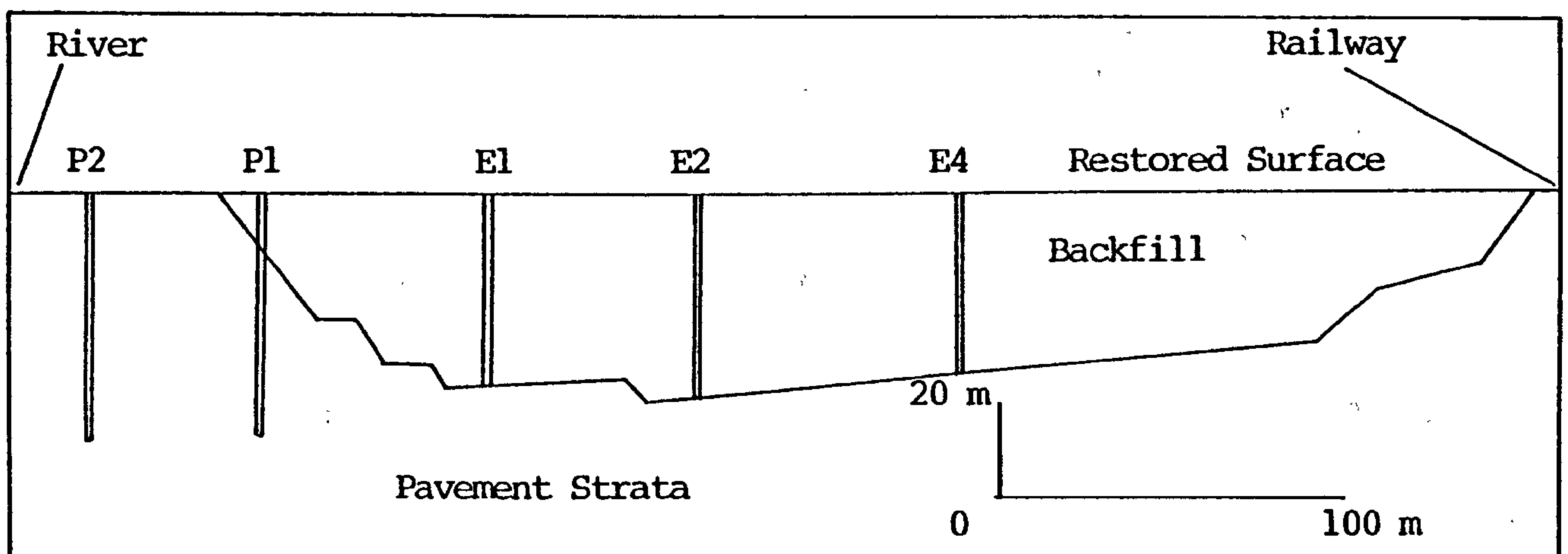


Figure 3.6b Instrumentation Scheme Section B-B′, Site A.

cross-sections across the backfill, both along strike and down-dip.

Installation and equipment were supplied by Geotechnical Instruments Limited of Leamington Spa, Warwickshire, whilst drilling operations were performed by Norwest Holst Soil Engineering Ltd of Leeds. The drilling and instrumentation of nine boreholes were completed over a three week period. Several delays were encountered both technical and mechanical.

3.4.2. Details of Installation Procedures.

The generalised installation procedures have been detailed in chapter 2. This section discusses the installation procedure conducted upon this site with special reference to some of the problems encountered.

a). Drilling.

The drilling of both the 149 mm boreholes for the extensometers and the 123 mm boreholes for the piezometers was performed by a Hands-England rotary drilling rig. The problems encountered with drilling and casing the borehole in fill were as follows:

i). Owing to the blocky nature of some areas of the fill, borehole diversion bought about difficulties in installing the borehole casing - particularly at depth. It frequently became necessary to rebore a borehole several times to succeed in a full depth casing.

ii). When boreholes were drilled with air flush, severe losses were accrued owing to air either escaping through fill to surface or by flushing into cavities within the fill section.

To facilitate a more stable standing borehole in the fill material, foam flushing replaced the standard air flush after about 10 metres of drilling with fair success.

b). <u>Installation of Instruments in Cased Boreholes.</u>

No problems were encountered in the installation of the extensometer instruments save on one occasion- during the drilling and casing of borehole E5, in the deepest fill. The casing operation had been exceptionally difficult owing to borehole deviation. Only seven metres of the 25 metre borehole could be successfully cased. An attempt to instrument this borehole was made after a reboring operation below the level of the casing, however in the time elapsed between removing the drill rods and installing the instrument the lower part of the borehole had collapsed preventing a successful installation. The instrument and casing were then removed and the borehole completely rebored.

On the first borehole instrumentated, E1, the drilling rig stayed over the borehole for the instrumentation process, enabling the use of the drilling mast as a support for a longer length of instrument.This enabled instrument lengths of 6 metres to be introduced into the borehole at a time and enabled a rapid installation on subsequent boreholes the rig moved off to continue drilling elsewhere and on these boreholes only 3 m lengths of instrument could be installed at a time slowing the process down considerably. A further disadvantage of moving the rig off the cased borehole is the difficulty in wet and muddy conditions of re-setting up over the casing to successfully pull the casing out of the ground following instrumentation.

All boreholes were backfilled using a weak bentonite grout which tended to flow out of the borehole into the fill. Grout losses were remedied by the application of bentonite pellets to the affected zone. The time to fill the borehole was however in general excessive and it is considered by the author that the use of fine, dry filter sand as a backfilling material to be superior.

c). General Site Considerations Relevant to Instrumentation.

Throughout the entire installation period, save for two days, weather prevented scraper activity and consequently little interference was experienced from moving plant. For boreholes which were not quite at final overburden level, the site staff were very helpful in raising the level of these areas either when a scraper was available or by using a bull-dozer. During installation the instruments were very vulnerable from moving plant and thus were marked by any large objects that were at hand, e.g casing, barrels, water bowsers etc.

Owing to the position of the topsoil storage mound, piezometer P1 could not be situated completely in solid, as space had to left to allow plant to approach the topsoil mound. The piezometer was thus situated two scraper widths off the mound which meant that in the 33 m depth of instrument the top 8 metres lay in fill.

3.5. PROTECTION OF INSTRUMENTS DURING THE REPLACEMENT OF SUB- AND TOP-SOILS.

Instrumentation was completed by 1 October 1984 as was the restoration to final overburden levels over the site. Contractual work remaining consisted of the replacement of sub- and top-soils which is not permitted in wet conditions, ie over the winter months. This soils replacement was thus left to the next Spring with work on the site being abandoned until that time. Prior to soil replacement it had been decided to bury the instruments below the levels of the restored overburden and to allow plant to replace soils with no hindrances. On completion of soiling the instruments would be re-excavated and extended from overburden level to final soil level a distance of around 1 metre.

3.6 EVALUATION OF FIELD RESULTS.

3.6.1. Groundwater Recovery Trends.

The sequence of groundwater recovery in the fill is illustrated in figures 3.7 a, b. Water levels were initially

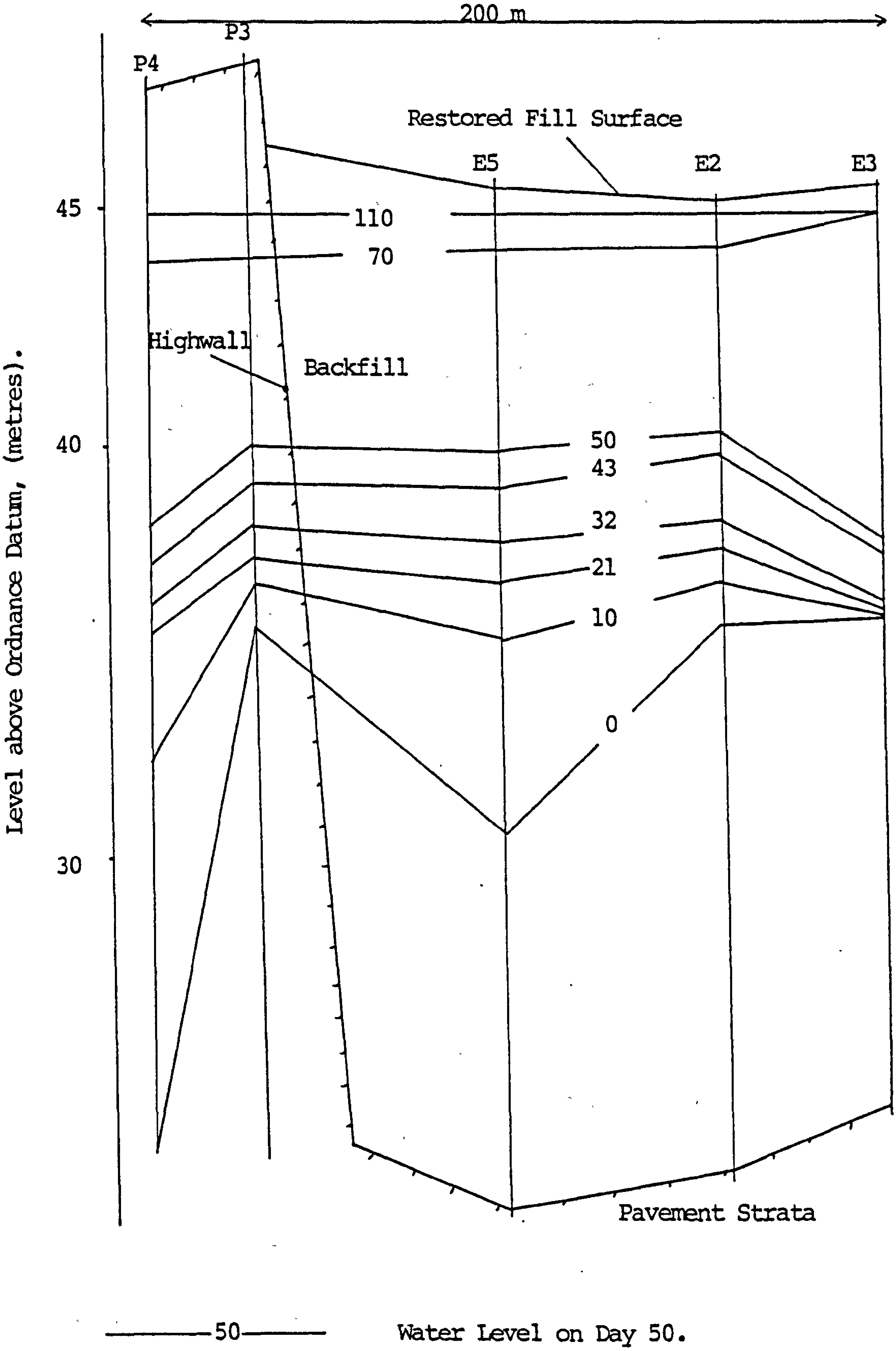


Figure 3.7a Water Recovery Patterns, Section A-A′, Site A.

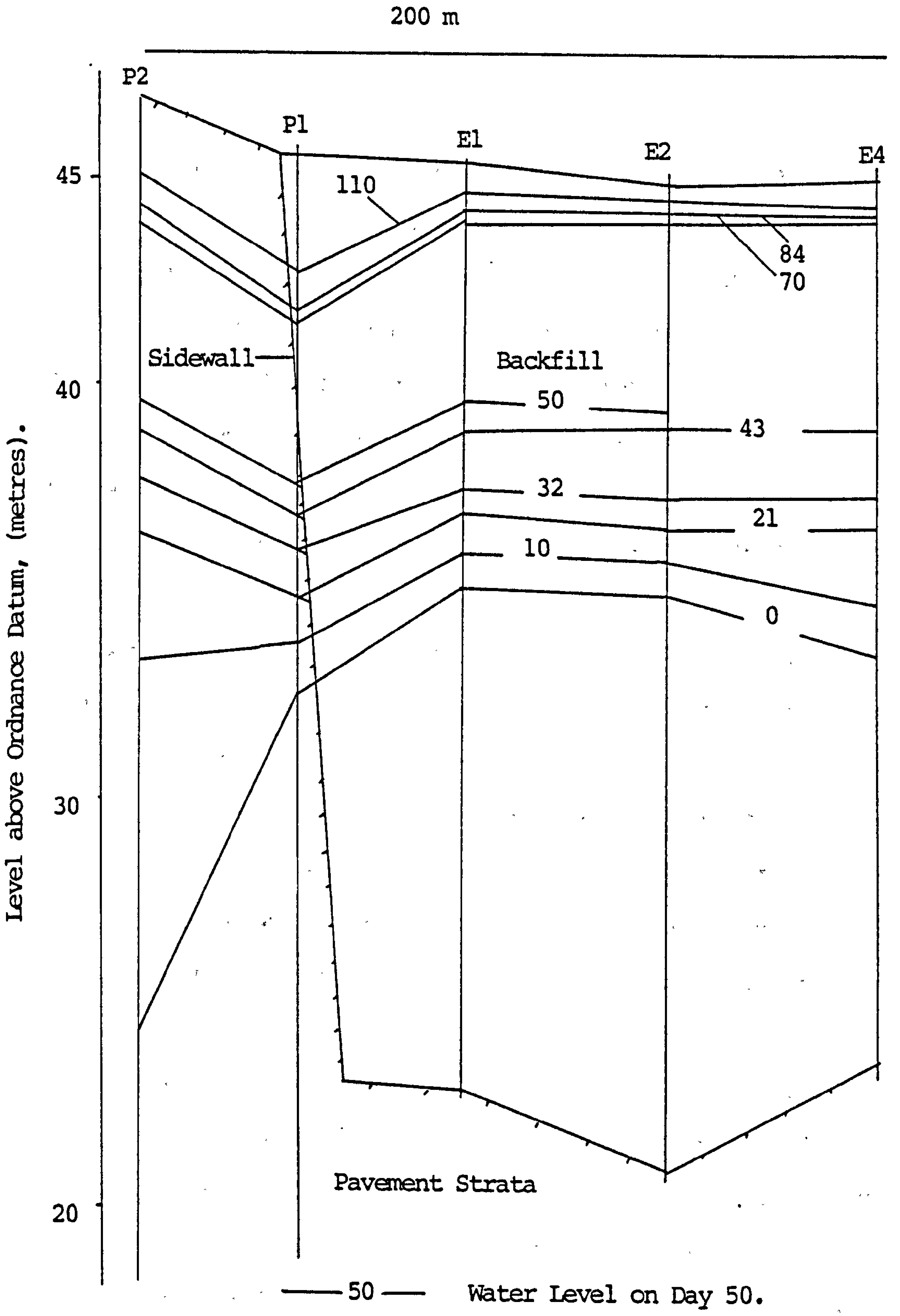


Figure 3.7b Water Recovery Patterns, Section B-B′, Site A.

recorded at lying 11 m below the restored surface, recovering to flood the area of the site within 120 days.

As the sequence of groundwater recovery is a continuous process, it was inevitable that some recovery monitoring would be lost. Monitoring commenced 48 days after the termination of pumping when it can be considered that the water levels around E5, (in the final void area), would have been close to the level of the pavement strata. Thus in the 48 'lost' days prior to monitoring the water levels in this area had recovered from around 24 m below the restored surface to 15 m, a recovery of 9 metres. In the first 48 days of monitoring levels rose by a further 9 m, and in the second similar period by 5 m. This resulted in 23 m of recovery in the 144 days from the termination of pumping.

Initial water levels displayed the expected trends of a drawdown curve lowering towards the final void area. The highest initial water level was registered on extensometer E3- the one furthest from the final void. Levels in instruments El and E2 were vitually the same whilst those in E4 were slightly lower. The difference in water levels between E3 and E2, (50 m apart) was, 0.77 m, whilst the difference in levels over the similar distance between E2 and E5 was 4.33 m. Whilst recoveries were subsequently measured in extensometers El, E2, E4, and E5, little or no recovery was monitored on instrument E3 for the first 15 days. Initial suspicions that the piezometer tip was faulty were soon discounted after this period when recovery re-commenced - only after the water level in E3 had become the lowest over the site.

Water levels in all the holes then rose steadily from day 15 to 50. In the following period of days 50 to 70 there was a spell of abnormally high rainfall which flooded areas of the restored surface, particularly around instuments E2 and E4 preventing the taking of a number of reading sets.

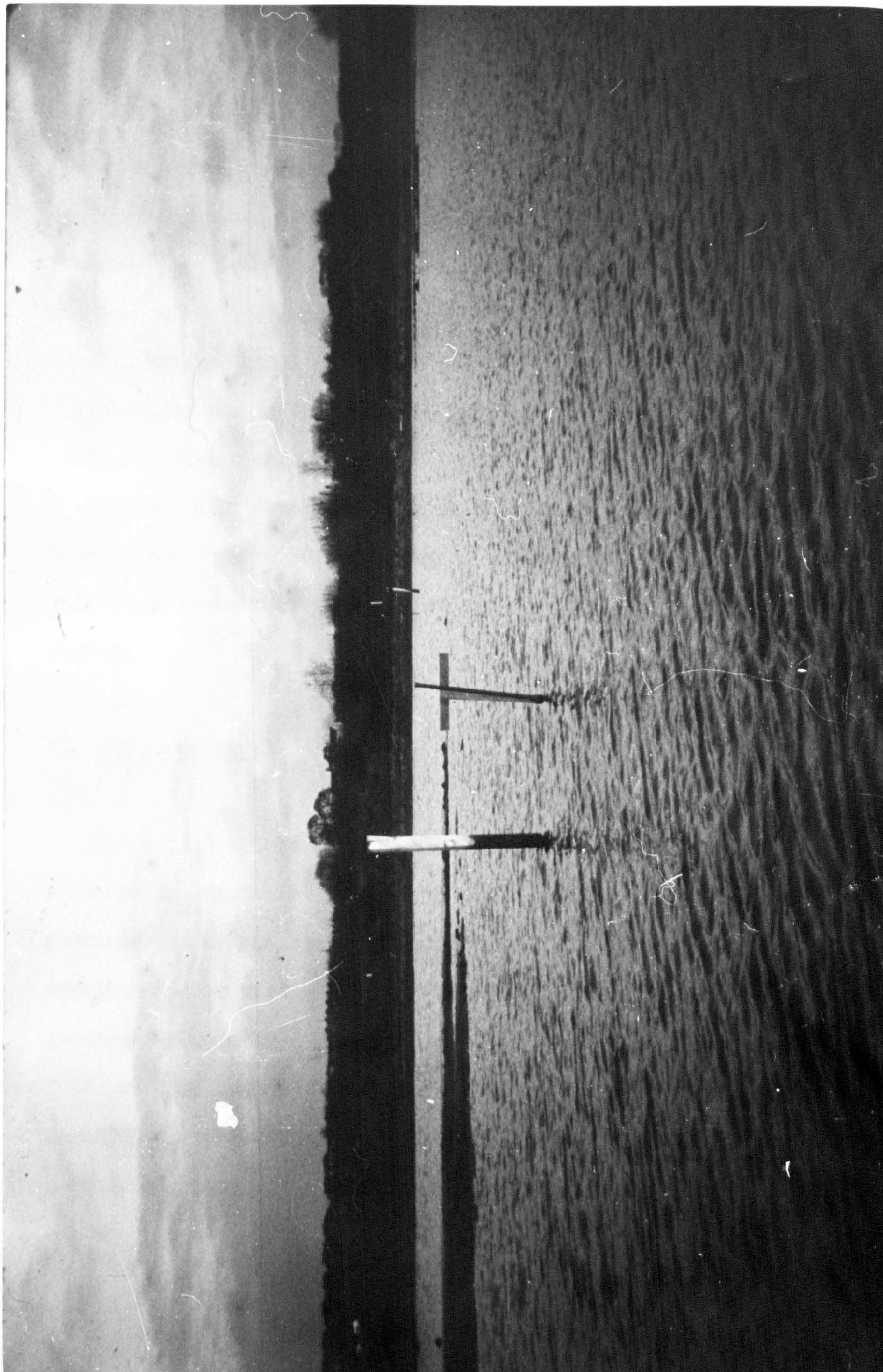
On day 70 the groundwater had recovered to just below the surface of each instrument, averaging a recovery of 6 m over the 20 day period. Water levels in instrument E3 actually rose in excess of 8 m during this time. At this point were the first indications that the groundwater level was to rise above the restored fill to permanently flood the surface. 110 days after the commencement of monitoring groundwater levels in the fill of E3 stood above the restored levels of E2. By day 120, the surface had become flooded making further readings impossible until day 170, (discussed in the post-recovery section). During this time the backfill surface had been flooded to depths of 1.5-2.0 metres. This time coincided with February 1985 and the ground remained in such a state for about two months before the contractor installed a pump on site in anticipation of soils replacement. Pumping succeeded in lowering the groundwater levels to just below the backfilled surface where they have remained. Since the replacement of the soils, levels have remained constant but standing water once again has formed over areas of the site - a consequence of surface water lying on the relatively impermeable fill surface.

PLATE 3.

FLOODING OF BACKFILL SURFACE.

TRUCK/SHOVEL SITE A.

Two white instrument marker posts can be observed to be flooded. Water levels eventually rose to one metre above the restored backfill surface.



3.6.2. Evaluation of Backfill Settlement during Recovery.

In order to evaluate the effect of groundwater recovery on the settlement of the mine backfill it is necessary to observe the behaviour of all the intermediate horizons with respect to the following criteria:

i). Dry conditions.

ii). Under the influence of the recoverying water table.

iii). Following saturation.

Results are detailed for each instrument and a collective summary of the findings made in the subsequent sections. Individual magnets are denoted SP1 to SP5 where SP5 is nearest surface.

a). Extensometer E1.

Figure 3.8 illustrates the settlement patterns for the magnets in E1.Table 3.2 details total settlements, horizon settlements, strain rates and groundwater recovery. The total settlement recorded on this hole during the period of groundwater recovery was 168 mm - an overall settlement of 8.46 mm per metre of fill depth. Four distinct phases of backfill settlement can be observed during the period of groundwater recovery.

i). Settlement occuring below SP3, days 0-30.

ii). Settlement occuring between SP3 and SP4, days 30-50

iii). Settlement occuring between SP4 and SP5, days 50-70

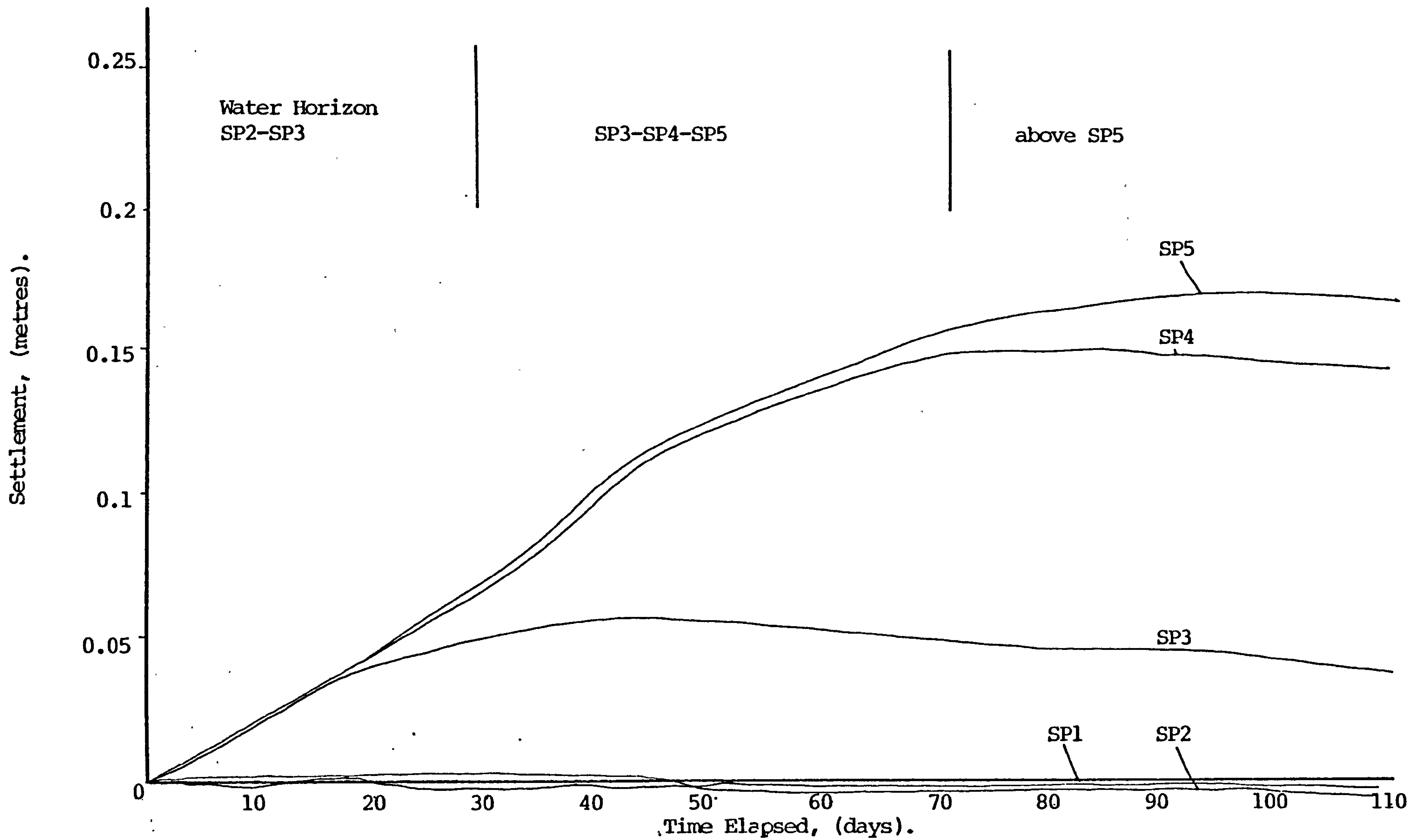


Figure 3.8 Settlement and Groundwater Characteristics, Extensometer E1, Site A.

Day	Cumulative Total Settlements SP1	SP2	SP3	SP4	SP5	Settlement registered at each horizon D-SP1 Total	D-SP1 Change	SP1-SP2 Total	SP1-SP2 Change	SP2-SP3 Total	SP2-SP3 Change	SP3-SP4 Total	SP3-SP4 Change	SP4-SP5. Total	SP4-SP5. Change	Water Horizon.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	SP2-SP3
4	+3	+1	+1	4	3	+3	+3	2	2	0	0	5	5	+1	+1	"
8	0	0	7	8	6	0	3	0	+2	7	7	1	+4	+2	+1	"
12	0	0	21	23	23	0	0	0	0	21	14	2	1	0	2	"
15	+2	+2	28	30	28	+2	+2	0	0	30	9	2	0	+2	+2	"
19	1	3	38	43	41	1	3	2	2	35	5	5	3	+2	0	"
21	2	4	40	45	45	2	1	2	0	36	3	5	0	0	2	"
25	0	2	41	45	46	0	+2	2	0	39	3	4	+1	1	1	"
29	+1	0	46	57	56	+1	+1	1	+1	46	7	11	7	+1	+2	SP3
32	0	2	51	71	68	0	1	2	1	49	3	20	9	+3	+2	SP3-SP4
36	+5	+1	52	85	83	+5	+5	4	2	53	4	33	13	+2	1	"
43	1	2	53	115	116	1	6	1	+3	51	+2	62	29	1	3	"
46	+4	+3	51	116	118	+4	+5	1	0	54	3	65	3	2	1	"
50	+1	+2	54	126	128	+1	3	+1	+2	56	2	72	7	2	0	"*
70	+2	+5	45	149	160	+2	+1	+3	+2	50	+6	104	34	11	9	SP5
78	+2	+6	44	150	166	+2	0	+4	+1	50	0	106	2	16	5	>SP5
84	+1	+5	44	150	170	+1	1	+5	+1	49	+1	106	0	20	4	"
94	+2	+6	44	148	173	+2	+1	+4	1	50	1	104	+2	25	5	"
110	+4	+9	38	142	168	+4	+2	+9	+5	47	+3	104	0	26	1	RECOVERY TERMINATES.

CUMULATIVE STRAIN CALCULATIONS.
(mm settlement/m original horizon thickness)

Day	D-SP1	SP1-SP2	SP2-SP3	SP3-SP4	SP4-SP5
0	0	0	0	0	0
4	+1.0	0.5	0	1.0	+0.6
8	0	0	1.5	0.2	+1.1
12	0	0	4.5	0.4	0
15	+0.7	0	6.4	0.4	+1.1
19	0.3	0.5	7.5	1.0	+1.1
21	0.7	0.5	7.7	1.0	0
25	0	0.5	8.4	0.8	0.5
32	+0.4	0.2	9.9	2.2	+0.6
36	0	0.5	10.6	4.1	+1.6
43	+1.7	0.9	11.4	6.7	+1.1
46	0.3	0.2	11.0	12.6	0.5
50	+1.4	0.2	11.6	13.2	1.0
70	+0.4	+0.3	12.1	14.6	1.1
78	+0.7	+0.7	10.8	21.2	5.8
84	+0.7	+1.0	10.8	21.6	8.5
94	+0.4	+1.0	10.5	21.6	10.6
110	+0.7	+1.0	10.8	21.2	13.3

* Period of Flooding Days 50-70.

\+ Denotes heaving movement.

Table 3.2 Summary of Settlement and Recovery Results, Extensometer E1, Site A.

iv). Small, slow heaving movements on all magnets following saturation.

Throughout the monitoring period only small heaving movements of less than 10 mm have been recorded on the lowest spider magnets SP1 and SP2, these magnets being in saturated fill for the duration of monitoring. Results from the cumulative strain rate calculations show that in the period of day 0 to day 36 the compressive strain in the fill horizon

Throughout the monitoring period only small heaving movements of less than 10 mm have been recorded on the lowest spider magnets SP1 and SP2, these magnets being in saturated fill for the duration of monitoring. Results from the cumulative strain rate calculations show that in the period of day 0 to day 36 the compressive strain in the fill horizon
between SP2 and SP3 steadily increased, corresponding to the position of the water table. Strain rates between magnets SP3 -SP4 and SP4-SP5 were of the order of those in the saturated parts of the fill. This shows that both dry and saturated fill materials have exhibited much slower strain rates than those experienced in the presence of a recovery water table. From day 36 the strain rate between SP2 and SP3 remains fairly constant with collapse settlement being replaced by small heaving movements assumed to be a result of mudstone swelling on saturation. From days 32-36 the strain between SP3 and SP4 begins to increase as the water table rises to affect this horizon, strain rates achieving equilibrium after day 70 at 21 mm settlement per metre of fill horizon. Water levels on day

70 were at the level of magnet SP5, but settlement in this horizon can still be observed by noting the increasing strain between SP4 and SP5 from day 70 to 110.

To characterise the settlement and groundwater recovery correlation on this instrument a number of points can be stressed.

i). In saturated and dry fill materials settlement rates are low as compared with fill horizons under the direct influence of a recoverying water table.

ii). On saturation collapse settlement is replaced by slow heaving movements.

ii). <u>Extensometer E2.</u>

The settlement and groundwater recovery results for extensometer E2 are presented in Figure 3.9 and Table 3.3. Magnets SP1, SP2 and SP3 were installed in saturated fill and show the same small heaving movements which were detected on the lower magnets of E1. The overall settlement on this instrument was 150 mm during the recovery phase an overall settlement rate of 8.13 mm/m fill depth. This value correspond closely to that achieved on E1 as would be expected as these instruments are sited in fill of a similar age. Many results for this instrument were lost owing to the surface flooding of the backfill surface.

From the commencement of monitoring settlement displacements were recorded on magnet SP4 with only slight movements on the lower magnets. Of importance is the fact that

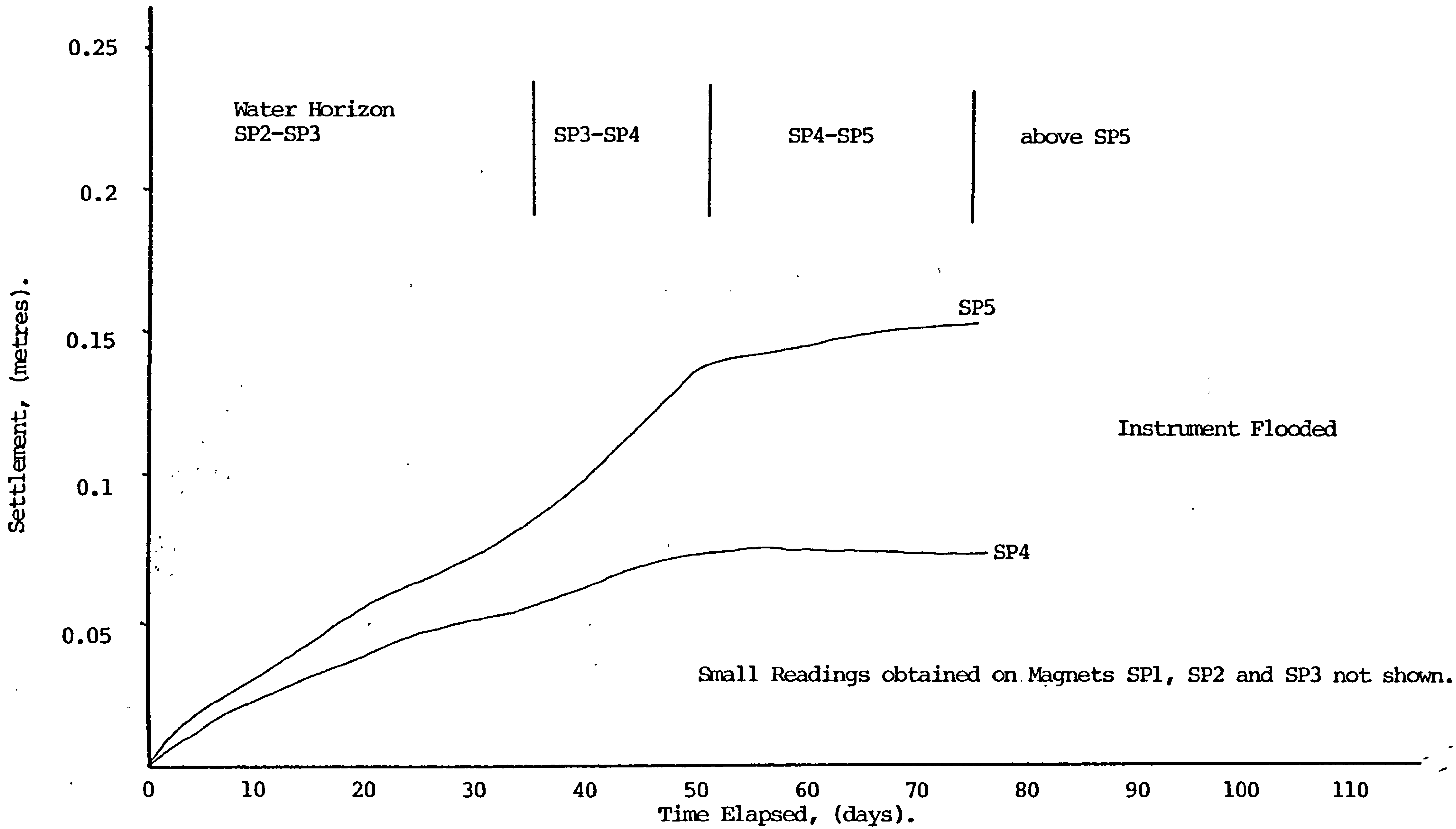


Figure 3.9 Settlement and Groundwater Characteristics, Extensometer E2, Site A.

Day	SP1	SP2	SP3	SP4	SP5	D-SP1 Total	D-SP1 Change	SP1-SP2 Total	SP1-SP2 Change	SP2-SP3 Total	SP2-SP3 Change	SP3-SP4 Total	SP3-SP4 Change	SP4-SP5. Total	SP4-SP5. Change	Water Horizon.
	Cumulative Total Settlements					Settlement registered at each horizon										
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	SP2-SP3
4	+2	1	+1	9	16	+2	+2	3	3	+2	+2	10	10	7	7	"
8	0	+2	+3	17	24	0	2	+2	+5	+1	1	20	10	7	0	"
12	+1	+2	+3	21	31	+1	+1	+1	1	+1	0	24	4	10	3	"
15	+1	+2	+3	26	39	+1	0	+1	0	+1	0	29	5	13	3	"
19	+1	0	3	41	56	+1	0	1	2	3	4	38	9	15	2	"
21	0	1	3	42	60	0	1	1	0	2	+1	39	1	18	3	"
25	+1	0	2	44	63	+1	+1	1	0	2	0	42	3	19	1	"
29	+1	1	4	48	71	+1	0	2	+1	3	1	44	2	23	4	"
32	1	1	4	56	82	1	2	0	2	3	0	48	4	26	3	SP3-SP4
DAYS 36-49 INSTRUMENT FLOODED.																
50	0	+3	+1	73	141	0	+2	+3	+3	2	+1	74	26	68	32	SP4-SP5
70	0	+2	+1	72	150	0	0	+2	1	1	+1	73	+1	78	10	>SP5
DAYS 71-110 INSTRUMENT FLOODED																

CUMULATIVE STRAIN CALCULATIONS.
(mm settlement/m original horizon thickness)

Day	D-SP1	SP1-SP2	SP2-SP3	SP3-SP4	SP4-SP5
0	0	0	0	0	0
4	+3.0	0.7	+0.5	1.8	1.4
8	0	+0.5	+0.2	3.6	1.4
12	+1.8	+0.3	+0.2	4.3	2.0
15	+1.8	+0.3	+0.2	5.2	2.6
19	+1.8	0.3	0.6	6.8	2.9
21	0	0.3	0.4	7.0	3.5
25	+1.8	0.3	0.4	7.5	3.7
29	+1.8	0.5	0.6	7.9	4.5
32	1.8	0	0.6	8.6	5.1
50	0	+0.7	0.4	13.3	13.3
70	0	+0.5	0.2	13.1	15.3

+ denotes heaving movements.

Table 3.3 Summary of Settlement and Recovery Results, Extensometer E2, Site A.

settlement was occuring in the region of SP3-SP4 whilst groundwater levels were indicated to be between SP2-SP3 during the first 30 days. Steady settlement was also seen to occur in the region SP4-SP5. Settlement results did appear to show direct water related trends from day 50 although interpretation is difficult owing to the loss in results owing to flooding. There is a possibility that a perched water table had formed which could not be detected by the single point piezometer. Conversely to this water may have recovered normally but piezometer reaction had been reduced by relatively impermeable horizons lower down in the borehole.

iii). Extensometer E3

Instrument E3 is sited in the oldest fill, furthest away from the final void area. The total settlement for the initial 110 day recovery period amounted to 134 mm corresponding to 6.53 mm settlement per metre of fill depth - less than E1 and E2 presumably due to the fact that the instrument is installed in more consolidated, older fill. Magnets SP1, SP2 and SP3 were installed in saturated ground, SP1 showing the typical saturated heave movements of E1 and E2, (Figure 3.10, Table 3.4). Contrary to what was observed on the other instruments, the intermagnet horizons of SP1-SP2 and SP2-SP3 showed compressive strains of up to 7.3 mm/m horizon thickness. Horizon SP2-SP3 continued settling for the initial period of 19 days corresponding to the time where the water level registered in the hole remained static - just above the

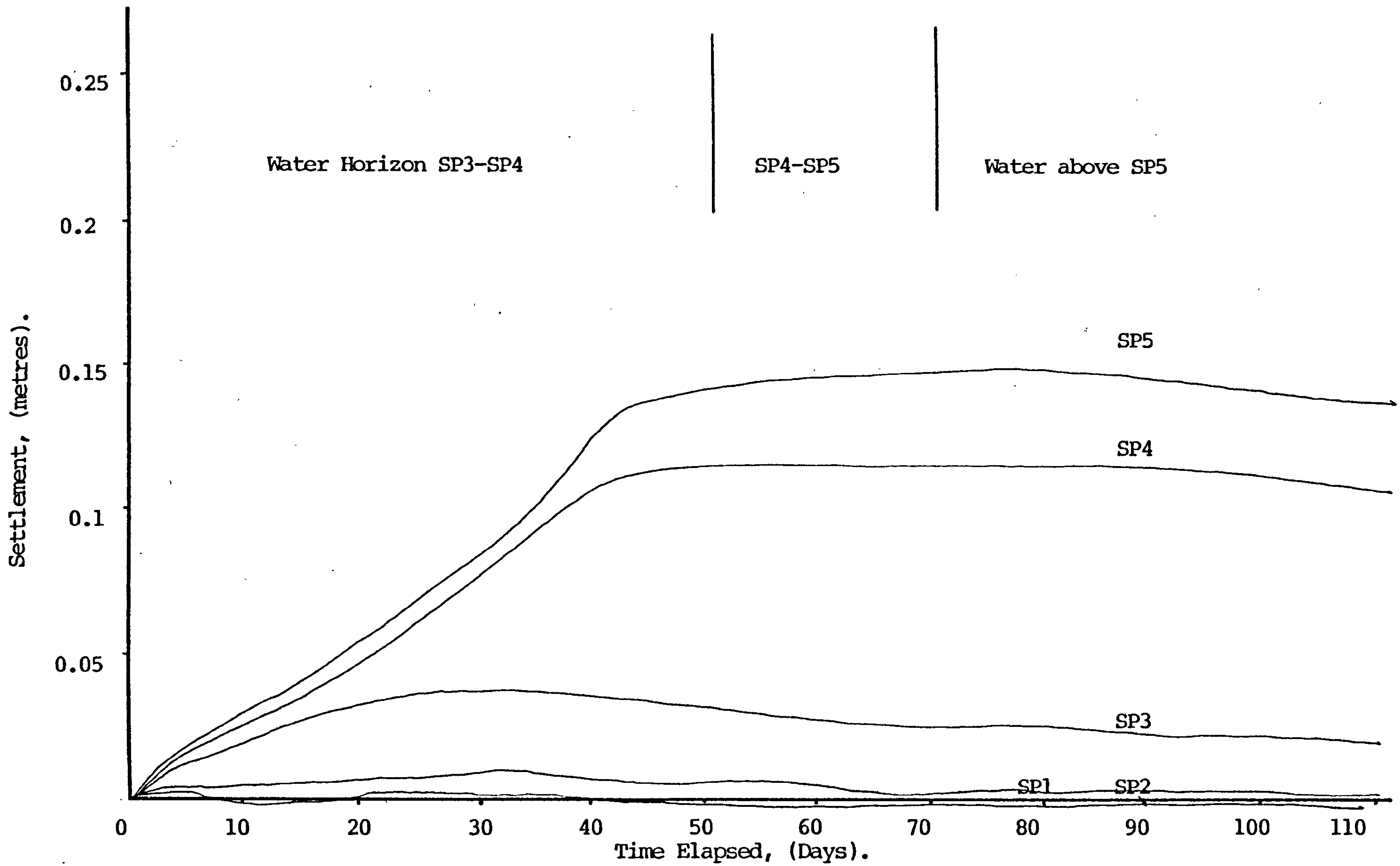


Figure 3.10 Settlement and Groundwater Characteristics, Extensometer E3, Site A.

Day	SP1	SP2	SP3	SP4	SP5	D-SP1 Total	D-SP1 Change	SP1-SP2 Total	SP1-SP2 Change	SP2-SP3 Total	SP2-SP3 Change	SP3-SP4 Total	SP3-SP4 Change	SP4-SP5. Total	SP4-SP5. Change	Water Horizon.
	Cumulative Total Settlements					Settlement registered at each horizon										
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	SP3-SP4
4	0	2	9	11	13	0	0	2	+2	7	7	2	2	3	3	"
8	+5	0	16	19	24	+5	+5	5	+3	16	9	3	1	5	2	"
12	0	6	25	28	32	0	5	6	+1	19	3	3	0	4	+1	"
15	+2	4	27	35	39	+2	+2	6	0	23	4	8	5	4	0	"
19	2	9	35	57	63	2	4	7	+1	26	3	22	14	6	2	"
21	1	6	33	56	63	1	+1	5	2	27	1	23	1	7	1	"
25	+2	6	32	62	68	+2	+3	8	+3	26	+1	30	7	6	+1	"
29	+3	9	35	74	82	+3	+1	12	+4	26	0	39	9	8	2	"
32	0	9	35	81	87	0	3	9	3	26	0	46	7	6	+2	"
36	+2	6	33	94	103	+2	+2	8	1	27	1	61	15	9	3	"
43	+2	5	30	115	137	+2	0	7	1	25	+2	85	14	22	13	"
46	+4	3	29	115	140	+4	+2	7	0	26	1	86	1	25	3	"
50	+4	4	30	115	141	+4	0	8	+1	26	0	85	+1	32	7	at SP4
70	+5	0	23	114	146	+5	+1	5	3	23	+3	91	6	32	0	at SP5
78	+7	+3	20	111	143	+7	+2	4	1	23	0	91	0	32	0	>SP5
84	+6	0	21	114	146	+6	1	6	+2	22	+1	93	2	32	0	"
94	+8	+2	20	112	144	+8	+2	6	0	22	0	92	+1	32	0	"
110	+8	+5	16	107	134	+8	0	3	3	21	+1	91	+1	27	+5	"

CUMULATIVE STRAIN CALCULATIONS.
(mm settlement/m original horizon thickness)

Day	D-SP1	SP1-SP2	SP2-SP3	SP3-SP4	SP4-SP5
0	0	0	0	0	0
4	0	0.8	1.9	0.5	0.4
8	+1.3	2.0	4.4	0.7	1.0
12	0	2.3	5.2	0.7	0.9
15	+0.5	2.4	6.3	1.9	0.9
19	0.5	2.7	7.1	5.3	1.3
21	0.3	2.0	7.3	5.5	1.5
25	+0.5	3.2	7.1	7.2	1.3
32	+0.8	4.7	7.1	9.3	1.7
36	0	3.5	7.1	11.0	1.3
43	+0.5	3.2	7.3	14.6	1.9
46	+0.5	2.7	6.8	20.4	4.7
50	+1.0	2.8	7.1	20.6	5.3
70	+1.0	3.2	7.1		
78	+1.3	2.0	6.3	21.9	6.8
84	+1.8	1.6	6.2	21.9	6.8
94	+1.5	2.4	5.7	22.3	6.8
110	+2.0	2.4	6.0	22.1	6.8

+ denotes heaving movements.

Table 3.4 Summary of Settlement and Recovery Results, Extensometer E3, Site A.

level of SP3. Settlement rates began to increase from day 19 in the horizon of SP3-SP4 when recovery recommenced

An acceleration in settlement between SP3 SP4 commenced on day 19 and continued to day 110, (although a large drop off in rate was encountered around days 46-50 coinciding with an increase in settlement occuring between SP4 and SP5. The groundwater levels indicated once again that these were collapse settlements.

Of specific note is the compressive strains between SP4-SP5 and SP3-SP4. Between SP3 and SP4, a horizon thickness of 4.2 metres a strain of 22.1 mm/m was recorded, whilst between SP4 and SP5, (4.7 metres) only 6.8 mm/m. This implies that despite the fact that both horizons have been fully saturated, surface layer settlement is much less than that which occurs within the main body of the fill. In a dump truck or dragline backfilling operation this may be expected as the near surface layers only are subjected to compactive effects from site plant or even scraper layering required to bring surface levels to requirements. Even the lower horizons in the fill which are affected by the self weight of fill above show commeasurable strains to the near surface layers. (e.g. SP2-SP3, (3.6 m), had a compressive strain of 6.0 mm/m).

Overall the trends are similar to the two previously discussed instruments although there is a anomoly in the lack of heaving movements on magnets SP2 and SP3 which were supposedly saturated prior to monitoring. Horizon SP2-SP3 in particular implies that the water table was rising through this area. Piezometer data indicates that from the start of monitoring, water levels were just above the level of SP3. Heave movements did not commence between SP3 and SP4 until day 25 when the water level stood above SP4.

iv). Extensometer E4.

Extensometer E4 was installed in the line of a haul road which had being used throughout the life of the mine. The total settlement measured was 25 mm over the 110 day period giving an overall settlement of 1.33 mm/metre of fill depth. Results are presented in Figure 3.11 and Table 3.5.

All horizons show similar strain rates with none of the trends of the previous instruments. This implies that the compaction of the haul road by moving plant has removed the collapse settlement characteristics. Even heaving movements previously experienced on saturation cannot be so precisely defined.

An analysis of 25 mm settlement in 18 m of fill material would be misleading if taken further, save to say that the degree of compaction afforded to the fill mass has been critical in affecting the overall settlement of the fill.

v). Extensometer E5.

Extensometer E5 was sited in the deepest fill, close to the final void area. The majority of the filll had been endtipped by dump trucks but the near surface layers, (ie the top 7-8 m) had been replaced by scrapers. A total settlement of 222 mm was recorded giving an overall displacement of 7.28 mm/metre fill depth. Results are presented in Figure 3.12 and Table 3.6.

Heaving movements were observed once again in saturated ground but overall, small degrees of settlement were still occuring in the lowest portions of the fill. On horizon SP2 -SP3, a major increase in settlement rate can be observed to occur between days 46 and 50 - when the water level was in fact just below the level of SP4. The settlements in regions SP3-SP4 and SP4-SP5 were observed to be low, not showing the anticipated effect of more major settlement on inundation. The most likely effect being due to the effect of scraper layering of fill near surface resulting again in compactive loads.

Whilst the lack of settlement in the upper layers is fairly comprehensive the acceleration in settlement in horizon SP2-SP3 between days 46 and 50 is not so clear, the groundwater achieving the level of SP3 by the 15th day of monitoring. Possible reasons include the possibility that large boulders are present in the fill at this level and have required a longer time spell to break down under the action of water. The drilling and especially the casing of the hole at this level was quite difficult implying that the hole may have deviated by the presence of such boulders. A second but probably less likely reason could be the presence of an relatively impermeable layer within the fill resulting in pressurised water beneath the barrier. This would lead to a type of sub-artesian condition where the water level registered in the piezometer tubing is in fact higher than

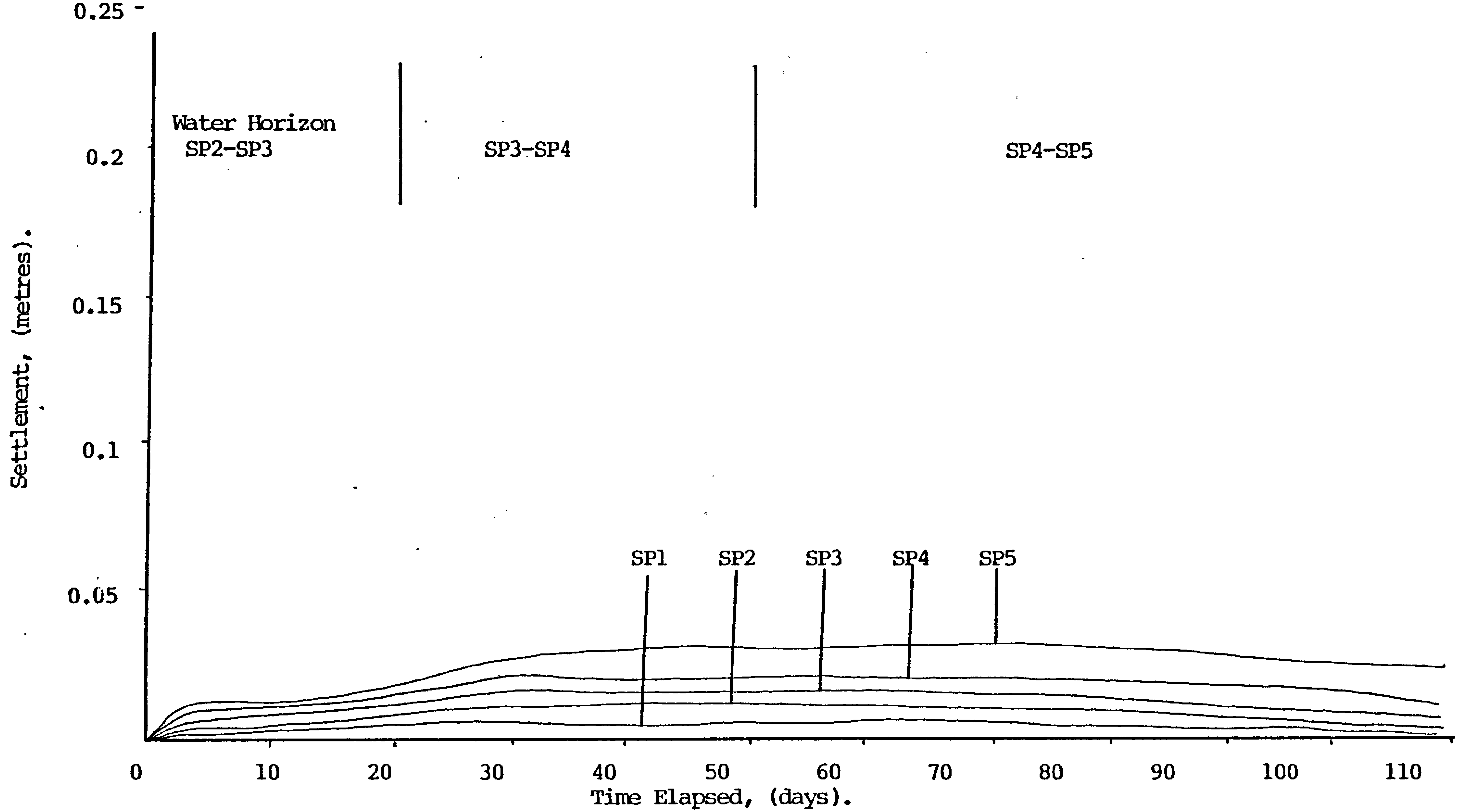


Figure 3.11 Settlement and Groundwater Characteristics, Extensometer E4, Site A.

Day	Cumulative Total Settlements SP1	SP2	SP3	SP4	SP5	Settlement registered at each horizon D-SP1 Total	D-SP1 Change	SP1-SP2 Total	SP1-SP2 Change	SP2-SP3 Total	SP2-SP3 Change	SP3-SP4 Total	SP3-SP4 Change	SP4-SP5. Total	SP4-SP5. Change	Water Horizon.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	at SP2
4	6	8	9	9	12	6	6	2	2	9	9	0	0	3	3	SP2-SP3
8	0	1	5	8	10	0	+6	1	+1	4	+5	3	3	2	+1	"
12	4	4	7	9	11	4	4	0	+1	3	+1	2	+1	2	0	"
15	3	4	8	10	13	3	+1	1	1	4	1	2	0	3	1	"
19	4	10	15	18	23	4	1	6	5	5	1	3	1	5	2	"
21	4	9	15	19	26	4	0	5	+1	6	1	4	1	7	2	at SP3
25	4	9	15	19	26	4	0	5	0	6	0	4	0	7	0	SP3-SP4
29	5	10	17	25	30	5	1	5	0	7	1	8	4	5	+2	"
32	4	10	19	23	30	5	0	6	1	9	2	4	+4	7	2	"
DAYS 36-49 INSTRUMENT FLOODED																
50	5	8	15	18	28	5	0	3	+3	7	+2	3	+1	10	3	at SP4
70	4	9	16	20	33	4	+1	5	2	7	0	4	1	13	3	SP4-SP5
DAYS 71-109 INSTRUMENT FLOODED																
110	4	5	9	12	25	4	0	9	4	4	3	3	+1	13	0	at SP5

CUMULATIVE STRAIN CALCULATIONS.
(mm settlement/m original horizon thickness)

Day	D-SP1	SP1-SP2	SP2-SP3	SP3-SP4	SP4-SP5
0	0	0	0	0	0
4	1.7	0.5	0.3	0	0.8
8	0	0.3	1.4	0.8	0.5
12	1.1	0	1.1	0.5	0.5
15	0.8	0.3	1.5	0.5	0.8
19	1.1	1.5	1.8	0.7	1.3
21	1.1	1.3	2.2	1.0	1.8
25	1.1	1.3	2.2	1.0	1.8
29	1.4	1.3	2.6	2.1	1.3
32	1.1	1.6	3.3	1.0	1.8
50	1.4	0.8	2.5	0.7	2.6
70	1.1	1.3	2.6	1.0	3.3
110	1.1	0.2	1.4	0.8	3.6

+ denotes heaving movement

Table 3.5 Summary of Settlement and Recovery Results, Extensometer E4, Site A.

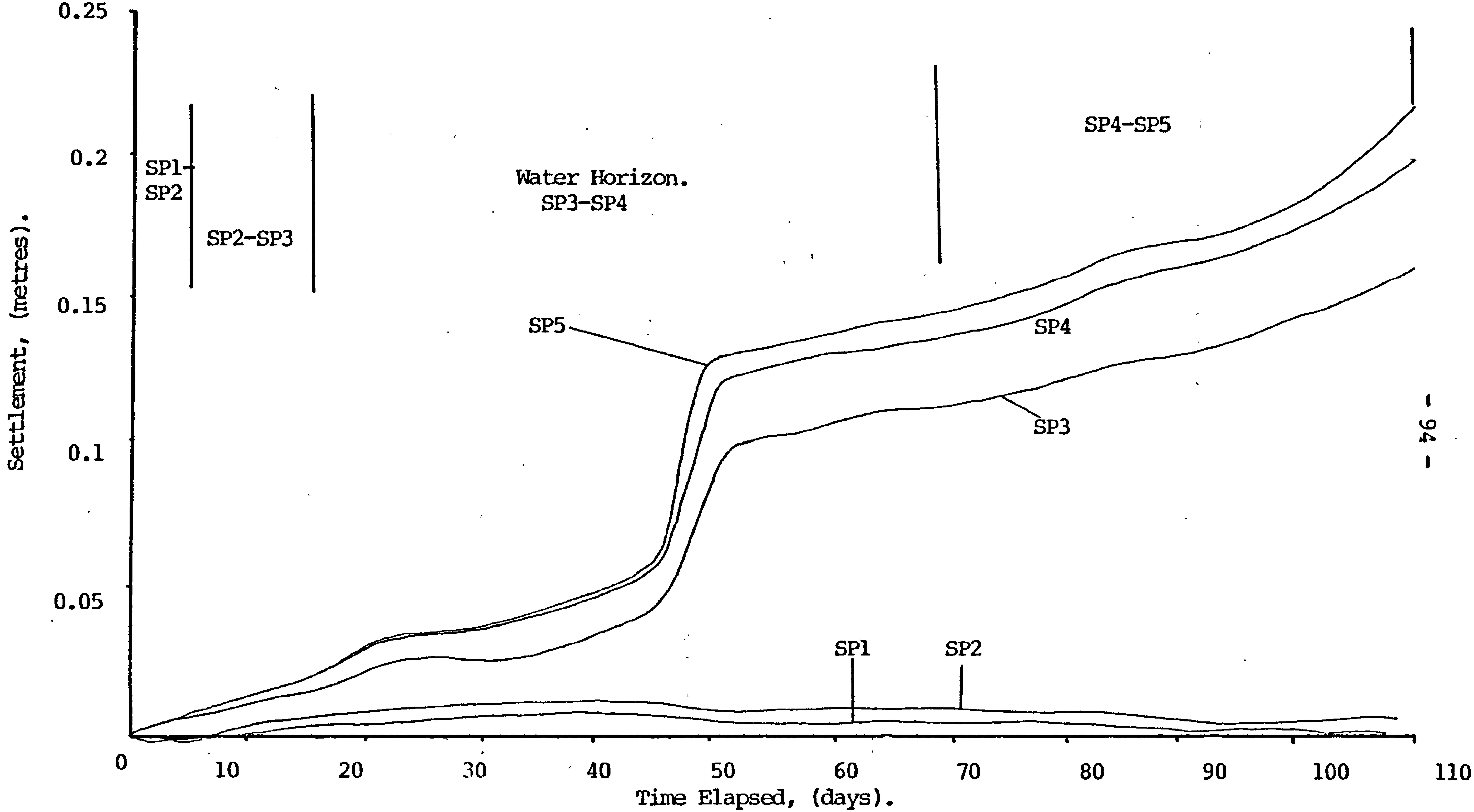


Figure 3.12 Settlement and Groundwater Characteristics, Extensometer E5, Site A.

Day	Cumulative Total Settlements SP1	SP2	SP3	SP4	SP5	Settlement registered at each horizon D-SP1 Total	D-SP1 Change	SP1-SP2 Total	SP1-SP2 Change	SP2-SP3 Total	SP2-SP3 Change	SP3-SP4 Total	SP3-SP4 Change	SP4-SP5. Total	SP4-SP5. Change	Water Horizon.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	SP1-SP2
4	+2	+1	1	2	2	+2	+2	1	1	2	2	1	1	0	0	SP2-SP3
8	5	7	6	14	13	5	7	2	1	+1	+3	8	7	+1	+1	"
12	2	5	11	16	16	2	+3	3	1	6	7	5	+3	0	1	at SP3
15	2	6	12	18	18	2	0	4	1	6	0	6	1	0	0	SP3-SP4
19	4	8	19	31	30	4	2	4	0	11	5	12	6	+1	+1	"
21	5	10	22	33	34	5	1	5	1	12	1	11	+1	1	2	"
25	5	10	24	35	37	5	0	5	0	14	2	11	0	2	1	"
29	7	12	26	37	41	7	2	5	0	14	0	11	0	4	2	"
32	2	7	24	35	37	2	+5	5	0	17	3	11	0	2	+2	"
36	5	10	31	42	48	5	3	5	0	21	4	11	0	6	4	"
43	2	7	32	48	49	2	+3	5	0	25	4	16	5	1	+5	"
46	6	11	40	54	57	6	4	5	0	29	4	14	+2	3	2	"
50	3	6	96	120	131	3	+3	3	+2	90	61	24	10	11	8	"
70	4	7	111	135	147	4	1	3	0	104	14	24	0	12	1	SP4-SP5
78	3	7	118	144	156	3	+1	4	1	111	7	26	2	12	0	"
84	3	7	128	156	168	3	0	4	0	121	10	28	2	12	0	"
94	0	3	131	161	170	0	+3	3	+1	128	7	30	2	9	+3	"
110	2	6	163	211	222	2	2	4	1	157	19	48	18	11	2	at SP5

CUMULATIVE STRAIN CALCULATIONS.
(mm settlement/m original horizon thickness)

Day	D-SP1	SP1-SP2	SP2-SP3	SP3-SP4	SP4-SP5
0	0	0	0	0	0
4	+0.4	0.3	0.4	0.2	0
8	0.9	0.4	+0.2	1.7	+0.3
12	0.4	0.8	1.2	1.1	0
15	0.4	1.0	1.2	1.3	0
19	0.8	1.1	2.2	2.5	+0.3
21	0.9	1.3	2.4	2.3	0.3
25	0.9	1.3	2.8	2.3	0.5
29	1.3	1.3	2.8	2.3	1.0
32	0.4	1.3	3.4	2.3	0.5
36	0.9	1.3	4.3	2.3	1.5
43	0.4	1.3	5.1	3.4	0.3
46	1.1	1.3	5.9	3.0	0.8
50	0.6	0.8	18.3	5.1	2.8
70	0.8	0.8	21.2	5.1	3.1
78	0.6	1.1	22.6	5.5	3.1
84	0.6	1.1	24.7	5.9	3.1
94	0	0.8	26.1	6.4	2.3
110	0.4	1.0	32.0	10.2	2.8

+ denotes heaving movement.

Table 3.6 Summary of Settlement and Recovery Results, Extensometer E5, Site A.

that present in the fill.

3.7 POST-RECOVERY SETTLEMENTS.

Details of all post recovery settlements are presented in Table 3.7. Of most importance is the fact that settlement movements over the period have been very small and the water table has remained stationary. All stations have shown only small movements with station E3 actually showing an overall heave movements. From the point of view of substantial ground movements all instruments have ceased to move significantly.

3.8 CONCLUSIONS.

The settlement and groundwater recovery observations on this site have resulted in a number of conclusions which can be made as follows:

a). Most settlement observations can be directly related to groundwater position as the prevalent factor.

b). Water recovery can be extremely rapid in shallow sites in wet areas, in this case 110 days to recover an average of 11 metres to surface.

c). Little or no settlement has been recorded since recovery completed. The sequence of recovery would have appeared to have converted all the mudstone material into impermeable clays.

d). Site plant compaction as monitored by instrument E4 has

Table 3.7

Post Recovery Settlement Results, Truck Shovel Site A.

Extensometer	Settlement. Day No.					Settlement Analysis Day 200	
	110	170	180	190	200	mm/m	mm/day
E1	0.168	0.178	0.188	0.187	0.186	9.36	0.93
E2	0.179	0.180	-	0.184	0.185	8.36	0.925
E3	0.134	0.135	0.137	0.136	0.135	6.53	0.675
E4	0.025	0.030	-	0.031	0.031	1.64	0.155
E5	0.170	0.202	0.222	0.224	0.225	9.64	1.125

significantly reduced the total amount of settlement in that area. The fill in this location of 18 metres depth has only displaced by 31 mm over 200 days of monitoring.

e). Results on instrument E2 and E3 have implied that the formation of perched water tables is possible. Formation of such water tables near the surface may well cause a flooding of the land.

f). Differential settlement over the site have produced areas of poorly drained land, i.e. flooded areas over the site. In addition the re-application of the soils have resulted in a seal which has prevented the draining the surface into the natural groundwater regime.

CHAPTER 4.

SETTLEMENT AND GROUNDWATER OBSERVATIONS ON A DEEP BACKFILLED DRAGLINE SITE.

CHAPTER 4. SETTLEMENT AND GROUNDWATER OBSERVATIONS ON A DEEP BACKFILLED DRAGLINE SITE.

4.1 INTRODUCTION.

This chapter examines groundwater and backfill settlement monitoring on a dragline site in the North-East of England, (denoted as Site B for the purposes of this thesis). The instrumentated part of the site was in fact an extension to earlier opencast workings. The original site which covered 230 hectares had been requisitioned from a service airfield, whilst the Extension site comprised 66 hectares of land made up from two small farms and a small holding.

Excavation on the original site commenced in 1974 and advanced northwards, (figure 4.1). The Extension which commenced in 1981 conversely commenced along the northern limit of the take and worked southwards. Both sites were worked by dragline operations and restored by end-tipping from dump trucks into the mine void together with conventional dragline spoiling. Coaling ceased on the Extension site in August 1984 and backfilling and soil replacement continued until Autumn 1986. The plant was taken off the site for the Winter of 1985/86 to continue resoiling in the following Spring.

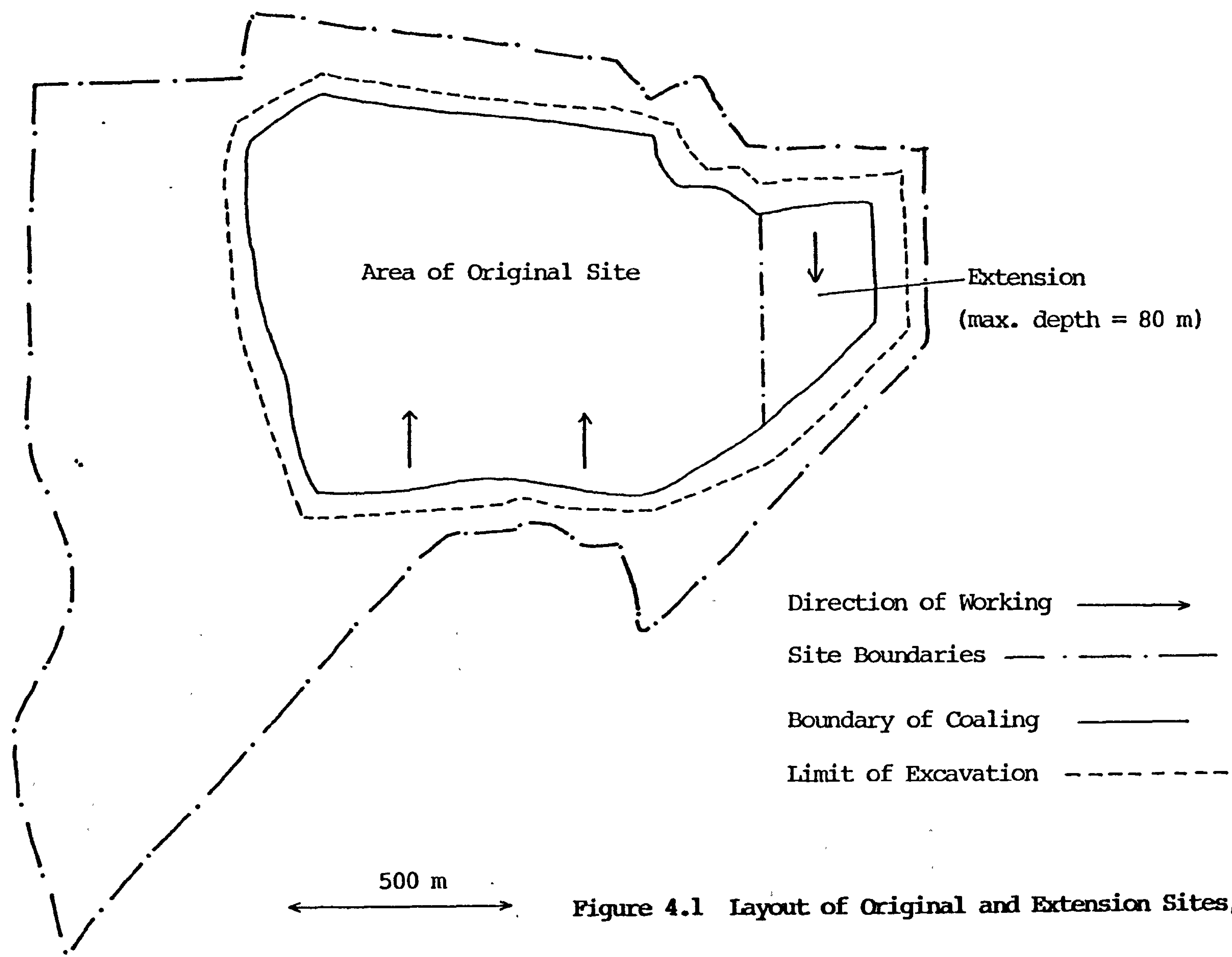


Figure 4.1 Layout of Original and Extension Sites, Site β.

The installed monitoring scheme observes groundwater patterns and settlement characteristics of a sandstone and mudstone backfill of up to 80 metres depth.

4.2 TOPOGRAPHY, GEOLOGY AND NATURE OF FILL.

The site is located on the flat Northumbrian coastal plain. The maximum pre-mining surface elevation stood at 138 m above site datum. (a.s.d, where a.s.d. = 100 m below Ordnance Datum). The minimum elevation was 124 m a.s.d. The final restoration contours for the site are illustrated in figure 4.2, along with proposed positions of water courses and a restored area of the site which was at the time of investigation no longer under National Coal Board control.

The take comprised of 9 seams showing a general North-South strike. The corresponding easterly dips averaged 1 in 14 but reached maximum values of 1 in 8. Figure 4.3 illustrates a typical geological section which was encountered across the mine. The superficial deposits consisted of boulder clays with interstratified sand and/or gravels together with areas of opencast mine backfill. Re-excavation of some of the original site fill was required during the working of the Extension site. Previous opencast sites had worked over a small part of the same area to limited depths in the 1940's. Boulder clay comprised the bulk of the drift deposits and increased from a minimum of 0.5 m thickness in the North to a maximum of 23 m in the South West, the average thickness being 10 m. The overburden consisted of mudstones, seatearths and sandstones

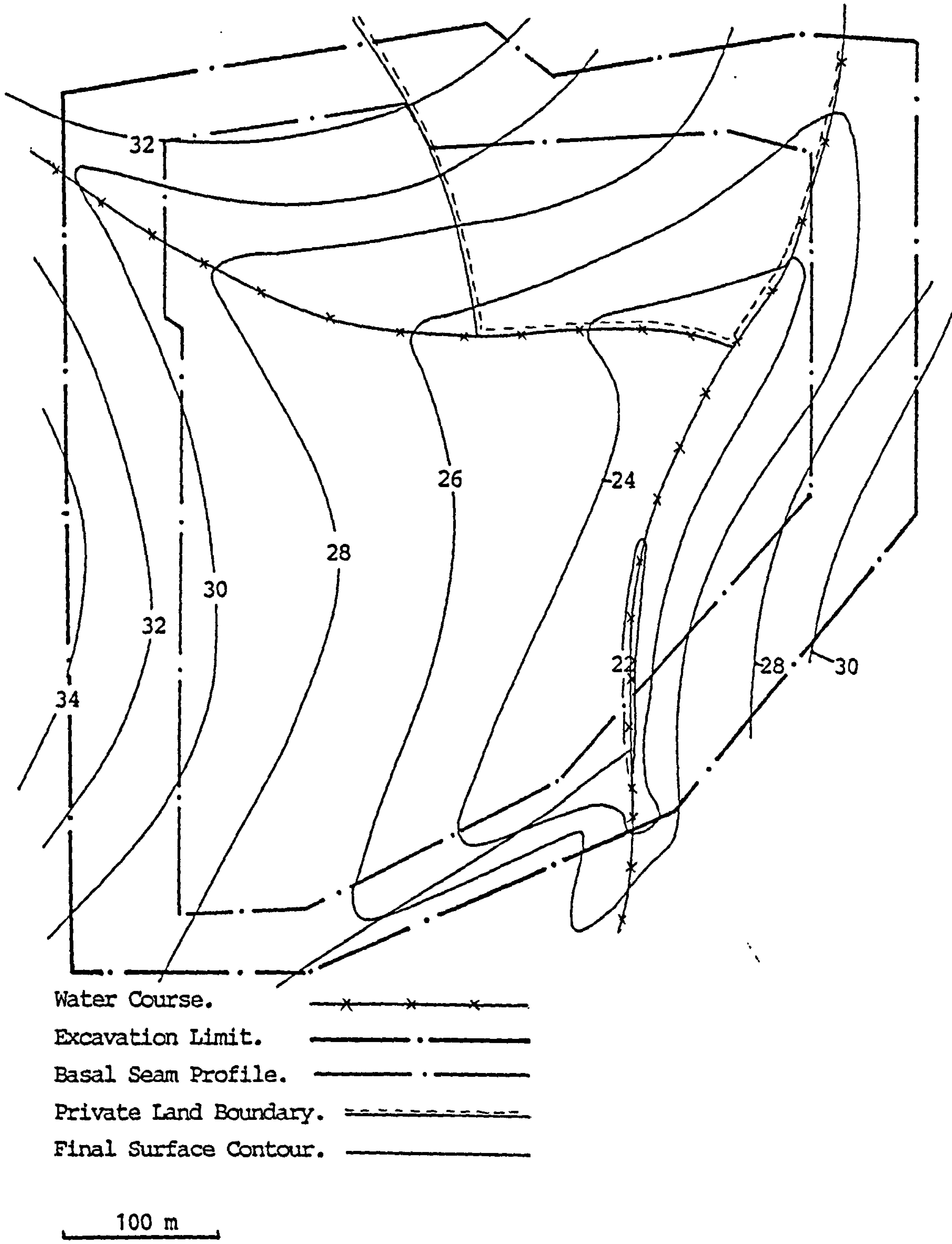


Figure 4.2 Final Restoration Contours, Site B.

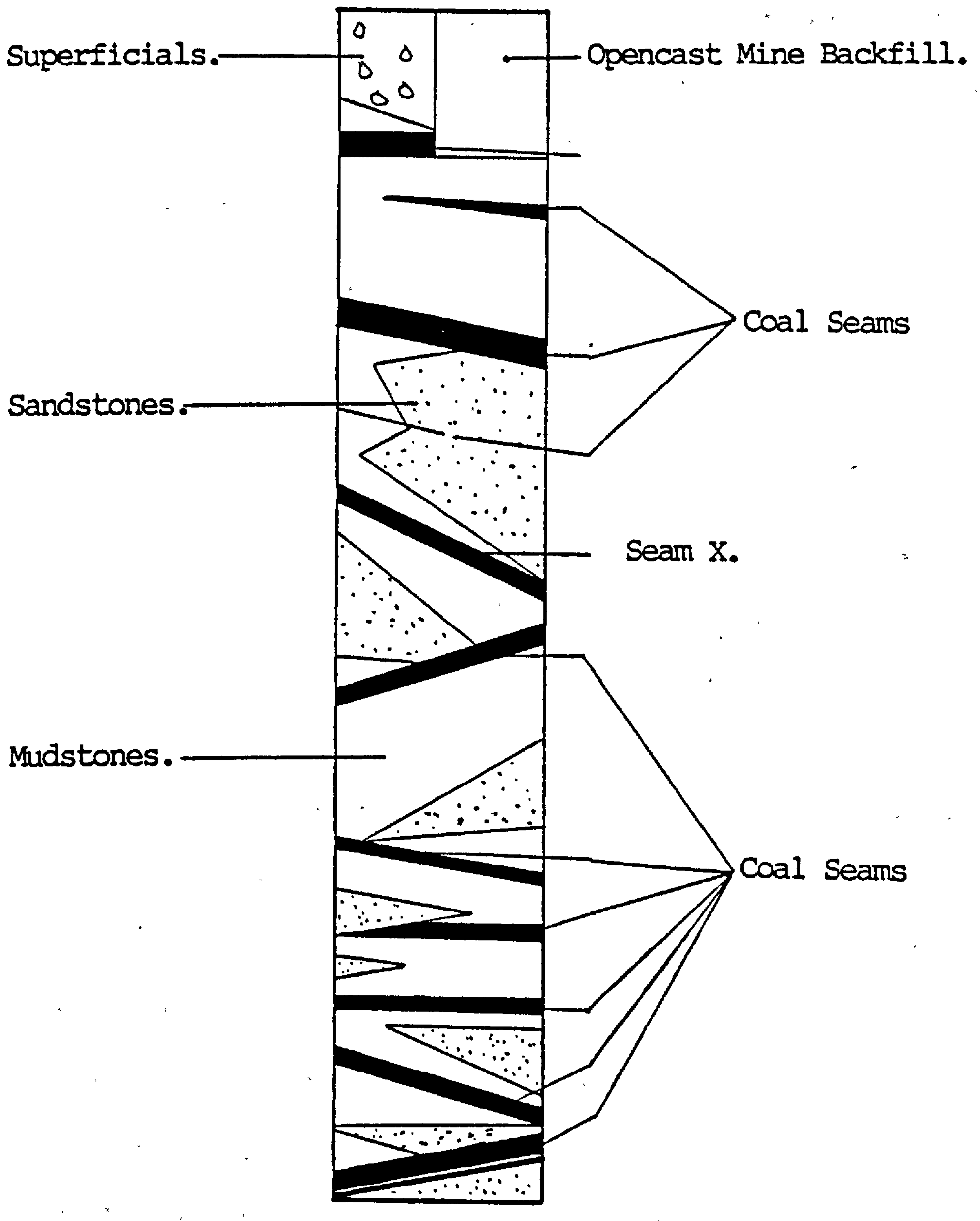


Fig. 4.3 Generalised Vertical Section.
Scale 1:500.

which graded laterally into silty mudstones, silty seatearths, shaly sandstones and siltstones. The rock strata above Seam X (figure 4.3) required little or no blasting during mining and deep mine workings were excavated in three uppermost seams in the progression.

The expected bulkage of the backfill was expected to be around 10 to 11 %. Figure 4.4 illustrates fill depths over the Extension site and shows how fill depths vary from 44 metres along the far eastern edge of the site to 80 m in the area of deepest excavation.

4.3 GROUNDWATER CONDITIONS.

The groundwater levels on both the original and Extension sites are subject to two principal phenomena:

a). The dewatering of strata by opencast excavations in the immediate area, and

b). The pumping of groundwater from a local abandoned colliery shaft.

In the case of a), the groundwater levels are affected by the excavation of saturated rock and by on-site pumping both of which serve to depress local groundwater levels.

Pumping currently being conducted in an abandoned mine shaft has a major effect on groundwater levels in the area, particularly as many of the seams which are being worked by local opencast mines are excavating abandoned room and pillar mine workings, forming a vast intersection of shafts and old deep mine workings. The distance between the colliery pump and

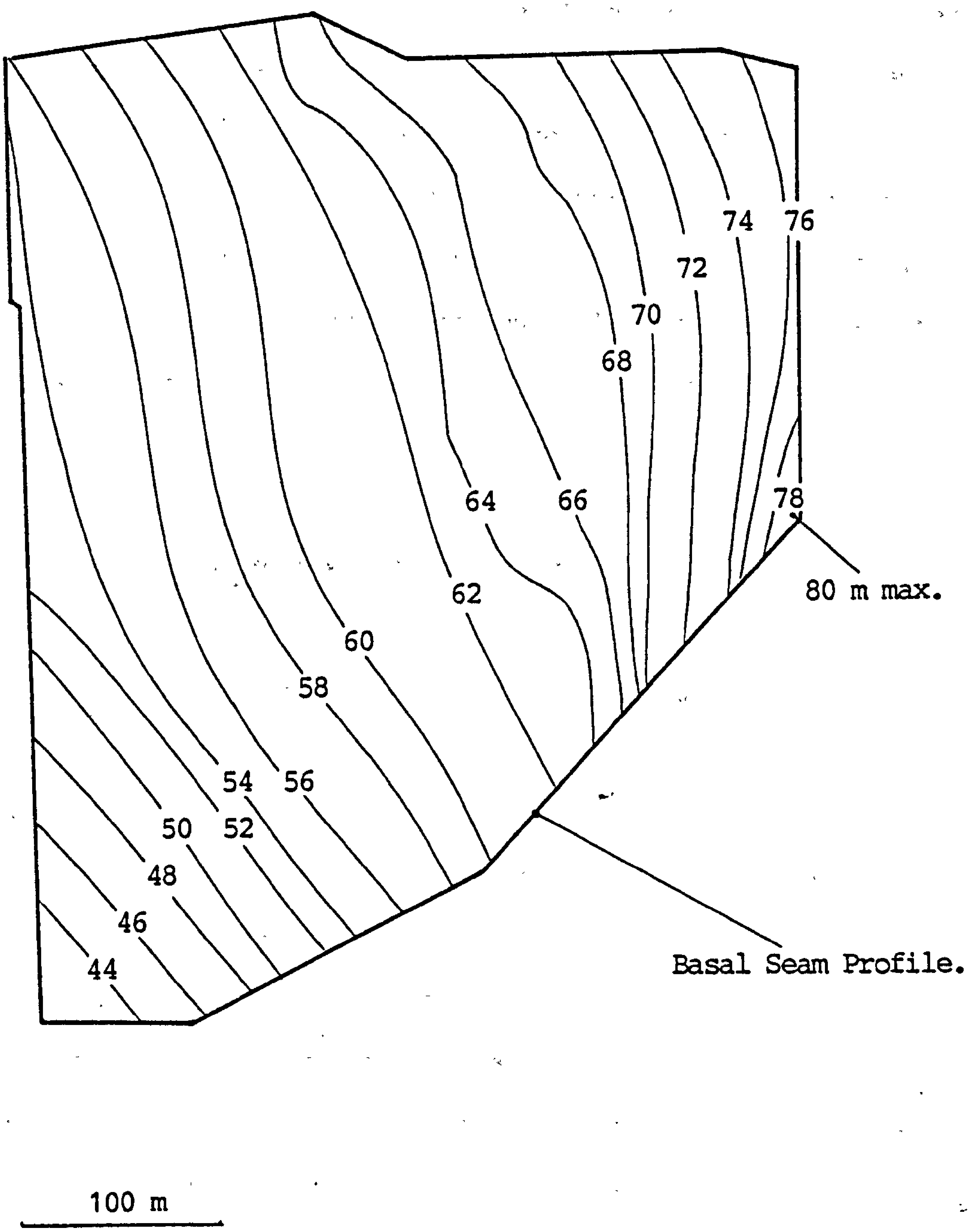


Figure 4.4. Final Fill Thicknesses - Site B.

the opencast mine site is approximately 4.3 km. The influence of this pumping is however restricted by semi-pervious barriers in the area such as major faults, igneous dykes and areas of solid unworked strata all having relatively lower permeabilities. Figure 4.5 illustrates the groundwater levels over the original and Extension sites as at the end of 1975, and reflects what must have been near-equilibrium conditions produced by continuous pumping in the deep mine shaft. Of specific note was the high hydraulic gradient between the sites occuring at the outcrop of seams which were directly connected to the mine pump.

4.4 PREDICTION OF GROUNDWATER RECOVERY.

The shaft pumping operations are expected to continue for at least another 10 years, so a prediction as to the final water levels in the restored fill will be made assuming this influence. Following the termination of this pumping, water levels may be expected to rise above these estimations. The temporary effects of local opencast mine sites either existing or projected will be for the moment neglected. The boundary between the unworked and worked deep mine strata corresponds to the outcrop of seams which have been previously worked by underground room and pillar workings, in particular the outcrop of seam X which is the deepest in the succession on the Extension site to have been previously worked. A standard measure on opencast mine sites with old mine workings such as these is to seal them off with clay to prevent water either

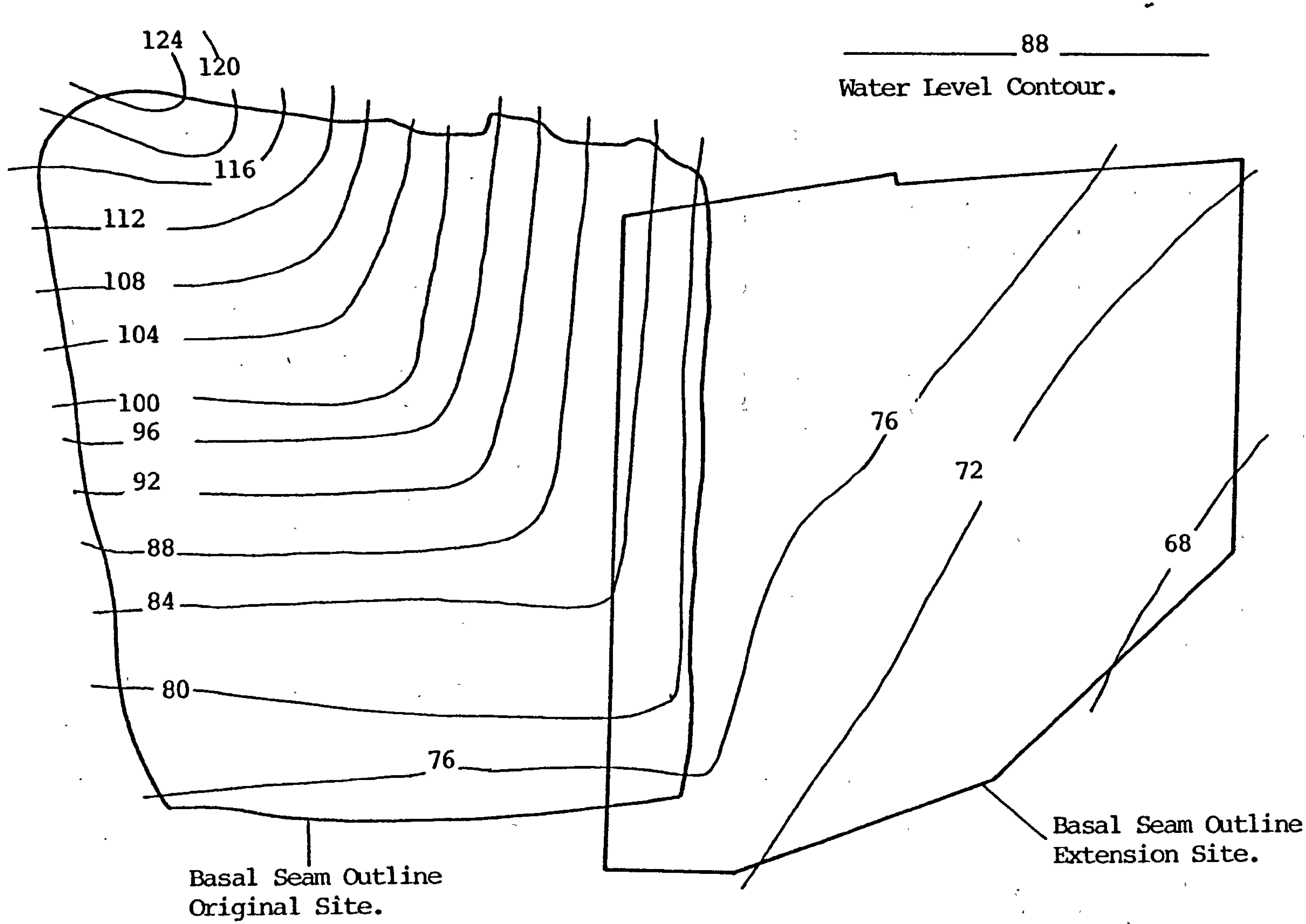


Figure 4.5 Original Groundwater Levels, (a.s.d.), - Site B.

entering deep mine workings or vica versa. If these seals are 100% effective then there should be a minimum of influence from the pumping shaft and water levels would rise to either the original equilibrium levels or more likely to above these. In this case it is possible to predict the minimum degrees of water table recovery in assuming that water levels will rise to the minimum level of seam X. After this water levels may either remain stationary and water drain through old workings directly to the shaft, (ineffective clay seal), or the water levels will rise further. This approach also neglects drawdown within the fill towards the intersection of the old workings.

In the position of the deepest point of excavation, the level of seam X workings were 80 m a.s.d., about 40 m below the final restored fill surface, and this was thus deduced to be the minimum level that the groundwater level will recover to. The pre-mining water levels over the extension site stood at 70 to 75 m a.s.d, whilst over the original site they lay in excess of 100 m a.s.d. which would indicate that the predicted degree of recovery is of the right order. The minimum measurable degrees of groundwater recovery over the Extension site are presented in figure 4.6. This prediction is vital to the siting of instrumentation, as obviously such equipment must be sited in the deepest fill to ensure maximum degrees of measurable groundwater recovery and consequently backfill settlements.

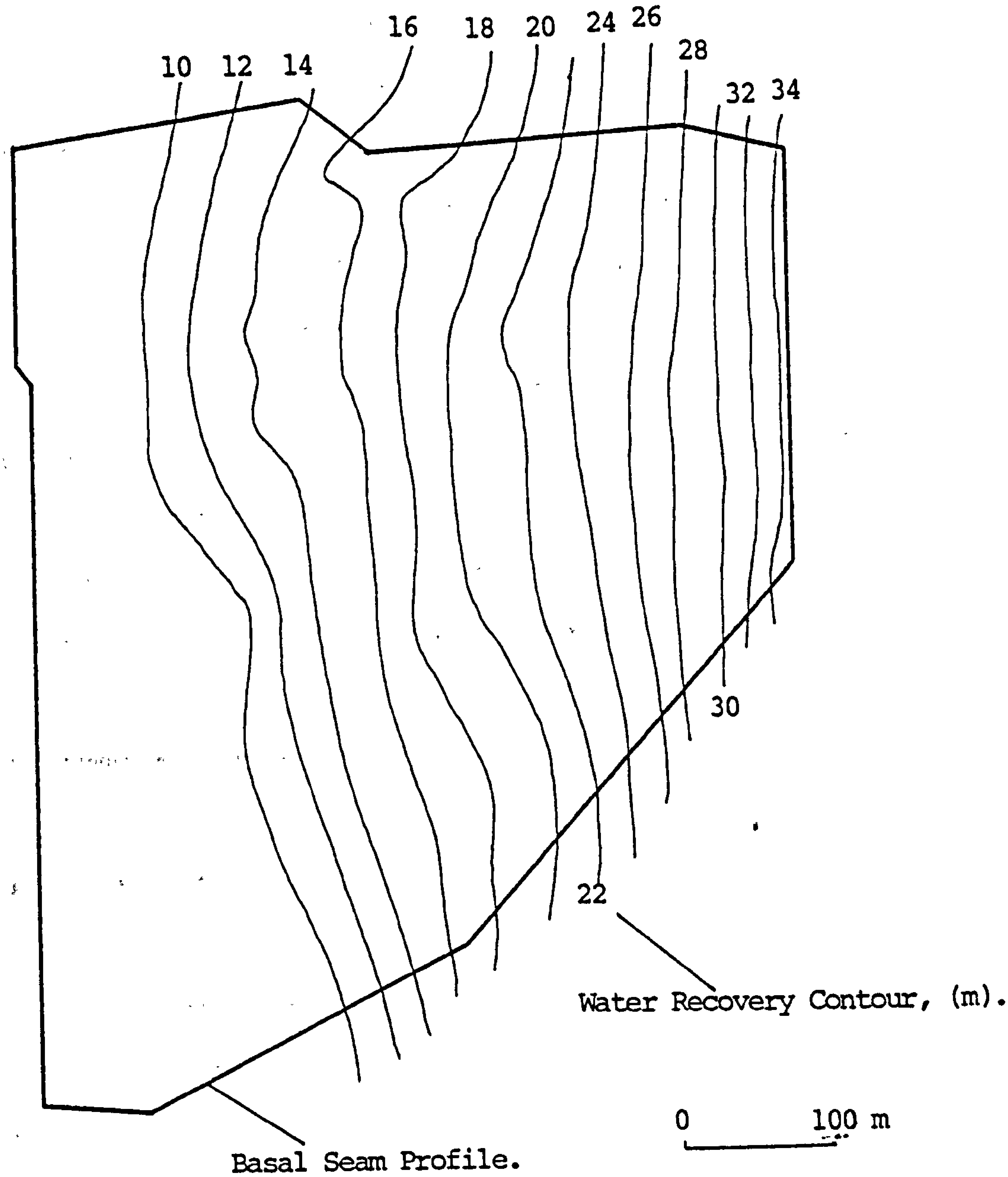


Figure 4.6 Prediction of Groundwater Recovery, Site B.

4.5 SITE PUMPING.

Site records traditionally record very little information concerning site pumping, generally only detailing the pumps used and hours of operation. This unfortunate fact has been partially rectified by the introduction of the Weekly Site Pumping Returns Form which was introduced in August 1984. Returns for the Extension site commenced on the 1 August 1984 and recorded pumping during the last week of coaling and subsequent weeks of backfilling. During this time water levels in the final void area remained a constant 60 m a.s.d. with pumping being conducted by a single FLYGT B2250 150 mm submersible pump averaging 12 hours pumping per day. The estimated volume of water in the final void sump was estimated to vary between 2×10^6 and 5×10^6 litres.

4.6 INSTRUMENTATION SCHEMES.

4.6.1 Initial Proposal.

The initial proposal for instrumentation of the Extension site followed similar lines as that performed on the Truck-Shovel Site A in the East Midlands discussed in the previous chapter. The central magnetic extensometer/ piezometer of the profiles was to be replaced by a multi-point piezometer, (chapter 2).

The proposed locations of the instruments relied on a number of important site restrictions together with the expected measurable degree of water recovery. The important criteria were as follows;

a). **The lines of installation of the proposed water courses.** To give adequate protection to the instruments it was recommended that 20 m clearance should be given to protect from moving plant which will be constructing the water course.

b). **The profile of the excavation of the basal seam,** - to ensure that instruments are placed in maximum depths of fill. The figure also shows areas of solid strata which were left intact owing to stability problems during mining. It was recommended that adequate clearance be given to these areas to compensate for any borehole deviation during drilling.

c). **The position of the final void area.** At the time of instrumentation this area was still being backfilled and in fact the area remained open for a further year until October 1985. Adequate clearance had to be given for plant operating in this area.

d). **The line of current subsoil placement.** Corresponding to the line of final overburden level. Over much of the site between 2 and 3 m of overburden were still to be replaced, so that it was considered best if instruments could be sited as close as possible to the edge of the completed restoration.

e). **The 20 m recovery line.** It was considered that the instruments should be sited so that a minimum of 20 m of groundwater recovery. This line marks the westward boundary of the instrumentation scheme.

The initial proposal aimed to accomplish an instrumentation scheme illustrated in figure 4.7. Four magnet extensometers/

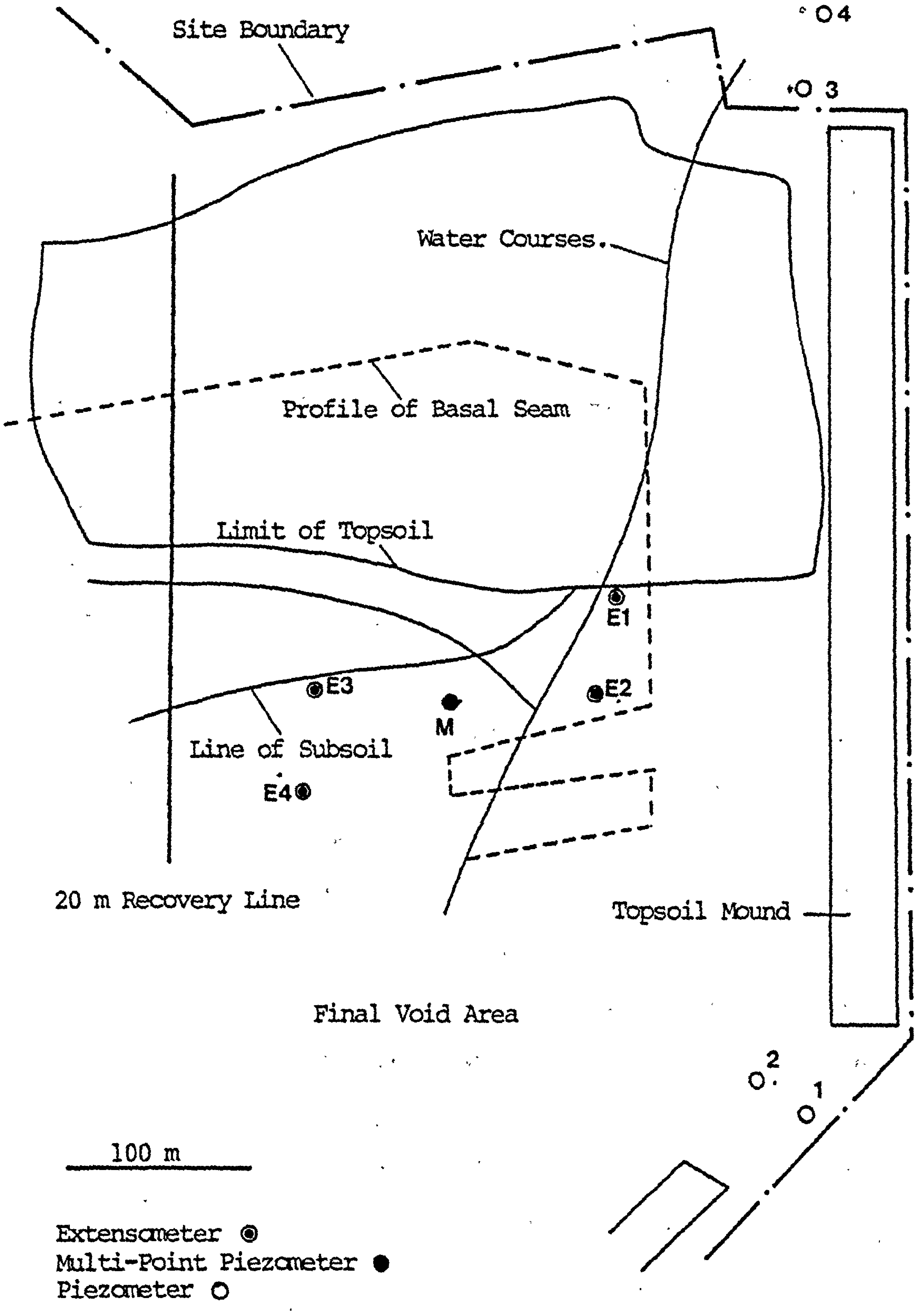


Figure 4.7. Initial Instrumentation Proposal - Site B.

piezometers with one multi-point piezometer in the fill and four piezometers in the solid. The most northerly piezometers were to be sited closer to the main instrumentation area but the damage that the drilling rig would have caused to the restored topsoil area would have been unacceptable. Drilling and instrumentation commenced on the project in November 1984.

4.6.2 Installation of Instrumentation, November 1984.

The instrumentation scheme commenced with the drilling company attempting to drill boreholes for extensometers E1 and E2. The boreholes were required to be drilled and cased to PX size casing, (133 mm). This borehole size accomodates the non-pneumatic release type extensometer, (chapter 2).

Whilst drilling in the fill was relatively uncomplicated, extreme problems were encountered in attempting to case the borehole and only 55 of the 80 m depth were successfully cased. The drillers avoided the use of foam drilling and just used the conventional air flush which probably contributed to the difficulty. An installation was attempted but owing to the weakness of the fill material below the casing, collapse rendered the installation impossible. The drilling company were then concerned over the tightness of the casing in the borehole and the drillers were ordered to remove the casing and abandon the borehole. During the removal of the casing the lower 18 m of pipes sheared off the threads resulting in the loss of this length of casing. The rig was eventually pulled off the fill drilling, (after the abandonment of a second 80 m borehole), and continued to drill in the solid strata for piezometer boreholes P1 and P2, on the Southen side of the void. These piezometers were successfully drilled and installed.

Following this unsuccessful extensometer installation attempt, a meeting was arranged with the National Coal Board to assess the future of this particular project and to revise instrumentation plans.

4.6.3 Revised Instrumentation Scheme 1.

The failure of the drilling company to successfully drill and case boreholes in backfill had resulted in a severe reduction in the available funds for the project. It was however agreed that a limited instrumentation scheme could continue. A new drilling company were appointed to the contract, who were prepared to use foam flushing whilst drilling. The agreed revised instrumentation plan was aimed at accomplishing the following installations.

a). Two standpipe piezometers in the solid on the Northern boundary of the site.

b). One Extensometer in circa 80 m of fill.

c). Two Multi-Point Piezometers in Backfill.

Suitable locations for the instruments were discussed at great length owing to reservations from the Lands Department in the Area. Instruments were agreed to be sited near to fence lines or shelter belts in order not to sterilize field areas. The revised instrumentation scheme (1) is illustrated in figure 4.8.

4.6.4 Installation of Revised Instrumentation, December 1984-January 1985.

a). Magnetic Extensometer/ Piezometer.

The first installation was that of the magnetic extensometer. The installation of this instrument consisted of installing the access tubing and piezometer tip, backfilling the borehole with gravel to the required level of a magnet, and pushing the magnet down the access tube from the surface through the casing. When the magnet was in position, the casing was pulled to the next magnet level and gravel was poured into the borehole to form a surface for the subsequent magnet to come to rest on.

The borehole was drilled using foam flushing initially drilled with an 200 mm bit, followed by 150 mm and finally 100 mm bits in the lower regions of the borehole. The borehole was completely cased to PX size casing, (133 mm).

The installation was long and laborious, mainly due to the fact that gravel had to be poured into the borehole in small sackfuls by hand. The installation took four days to accomplish, (borehole depth = 70 m) and consequently resulted in unacceptable rig standing times.

The use of pea gravel is not to be recommended for a speedy

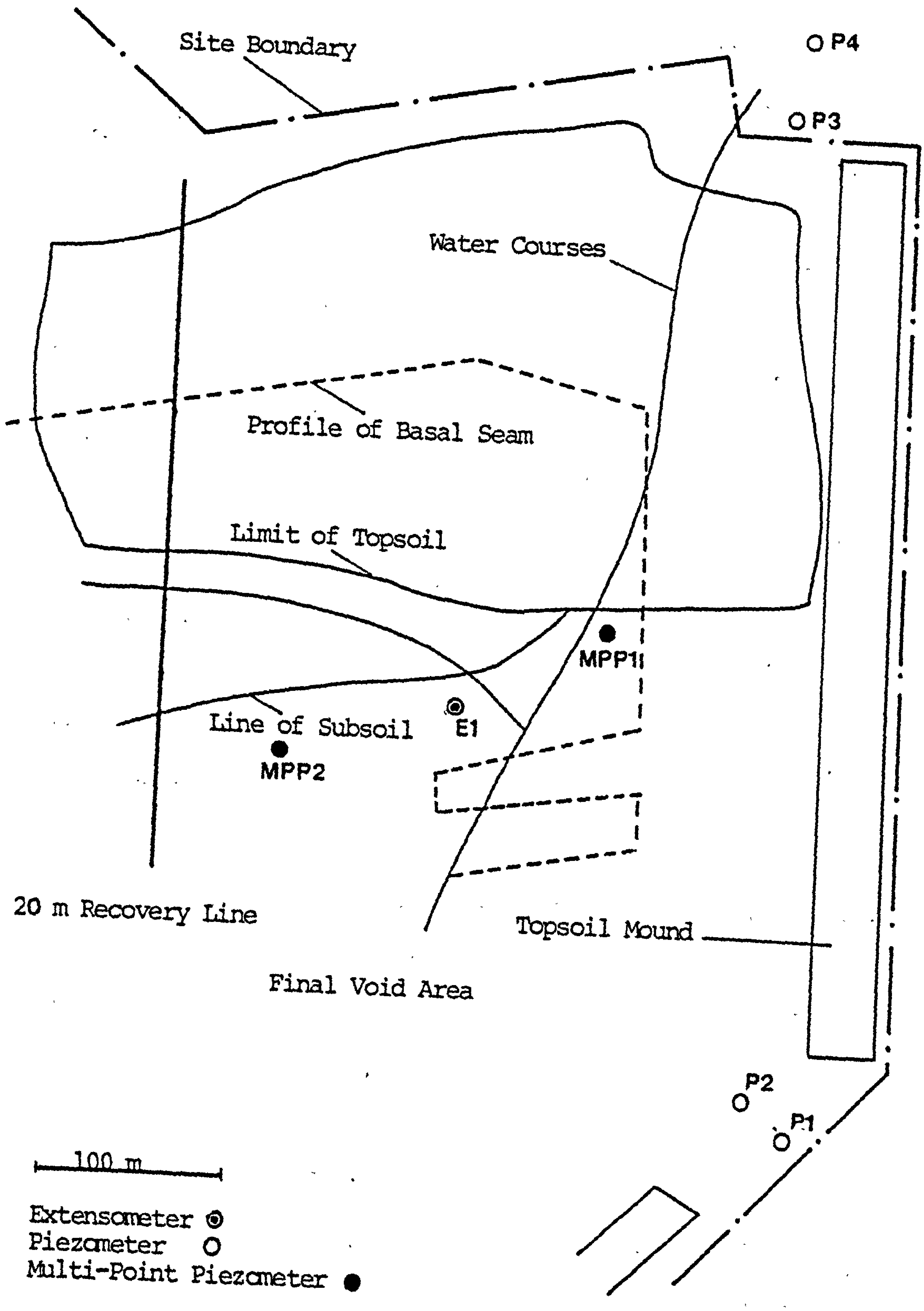


Figure 4.8. Revised Instrumentation Proposal (1) - Site B.

installation as it was quickly found that the material was notorious for bridging in the borehole. The use of fine filter sand as a borehole backfilling material is once again recommended.

Overall the installation appeared successful but when the initial measurements were being taken it was found that the Reed Switch Probe could only pass down to 55 m, - 15 m above the level of the datum magnet. Initial suggestions proposed that the blockage was due to the presence of either gravel or dirt in the access tubing at that level. A steel probe was lowered down the tube to attempt to free the blockage by impaction. The device passed down to the blocked horizon and easily became tight in the tube. The device in fact could not be retrieved and it was this that led to a supposition that a shearing movement had broken the tube at this level preventing the reading of the datum. After the passage of the next weekend however, a blockage had appeared at about 20 m below the surface, once again this could not be removed and a supposition of shear was again postulated.

The condition of this instrument as an extensometer and water level indicator has thus been effectively negated. As this was the only extensometer type instrument to be installed on this proposal of instrumentation it was clear that for the purposes of the project the site would be inadequately instrumentated. This condition is discussed in detail in the next section, Revised Proposal (2).

b). Multi-Point Piezometer Installations.

Both the multi-point piezometers were installed with five tips in each borehole in a manner detailed in chapter 2. Again the use of pea gravel is not recommended owing to its tendency to form bridges within the borehole. The installation although slow were on the wborehole successful. Generally one and a half days were required to install each instrument with a corresponding standing time, (save occasional removal of casing operations), for the rig.

On instrument MMP1, (fig 4.8), only four piezometers are working owing to a probe becoming stuck at depth inside one of the piezometer tubes. The tape connecting the reel to the probe had to be cut. This again could be due to a breakage in the piezometer access tubing at depth. In all cases however it has become apparent that some of the sondes on Reed Switch Probes and Dip Meters alike were far too long and bulky for safe use in holes such as these where tubes could be liable to even small shear movements. The smaller more compact probes are considered safer.

c). Standpipe Piezometers.

The four standpipe piezometers were installed in the solid to depths of up to 102 m without complications. The holes were backfilled using the drilling chippings.

4.7 APPRAISAL OF INSTRUMENTATION TO 9. JANUARY 1985.

The problem that was faced on the site at this stage was that owing to the loss of the extensometer there were no instruments at all which were directly measuring settlements in the zone of water recovery and thus the site was inadequatley instrumentated for the purposes of the project. At this time the following points were of specific attention:

o The National Coal Board Opencast Executive were uncertain whether they wished to finance a further drilling and instrumentation programme.

o If instruments had been lost owing to shearing movements in the fill then a different type of instrument must be installed to prevent a reoccurrence.

The University proposed that the installation of Tension-Wire Extensometers would overcome the problems of shear, partly by actual shear measurement. The National Coal Board finally agreed to finance two further boreholes using these types of instruments.

4.8 TENSION WIRE EXTENSOMETER INSTALLATION.

4.8.1 Instrumentation Details.

The object of this work was to install two tension wire extensometers with permeability testing facilities to depths of around 80 m in the fill. The locations of these two instruments are shown in fig 4.9 along with the positions of other instrumentation. Also illustrated is the location of the mains water supply which was used to conduct the pumping tests.

4.8.2 Proposed Method.

In order to describe the proposed method of extensometer installation, figure 4.10 is referred to which details the components of a complete extensometer installation. For simplicity only two seals are illustrated, along with the datum weight. The theoretical method of installation involves pushing the seals over the yellow tubes/wires into position using steel installation rods. The seal is then resin grouted into position and the installation rods disconnected from the seal by means of a left hand screw thread. The principle is illustrated in figure 4.11. The actual structure of a mechanical seal has previously been presented in figure 2.8.

The installation procedure was as follows.

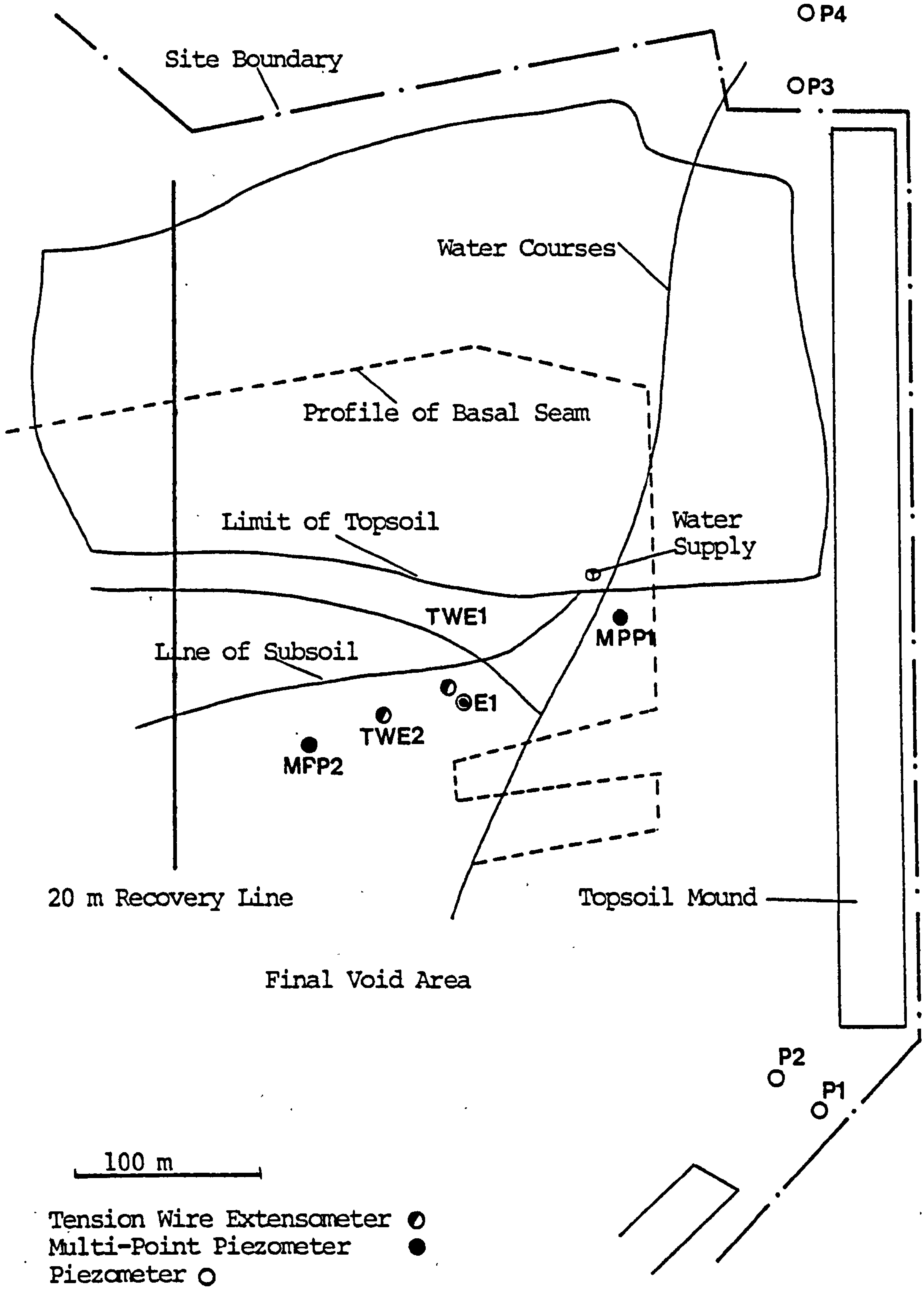


Figure 4.9. Final Instrumentation Plan, Site B.

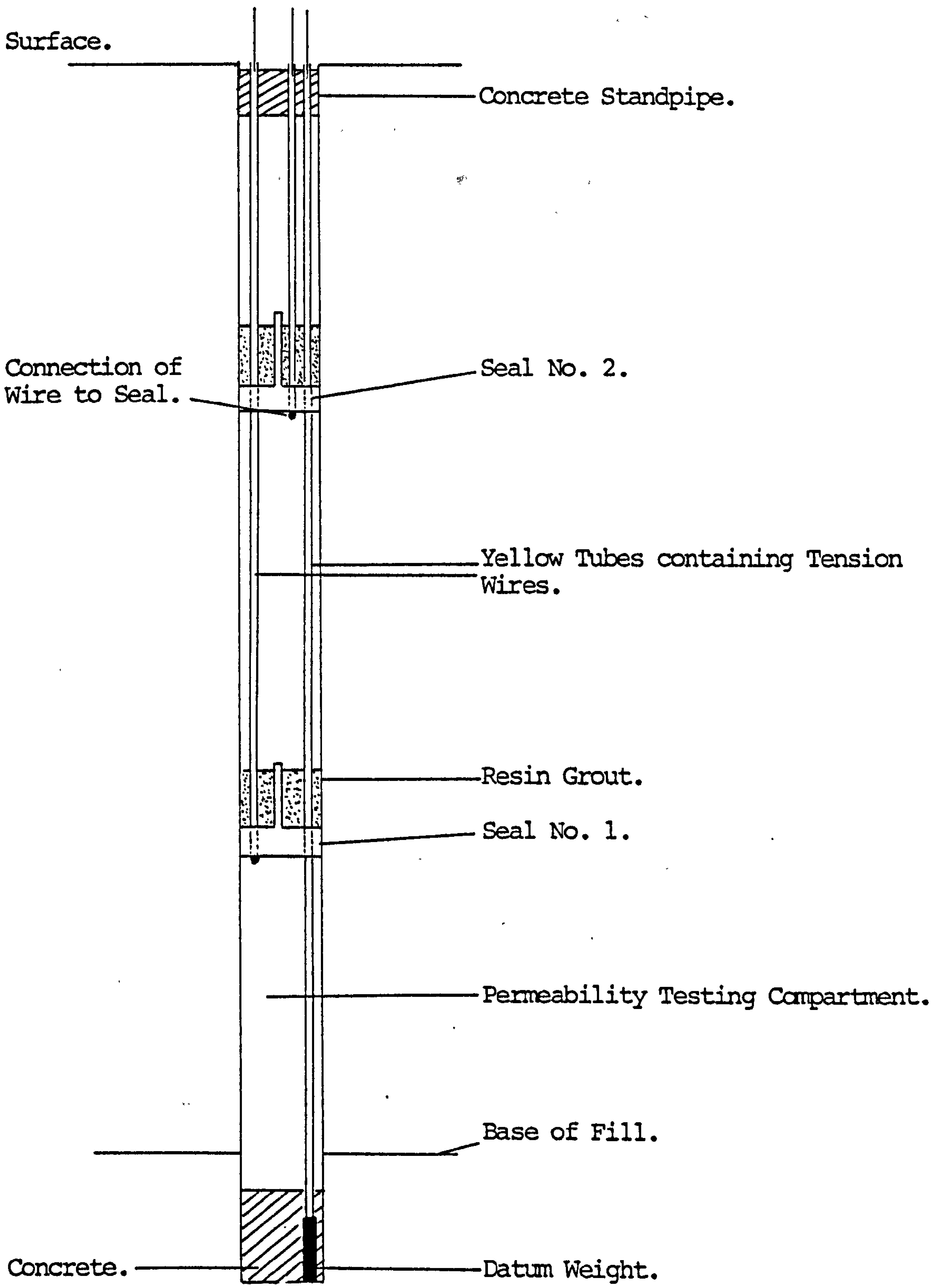


Figure 4.10 A Complete Extensometer Installation.

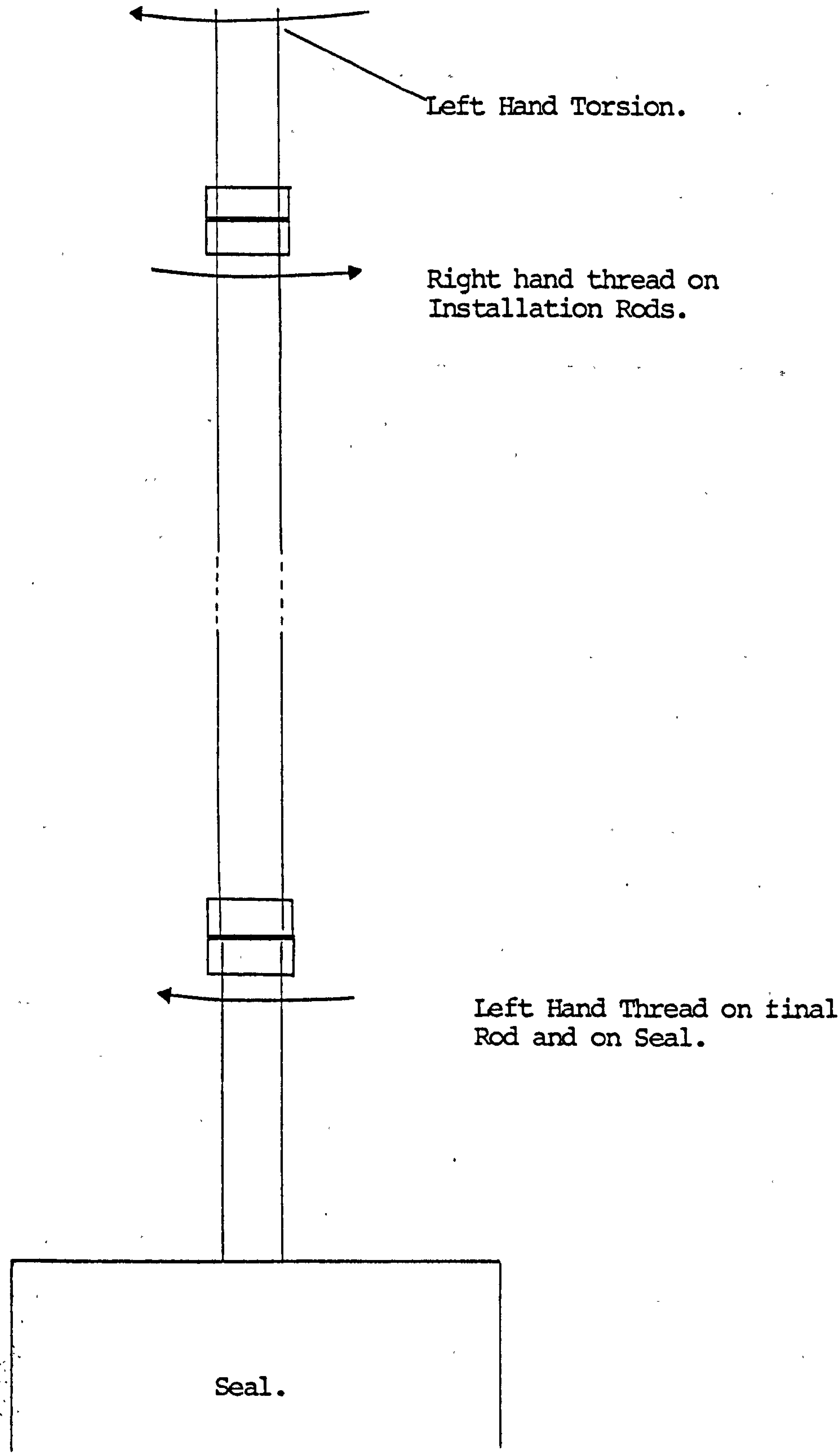


Figure 4.11 Principle of Seal-Rod Uncoupling.

1). The datum weight and wire was lowered to the base of the hole. This weight was then cemented in place. The cement must be mixed prior to pouring down the hole and must never be tipped down dry. Casing is pulled to the required level of the first seal.

2). The first seal was threaded onto the datum yellow tube. To the first seal was attached a tension wire which is housed inside another continuous length of yellow tubing. The seal was then pushed down the hole into position using three metre installation rods which couple to each other with a right hand thread. Once in place resin grout was pumped down the borehole to cover the seal. For this a grout pump and a 19 mm continuous tube was utilised to ensure that the grout was pumped to the correct position. Once the grout was cured, (about 1 hour), the rods were disconnected from the seal by means of a left hand thread between the two. A steel plate welded onto the seal prevented the seal from rotating in the grout if by chance the grout was improperly set. The rods were then withdrawn from the hole ready for the next seal insertion, and the casing was then pulled to the level of the second seal. Previously to this project this procedure had being successfully applied to a horizontal borehole 55 m in length which was uncased. Thus installation of this type of instrument to depths of 70 metres in opencast backfill posed an entirely new problem.

4.8.3. Field Experience.

The first installation of this type of extensometer on the site showed that there were a great deal of flaws in the proposed method. These will be summarised as follows.

i). Tensioning of Wires/ Tubes.

For a successful installation in a vertical borehole it is essential that the wires and tubes are under tension at all times. In this method the casing was being gradually withdrawn and thus during these periods it was impossible to maintain tension. This induced the problem that the wires and the tubes were bing pulled down the borehole under their own weight, and thus there was no control over these tubes save taping then all together at the top of the hole. When slippage occured the tubes had to be then retrieved using a length of PVC access tubing to which was attached a hook which could latch on to the tape loop on the top of the tubes. The problem of the lack of tension was extremely serious and after three aborted attempts at installation, mainly due to this problem it was decided that the installation would be more successful if installed in an uncased borehole. This however risked the chance of the borehole caving in during the installation. Fortunately on this particular hole the walls of the hole were very stable, (aided by foam flushing during drilling), and such caving did not occur. It should be pointed out that this is considered the exception in holes of this depth in unconsolidated material and not the rule. The driller generally has a fair idea of how the hole is likely to stand in such circumstances and his advice should be sought before any decision is taken. On any other attempt of such an installation a tensioning rig is recommended.

ii). <u>Installation Rods.</u>

It was quickly apparent that the use of heavy steel installation rods to push the seal into position was undesirable from the point of view of ease of installation. The rods were designed to be heavy so that they could push the seal easily down the hole. There was opinion that these rods were overdesigned making them awkward to handle in the field. The joints on the rods had been made up at the University Workshops and the threads on these had being made to a gas tight specification. Consequently the actual coupling and uncoupling of the rods in the hole was extremely difficult. In some cases the threads on some rods were unable to be coupled.

Perhaps the biggest problem was the uncoupling of the left hand thread between the first rod and the seal. The nature of the installation made this practise practically impossible. When it is considered how 50 or 60 metres of heavy installation rods will lie within an uncased borehole, fig 4.12, it can be appreciated that the turning of the rods at the surface in order to transmit torsion to the screw thread is unpractical. This situation was eventually relieved in the field by dispensing of the installation rods entirely and

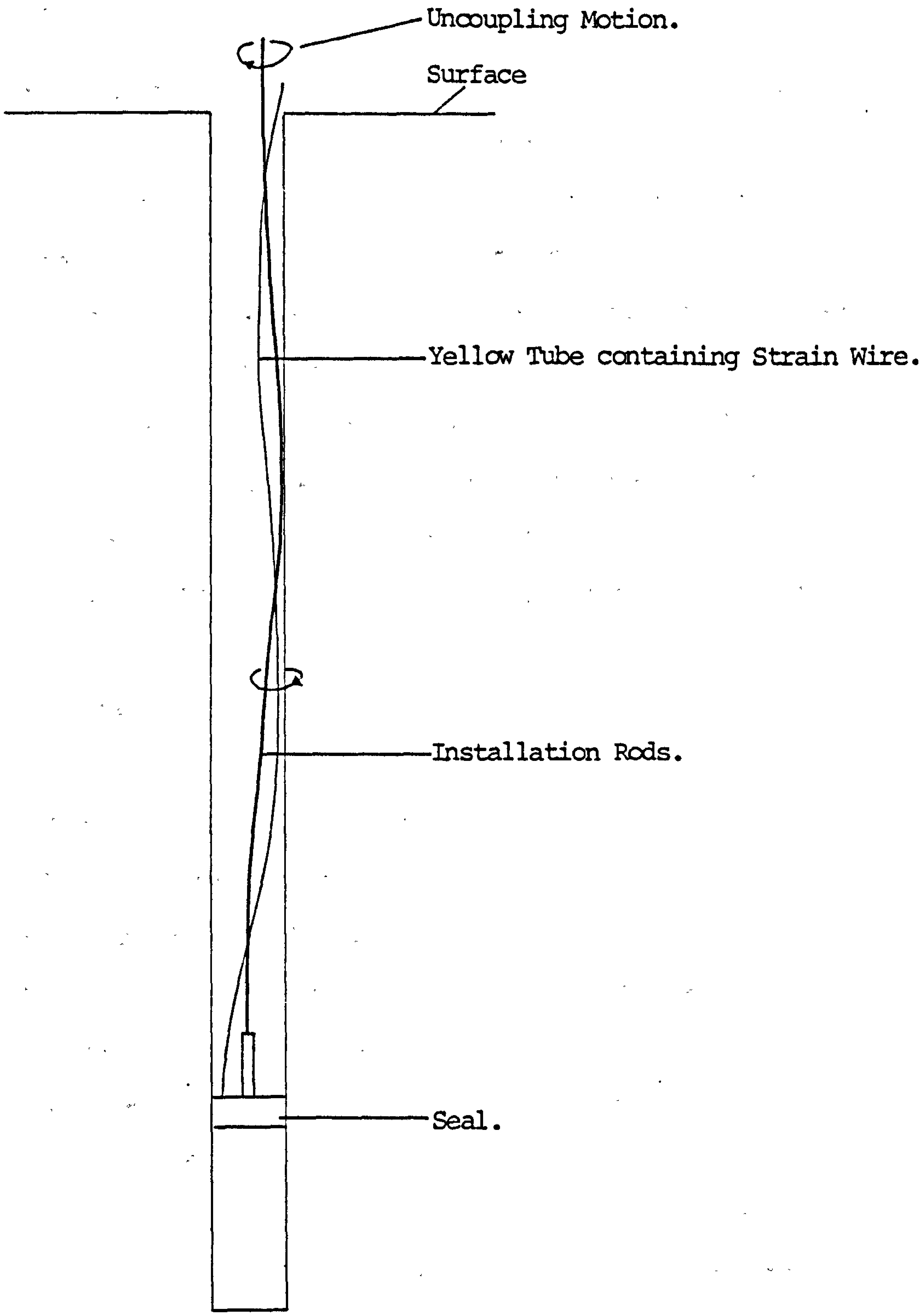


Figure 4.12 Exaggerated Nature of Installation Rods in Borehole

replacing these with magnet extensometer access tubing which had been left over from the previous set of installations. This tubing fitted over the top of the seal and thus could be pushed down into position and directly pulled off. The weight of these rods were considered adequate to install the seal although care must be taken so that the PVC joints are not broken during installation. The coupling would also require modification as problem could occur if the tubing became disconnected from the top of the seal. A bayonet style linkage would be required if the method were to be used again.

iii). <u>Damage to the Yellow Tubing.</u>

Both the 12 mm yellow tube which housed the strain wires and the 19 mm tubing used for pumping resin grout suffered from bending and kinking. Once a kink was inflicted it was then practically impossible to remove. Past experience showed this partly due to a reduction in the tube wall thickness by the manufacterers, Celtite Selfix Ltd, Alfreton, Derbys.

For the first installation the yellow tubing had been supplied in 30 m lengths and thus required the construction of joints to make up lengths of 40, 50, 60 metres etc. These joints became a major problem during installation owing to the fact that there was great difficulty in feeding the seals over them. On a few occasions the joints came apart as the seal was pushed over them thus losing the permeability testing facility on that particular pipe. This problem can only be rectified with the use of continuous extruded lengths of the yellow tube

PLATE 4.

PREASSEMBLY OF SEALS, TUBES AND WIRES ON SURFACE

PRIOR TO INSTALLATION, SITE B.

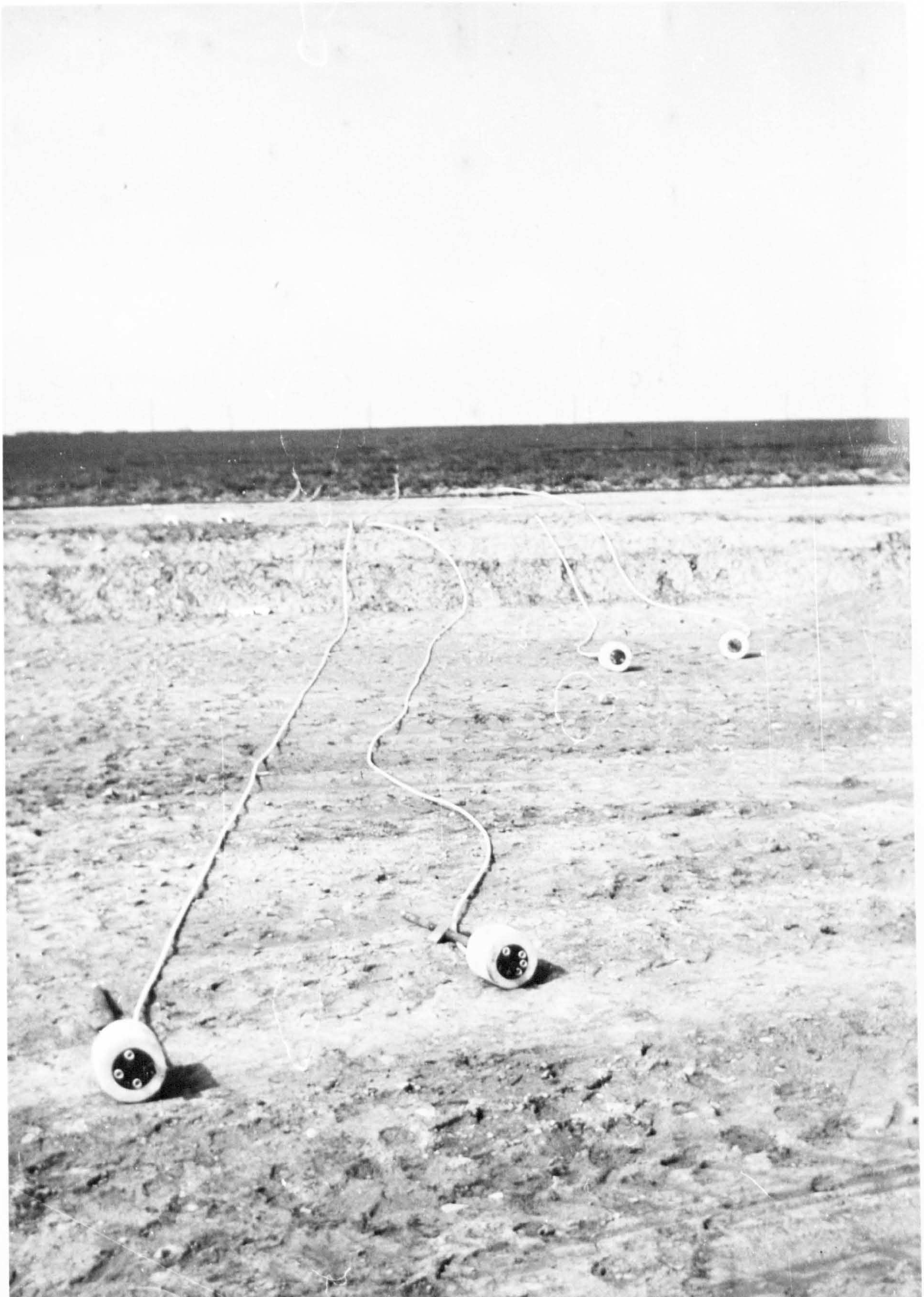


PLATE 5.

RESIN GROUT MIXING AND PUMPING OPERATIONS.

SITE B.

which require no joints.

4.8.4. Details of the first Multi-Wire Installation.

The depth of fill in the first hole was 71 metres and this corresponds to the depth of the datum wire. The second seal was emplaced at 42 metres but unfortunately owing to failure of the joints both the wire and the tubing were lost. Seals were then installed at 28, 19, 14, 11, 6, 3 and 1 metres. This gave a total of eight strain wires in the hole. The water level in the hole stood at 55 metres. It was considered best that seals were not placed in the saturated ground owing to problems in getting the grout to set.

4.8.5. Modifications for the second Multi-Wire Installation.

Following the installation of the first extensometer a period of five days were available for instrument modification, (3 days for drilling and a weekend). The following modifications were employed.

1). All yellow tubing used should be continuous, ie no joints.

2). The Instrument would be installed in an uncased borehole.

3). The instrument would be completely pre-fabricated on the surface and lowered into the hole using a large weight on the datum wire.

4). The seals would be redesigned and have individual grout pipes.

5). A nylon cord of shorter length than the yellow tubes would be placed between each seal. This would take the weight of the structure rather than the yellow tubing.

The structure of the prefabricated instrument is shown in figure 4.13. The redesign of the mechanical seals is illustrated in fig 4.14.

4.8.6. Installation of the Prefabricated Extensometer.

The aim of the installation was to feed one continuous length of instrument into an uncased borehole. This assumed that the hole conditions would be akin to those experienced on the first hole, ie no backfill caving. Unfortunately the drillers reports were unoptimistic with expected caving at and below 32 metres depth. Nevertheless the instrument had been prefabricated in part at the University and finally on site and thus a decision was taken to attempt an installation, and the casing was pulled out of the hole. The instrument was lowered into the hole and unfortunately, more or less as expected the instrument was stopped by caved ground at 32 metres. Seals were then installed in the previous manner at depths of 20, 15, 10 and 5 metres. The total hole depth was around 73 metres.

The final instrumentation characteristics and depths are presented in table 4.1.

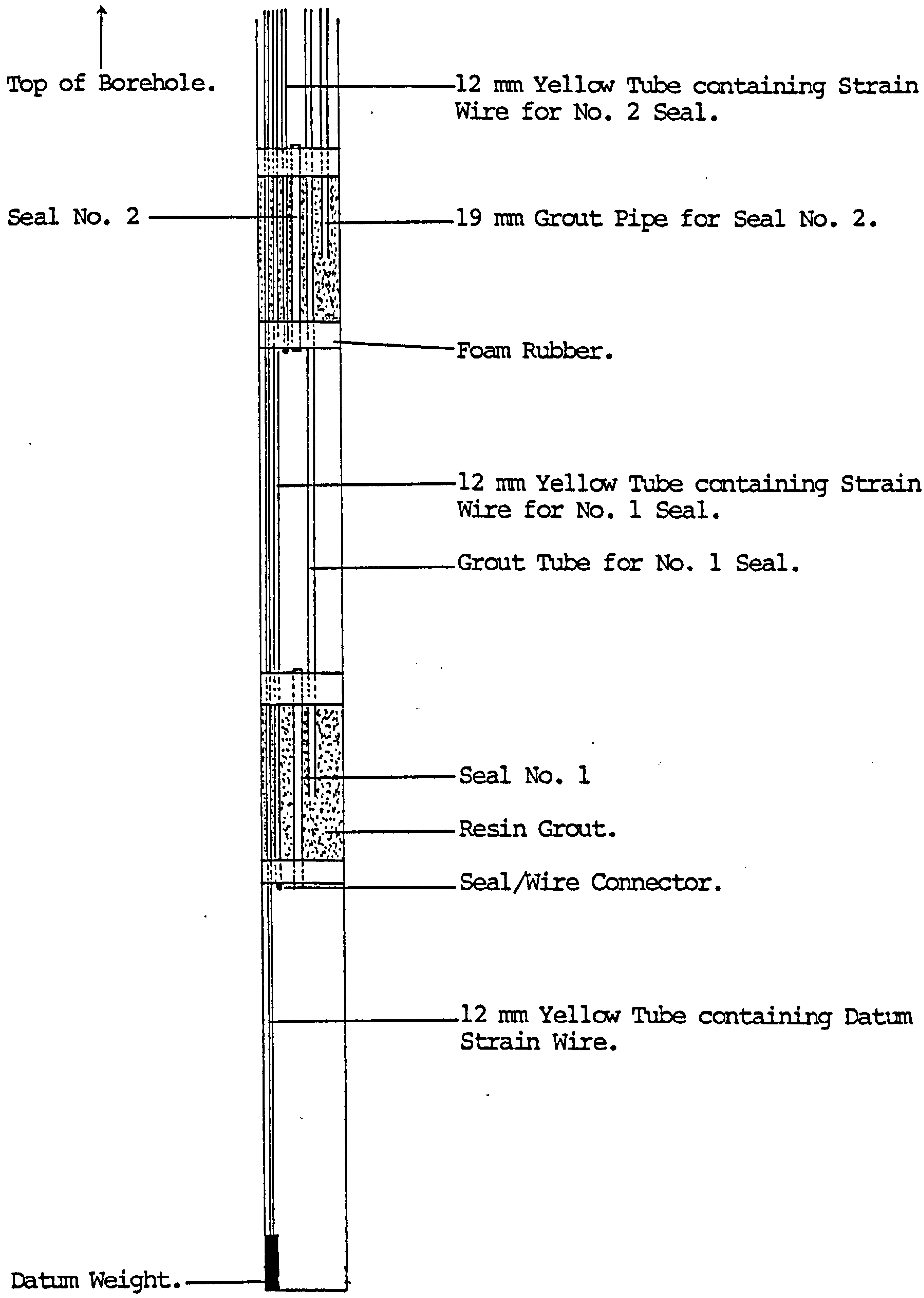


Figure 4.13 The Pre-Fabricated Extensometer Instrument.

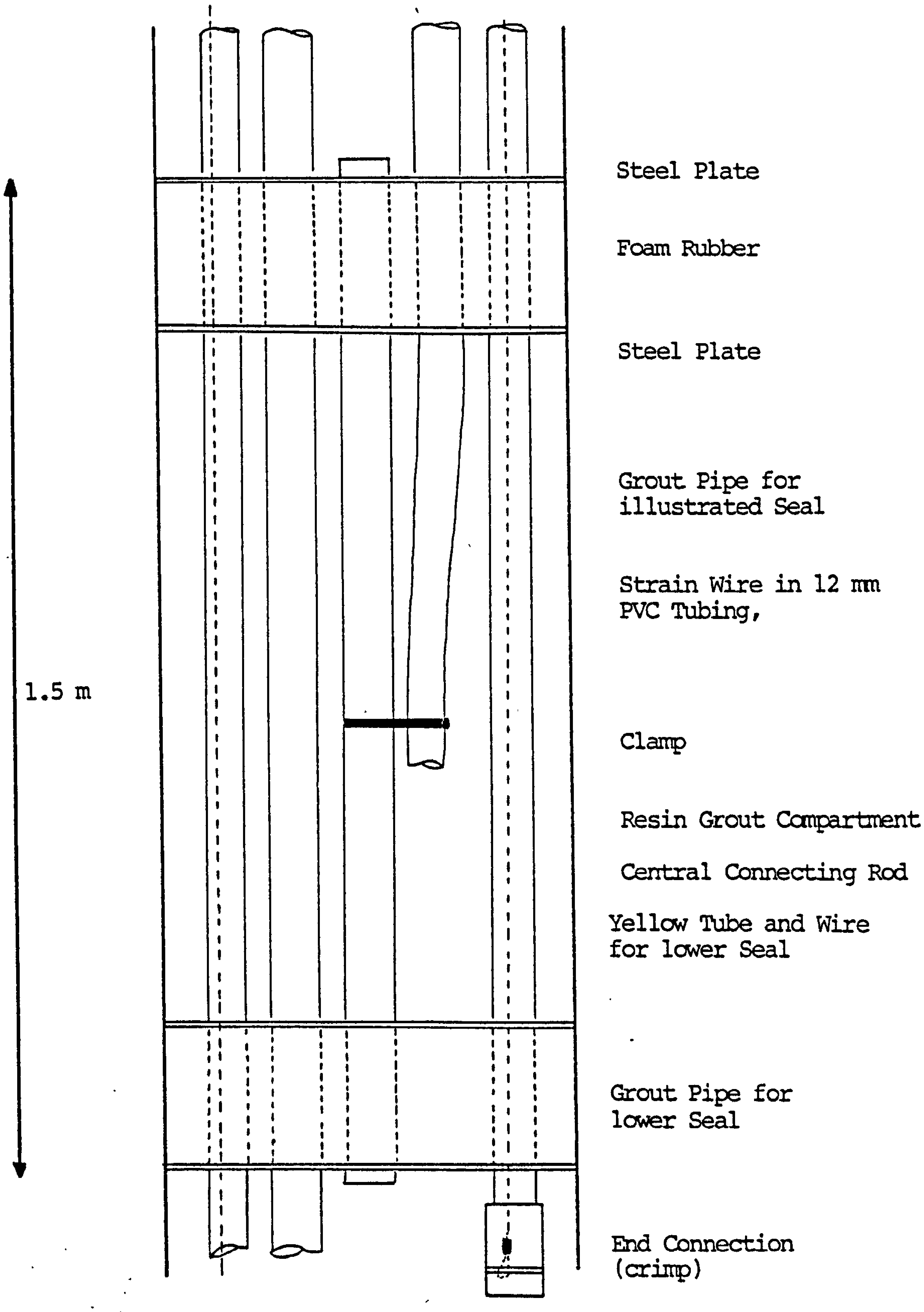


Figure 4.14 Re-design of Extensometer Seals.

PLATE 6.

TENSION WIRE EXTENSOMETER SEAL, SECOND INSTALLATION.

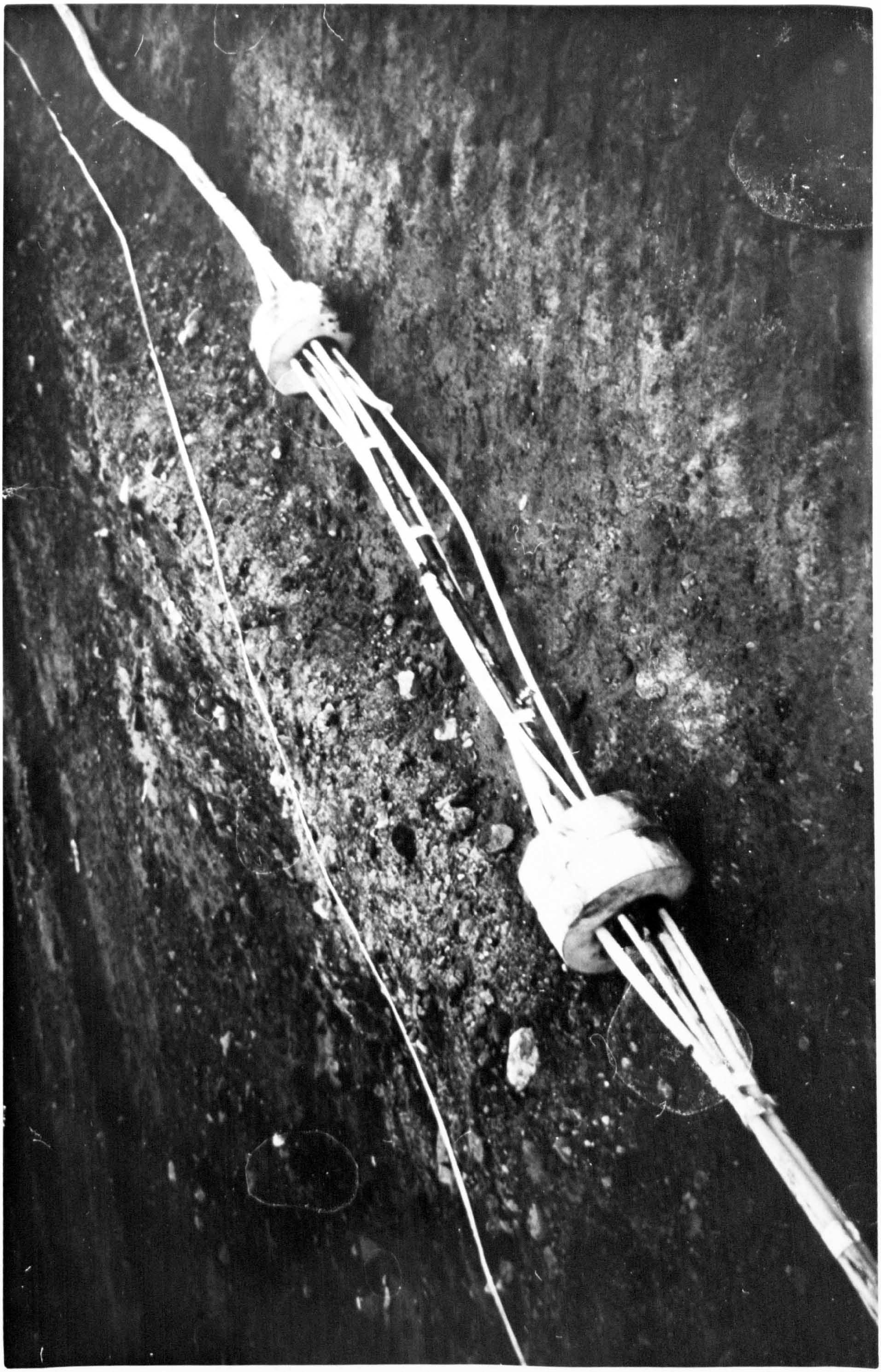


PLATE 7.

PREASSEMBLY OF TENSION-WIRE EXTENSOMETER.

SECOND INSTALLATION, SITE B.

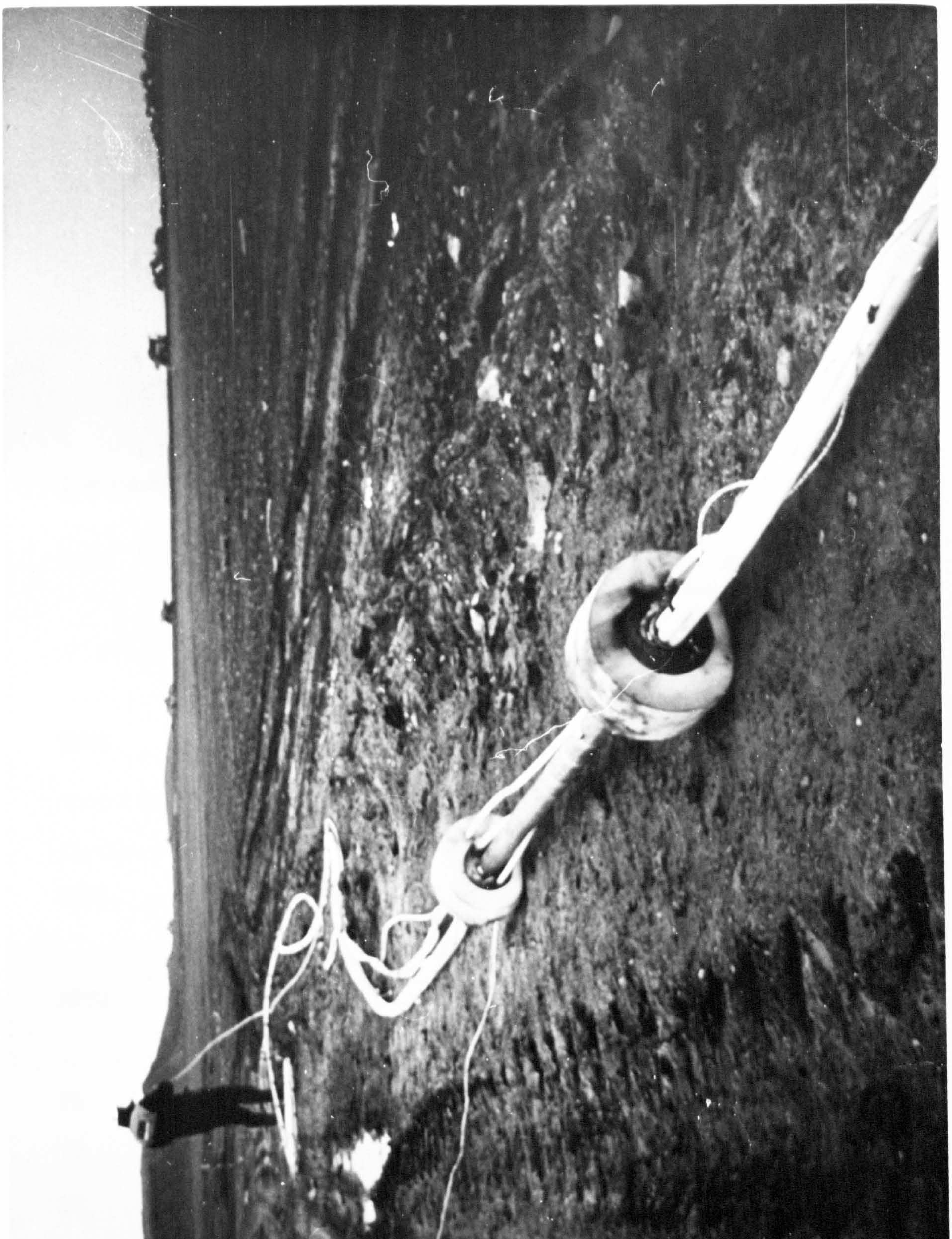


Table 4.1

Summary of Instrumentation; Site B.

Instrument	Depth (metres)	Characteristics
TWE1	71	Tension-Wire Extensometer with facilities for permeability testing. Seal and wires at 71 m, 38 m, 19 m, 14 m, 11 m, 6 m, 3 m and 1 m. Installed in Fill.
TWE2	73	Tension-Wire Extensometer with facilities for permeability testing. Seals and wires at 20 m, 15 m, 10 m and 5 m. Installed in Fill.
MPP1	71	5 piezometers in hole at 71 m, 51 m, 33 m, 21 m and 6 m. Installed in Fill.
MPP2	79	4 piezometers in hole at 79 m, 43 m, 31 m and 6 m. Installed in Fill.
P1	102	Standpipe piezometer in Solid.
P2	102	Standpipe piezometer in Solid.
P3	85	Standpipe piezometer in Solid.
P4	80	Standpipe piezometer in Solid.

4.9 APPRAISAL OF RESULTS.

4.9.1. Groundwater Recovery in the Solid Strata

The water levels recorded in the standpipe piezometers, P1, P2, P3 and P4, are presented in figure 4.15. The two piezometers on the Southern side of the excavation have shown very similar trends with water levels recovering by around 5 metres to 78 metres a.s.d. This level is particularly significant as it corresponds to the approximate position of the seam X old workings, directly linked to the deep mine shaft pump. A similar recovery has been recorded on the Northern instruments, P3 and P4, however the water levels themselves are much lower than in the South. In addition there is a far greater degree of drawdown between instruments P4 and P3 than there is between P2 and P1, the distance between each instrument sets being 25 metres. The water level in P3 stood in January 1986 at just over 68 m a.s.d with the level in P4 at 60 m a.s.d, a drawdown of 8 metres over 25 metres horizontal distance. In addition the water level in P3 is also 10 metres below the levels recorded in piezometers P1 and P2 in the south.

The conclusions which may be drawn are that whilst water recovery has appeared to have slowed considerablely over the monitoring period, (although water levels are increasing by 10-20 cm per month), recoveries in excess of 10 metres may still be expected in the North given that no external influences, (e.g. adjacent opencast mine sites), prevail.

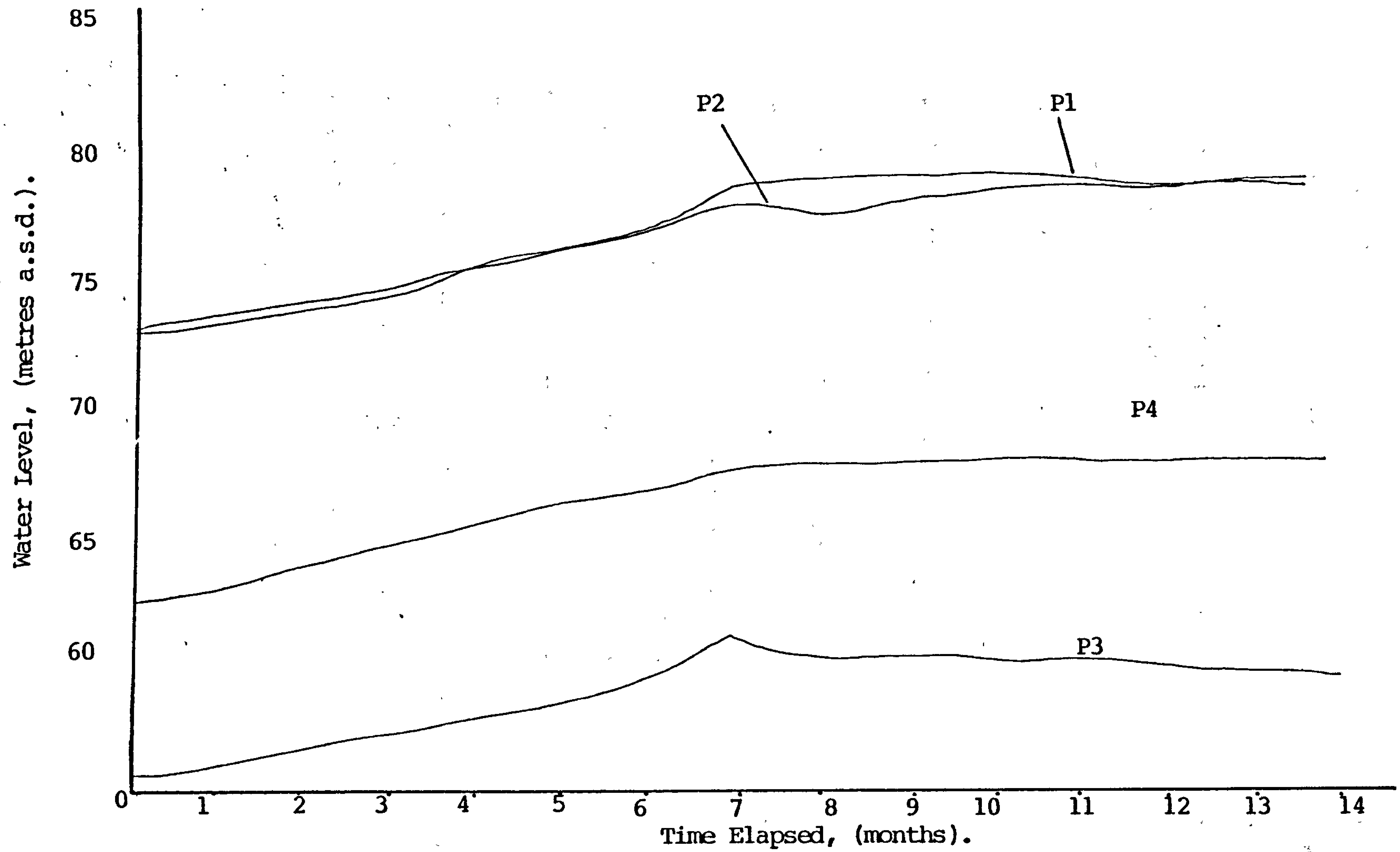


Figure 4.15. **Groundwater Recovery in Solid Strata, Site B.**

The rate of recovery is also of importance. In the last chapter a recovery of 24 metres had been recorded over 144 days in a small site in a wet area. On this site however the recovery in the solid strata has only being 5 metres over a period of a year. It is considered that the size of the site and thus the volumes of water required for recovery is the prime reason. In addition to this the old deep mine workings are acting as a drain for groundwater in contrast to those recharging the fill of the shallow mudstone site of Chapter 3.

4.9.2. Recovery in the Fill Material.

The results from the two multi-point piezometers, MPP1 and MPP2 installed in the backfill have given some indication of the characteristics of a recovering water table within such a rockfill mass. The results are presented in figure 4.16.

Water levels from January to July 1985 were indicated by only the lowest piezometers, i.e. those which were installed at the base of the backfill. Result indicated a recovery of 10 to 15 metres over this period to levels around 80 a.s.d in each borehole. From this point water levels began to be observed in two piezometer access tubes for both instruments. The results indicated differences in water pressures between the two point on both instruments most notably on instrument MPP2, (furthest east). In December 1985 the difference in water levels between the two tips registering water in MPP2 was 13 metres which had increased from differences of 2 metres from the months before, and decreasing to 6 metres the month

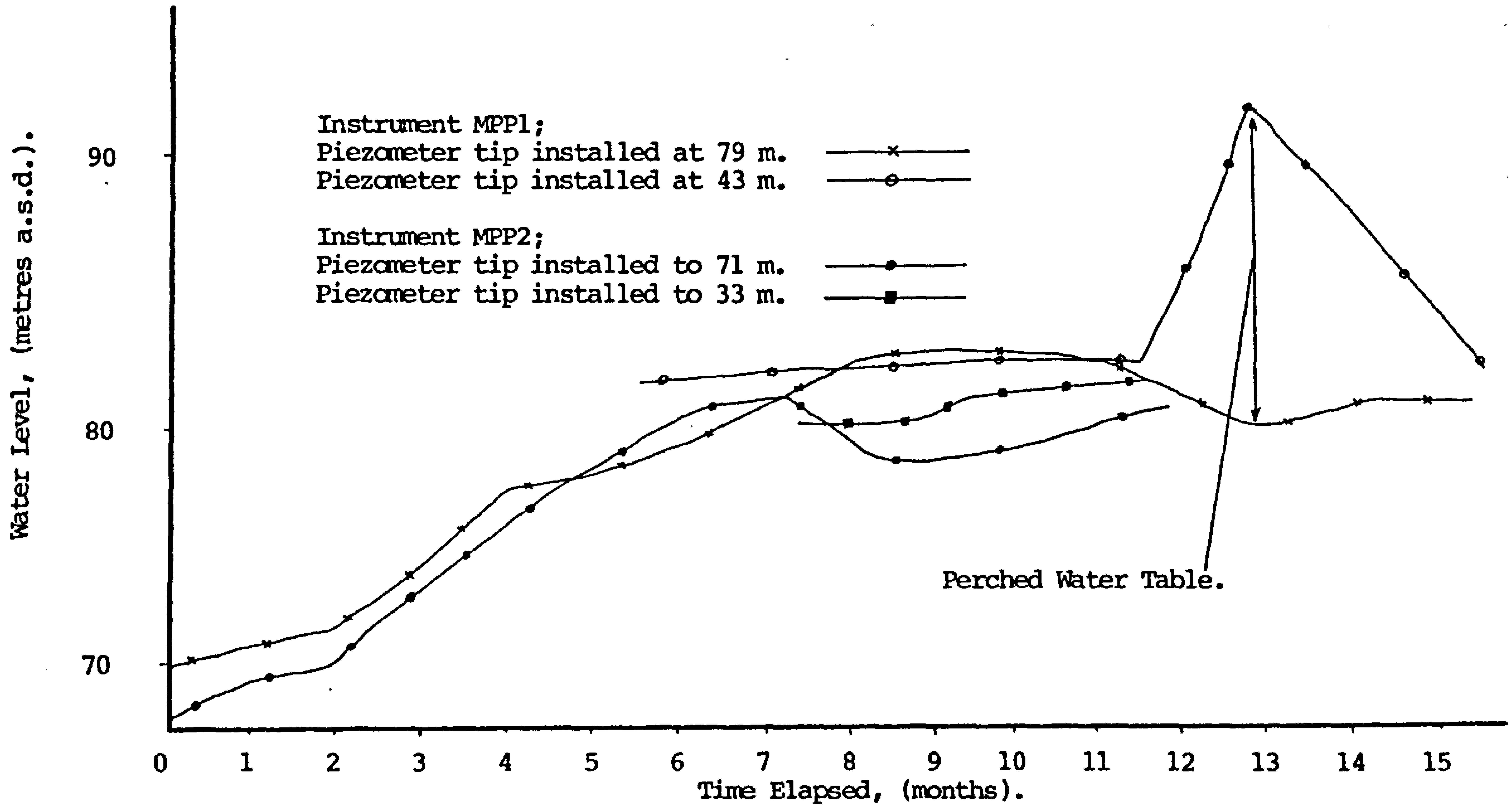


Figure 4.16. Groundwater Recovery within the Backfill, Site B.

after. These results illustrate the complex nature of groundwater within such a rockfill mass. It is possible for several perched water tables to occur with numerous flow paths through the broken rock material.

4.9.3. Tension Wire Extensometer Readings.

Both the tension wire extensometers have appeared to be work satisfactorily over the monitoring period, however owing to the fact that instrument TWE1, (fig 4.9), has many more wires and seals than TWE2, so the results for TWE1 have proved more meaningful. A Summary of the results for both extensometers are presented in tables 4.2 and 4.3, which give the overall movement of each wire as either an effective settlement or a shear movement. Also presented in table 4.2 are the net displacements which have occured between each pair of seals on borehole TWE1, i.e. in the compartments used for permeability testing. Shear movements are designated as positive values whilst settlement is designated as negative. Over this period the water table remained in the region between the datum and second seals. No saturation or collapse settlement due to the standing water level can be assumed to have occurred above the second seal. This does not take into account collapse settlements resulting from perched water tables. Heave movements are registered as shear displacements in this analysis.

Whilst interpretation of the actual results is complicated task with many shear and settlement occurences interacting

Table 4.2.

Summary of Tension-Wire Extensometer Readings.

Instrument TWE1.

Wire No.	Depth	Jul 1985	Aug	Sep	Oct	Nov	Dec	Jan 1986	Feb	Mar	Apr	May
		Overall Seal Displacements.										
1	71	0	0	+30	+30	+30	+40	+35	+40	+45	+40	Instrument buried
2	38	0	-5	+45	+45	+55	+65	+45	+45	+35	+40	
3	19	0	+15	-165	-170	-165	-145	-145	-145	-150	-150	
4	14	0	+25	+50	+45	+50	+30	+15	+20	+20	+20	
5	11	0	0	+10	+5	+10	+20	+20	+40	+120	+120	
6	6	0	-10	+10	+5	+10	+20	+5	+250	+250	+250	
7	3	0	+10	-145	-150	-145	-185	-195	-195	-185	-180	
8	1	0	+30	+70	+60	+70	+40	+30	+40	+45	+45	

Horizon.	Thickness (m)	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
		Net Displacements between Seals.									
1-2	33	+5	-15	-15	-25	-25	-10	-5	+10	0	
2-3	19	-20	+210	+215	+220	+210	+190	+190	+185	+190	
3-4	5	-10	-215	-215	-215	-175	-160	-165	-170	-170	
4-5	3	+25	+40	+40	+40	+10	-5	-20	-100	-100	
5-6	5	+10	0	0	0	0	+15	-210	-130	-130	
6-7	3	-20	+155	+155	+155	+205	+200	+445	+435	+430	
7-8	2	-20	-215	-210	-215	-225	-225	-235	-230	-225	
8-Surface.	1	+30	+70	+60	+70	+40	+30	+40	+45	+45	
Net Movement.		0	+30	+30	+30	+40	+35	+40	+45	0	

+ denotes shear movement, - denotes settlement.

Table 4.3.

Summary of Tension-Wire Extensometer Readings.

Instrument TWE2.

Wire No.	Depth	Overall Seal Displacements. Jul 1985	Aug	Sep	Oct	Nov	Dec	Jan 1986	Mar	Apr	May
1	32	0	0	0	+10	0	0	0	0	0	0
2	20	0	0	-5	-5	-10	-5	+5	-5	+10	+25
3	15	0	+5	+5	0	-20	-35	-40	-40	-40	+10
4	5	0	0	+10	+15	+10	+20	+20	+40	+40	+60

Horizon.	Thickness (m)	Net Displacements between Seals. Aug	Sep	Oct	Nov	Dec	Jan	Mar	Apr	May
1-2	12	0	+5	+15	+10	+5	-5	+5	-10	-25
2-3	5	-5	-10	-5	+10	+30	+45	+35	+50	-15
3-4	10	+5	-5	-15	-30	-55	-60	-80	-80	-50
4-Surface	5	0	+10	+15	+10	+20	+20	+40	+40	+60
Net Movement, (mm).		0	0	+10	0	0	0	0	0	-30

+ denotes shear movement, - denotes settlement.

together, the general trends from TWE1 show that shear or lateral movements are very significant. Shear zones can definitely be seen to exist and have a greater magnitude of displacement than settlement movements. It is unfortunate that these instruments cannot indicate the direction of lateral movement (as say an inclinometer can), although it is reasonable to suppose that movement is directed towards the final void area which was finally infilled by October 1985. It is these shearing movements which are judged responsible for the failure of the initial magnetic extensometer and also contributory to the problems of dipping the multi-point piezometers with a relatively large dip meter probes.

One of the most important results obtained from the observations on instrument TWE1 has been that the net overall movement of the fill surrounding the borehole has been one of shear, i.e. the magnitude of the shear movements have exceeded the degree of settlement recorded. In past studies it has always been the vertical movements which have been considered as the prime phenomenon critical to backfill stability. These results however, (as in cases of longwall coal mining subsidence in underground mines), have indicated that particularly in the surface fill layers, lateral displacements more likely to be of superior importance.

As an example as to the magnitude of lateral movements occurring within the fill, the results for March 1986, (table 4.2), indicate a vertical settlement of at least 400 mm in the region of seals 3 to 6, i.e. in the interval 6 to 19 m below the fill surface. (This estimate is based on the net displacements for each interval; 3-4 = -170 mm, 4-5 = -100 mm, 5-6 = -130 mm). The net displacement of horizon 6-7 has been determined as a 435 mm shear movement. However this horizon must also have settled by at least 400 mm on top of the fill horizons below it. Thus the minimum shear in this horizon 6-7 must be 400 + 435 mm, or 835 mm. The overall conclusion which can be made is that a lateral movement in addition to settlement has occured in the region of seals 6-7 of at least 835 mm. The region of seals 6-7 lies 3 to 6 metres below the restored fill surface.

Considering the horizons above this zone of shear, the interval between seals 7-8 has indicated a settlement of 230 mm which has occured in 2 metres of fill, lying 1 to 3 metres below the surface. This magnitude may well be caused by infiltration of water during pumping tests, and is discussed in section 4.9.4. The topmost metres of fill which has been most subject to the compactive load of passing plant has registered shear movements of between 30 and 70 mm. The magnitude of shear can be observed to be differential with depth. The construction of a structure with deep foundations in excess of say 3 metres say will thus be liable to severe damage if constructed on a fairly new fill surface. Of importance is to note that a large shearing movement of 245 mm occured in the region 6-7 during February 1986, 8 months after monitoring commenced and at least 24 months after the fill had been placed.

Of note are the low overall displacements in the region between seals 1-2 - the lower half of the borehole. This is the zone in which the groundwater recovery is occuring, and illustrates that saturation affects both lateral as well as vertical collapse.

The results from instrument TWE2, (table 4.3), show little relative movement has been recorded on all the wires, the lowest wire being installed at 32 metres, in a fill depth of 70 metres. This illustrates that all the movements whch are occuring in this borehole are in the lower parts of the fill, thus tying in with water table position. No significant shear movements have been observed in the upper fill region. During the drilling of this borehole the fill was found to be quite saturated, although the standing water table corresponded to the position of that in TWE1. It may be possible that during drilling the borehole intersected a perched water table, which subsequently was allowed to drain through the borehole. This would explain the instability of the drilled hole as well as the degree of consolidation measured to date.

The perched water table identified in this part of the fill during the period of January to March 1986 in the region between seals 2 and 3 has not appeared to have initiated any large collapse movements. The net fill movement between these two seals has varied from 20 mm settlement to 215 mm shear and are akin to the shear movements registered in the interval between seals 6 and 7. The presence of fluctuating water at this horizon must have had an affect on fill stability.

4.9.4. Permeability Test Results.

The objectives of the permeability tests in the borehole compartments are to monitor changes in permeability as related to compaction and also the changes in permeability as a function of fill depth. The testing apparatus has already been described in Chapter 2 along with an example of a permeability calculation.

The values of permeability are generally in the range of 10^{-5} m/s in the region of the near surface fill, (Table 4.4). It was generally found that it was impossible to fill the compartments which were lowest in the borehole. This implies that the permeabilities of these compartments are so great that the borehole has no capacity for holding water. This observation fits in well with the generalisations made in chapter 2 implying that the base of a dragline or dump truck fill would consist of larger rock masses with smaller rock sizes occuring nearer surface - a result of gravitational separation on tipping.

Of importance is that on the compartments which can be measured there is a trend of decreasing permeability and increasing compaction with time. Permeability of the nearest surface layers have been found to be exceptionally low, ~ 10^{-6} m/s, presumably owing to site plant compaction effects. An importance of this is the fact that surface runoff will be much greater and infiltration into the fill less. A danger exists that as for the mudstone truck shovel site, insufficient surface drainage may result. The rooting of

	Coefficient of Permeability, m/s.	
	December 1985	April 1986.
Instrument TWE1.		
Horizon.		
Surface- 1 m	2.5×10^{-6}	3×10^{-4}
1 - 6 m	7×10^{-6}	5.1×10^{-6}
6 - 11 m	1.4×10^{-5}	6.7×10^{-6}
11 - 14 m	1.8×10^{-6}	3.2×10^{-5}

Below this level steady-state
conditions could not be achieved.

Instrument TWE2.		
Horizon.		
Surface- 5 m	5.6×10^{-6}	5.5×10^{-5}
5 m - 10 m	4.2×10^{-5}	2.3×10^{-5}

Below this level steady-state
conditions could not be achieved.

Table 4.4. Coefficients of Permeability obtained from Constant Head Tests, Site B.

the top and sub soils will for a period of time ensure that the surface does not flood, but with groundwater action the clayey nature of these materials may again form a seal which results in ponding. These observations stress the importance of good surface gradients and the introduction of drainage channels to maintain adequately drained land. The importance of seeding in the maintenance of well draining soils should also be appreciated.

In the conduction of a pumping test, the time required to fill some of the compartments in the boreholes were in excess of several hours, by water supplied from the domestic mains supply, (80 p.s.i.). This water will obviously have had an effect on the stability of the fill through which it passes. In the conduction of a test wire measurements were taken before and after pumping, in order to observe if any immediate collapse settlement had occurred - and none was measured. It is however possible that collapse settlements occured shortly after pumping ceased and after the second reading. This observation may explain in particular the collapse of 230 mm over 2 metres thickness of fill material in the upper section of the borehole. Surface infiltration may be to a certain extent ruled out owing the the impermeable nature of the surface soil layer. Over the period of January to May 1986, the surface of the site was frequently flooded with surface water.

4.10 CONCLUSIONS.

The following conclusions may be made from an analysis of the results from this chapter.

a). On large opencast sites the rate of groundwater recovery may be very slow. Recovery was observed to be more rapid in the fill than in the solid, presumabley owing to differences in permeabilities between the two formations. The rate of recovery in the solid strata surrounding the excavation was approximately 5 metres per year. This contrasts with the rapid recovery observed on site A, (Chapter 3), where old mine workings were discharging water into a shallow fill.

The effect of pumping in the nearby colliery shaft has been observed to have had an effect on the rate and degree of recovery. The present water levels are standing around the level of the abandoned deep mine workings of seam X. Despite the application of clay seals to these horizons, it would appear that water are draining from the site to the shaft pump. Groundwater levels are expected to rise further in the fill owing to drawdown effects occuring in the backfill towards the incrop of the abandoned mine workings.

It is expected that the pumping in the colliery shaft will continue for at least a further 10 years, and consequently dictate to a large degree the nature of water levels in the local area. When pumping ceases then once again recovery will initiate and water levels rise. This situation will be similar to that presented in Chapter 2, where a similar recovery was initiated by the termination of pumping by an underground mine. Severe structural damage was inflicted upon a housing estate which had been constructed on the fill.

b). Perched or irregular water tables have been shown to exist in backfill materials. There need not necessarily be only one free water surface in the backfill. Perched water was indicated in both of the multi-point piezometer instruments, and may well explain the instability of the borehole which was drilled for instrument TWE2. The lack of movement in the upper layers of the fill may well be due to the fact that a perched water table had pre-saturated the area prior to monitoring. This perched water table will have been drained by the drilling of the borehole in the fill. In general the presence of a perched water table did not result in a collapse settlement, but shear displacements did tend to be of a significant magnitude in the areas of perched water.

c). Backfill lateral displacements have been found to exceed the magnitude of the vertical settlements. These shear movements are considered responsible for the damage inflicted to the original magnetic extensometer as well as being contributory to the loss of a probe in one of the piezometers installed in instrument MMP1.

Shear movements in excess of 800 mm have been recorded in the near surface layers of the fill, and in addition the topmost metre of fill has exhibited shear movements of between 30 and 70 mm. Shear has been shown to be differential in magnitude in the near surface layers and consequently a hazard to the construction of structural foundations. These movements will obviously stabilise after a period of time. A continued monitoring programme would be instrumental in determining a suitable time lapse. Owing to the slow recovery of the groundwater table it has been so far impossible to correlate settlement to recovery in the lower reaches of the fill. The lower half of the fill does however show a small net shear movement, which may imply that settlement and shear in the region of the water table are of equal magnitude.

d). Permeabilities have been measured throughout the vertical section of the borehole and have shown that the lower layers of fill are very much more permeable than those nearer surface. On the lower compartments in the borehole it was found that it was not possible conduct the tests as they were so permeable that a steady state water pressure could not be established, (at least within a reasonable time period). The upper sections of fill averaged permeabilities of 10^{-5} m/s, equivalent to intact coal measures strata encountered in the region. The uppermost metre of fill was found to have a permeability of around 10^{-6} m/s, and generally were very impermeable. The surface area of the site was frequently flooded in the period of December to May 1986, illustrating the lack of surface infiltration which was occuring into the fill through the surface layers. Surface water was eventually removed by the installation of a pump, enabling the surface of the mine to dry out for the remainder of the restoration programme, (May to October 1986), the relayering of soils. It is considered that the pumping tests themselves induced some degree of collapse settlement, notably a settlement of 230 mm in a 2 metre thickness of spoil material which lay just under the impermeable surface fill layer.

CHAPTER 5

FILL DEFORMATION INVESTIGATIONS PRIOR TO ROAD CONSTRUCTION UPON A VARIABLE THICKNESS BACKFILLED SITE.

CHAPTER 5. FILL DEFORMATION INVESTIGATIONS PRIOR TO ROAD CONSTRUCTION UPON A VARIABLE THICKNESS BACKFILLED SITE

5.1 INTRODUCTION.

This Chapter presents an investigation into the stability of a variable thickness opencast mine backfill destined for surface development. A minor road is to be constructed over the fill which varies from 30 to 70 metres in the area of instrumentation. This site is designated as Site C for the purposes of this thesis.

The site forms an extension to the south of the original surface mine but is separated from it by a minor road. The original site being worked in three phases. The relationship between the extension and original site is shown in figure 5.1.

The extension site commenced working in March 1977 and was totally backfilled by July 1985. The site produced 5.2 million tonnes of coal involving the removal of 18.7 million tonnes of overburden by conventional truck and shovel methods. The deepest point of excavation was around 70 metres.

5.2 PRE-MINING SITE GEOLOGY.

The coal seams which numbered 17 belonged to the Passage age group. The average thickness of coal over the site was 29.53 metres.

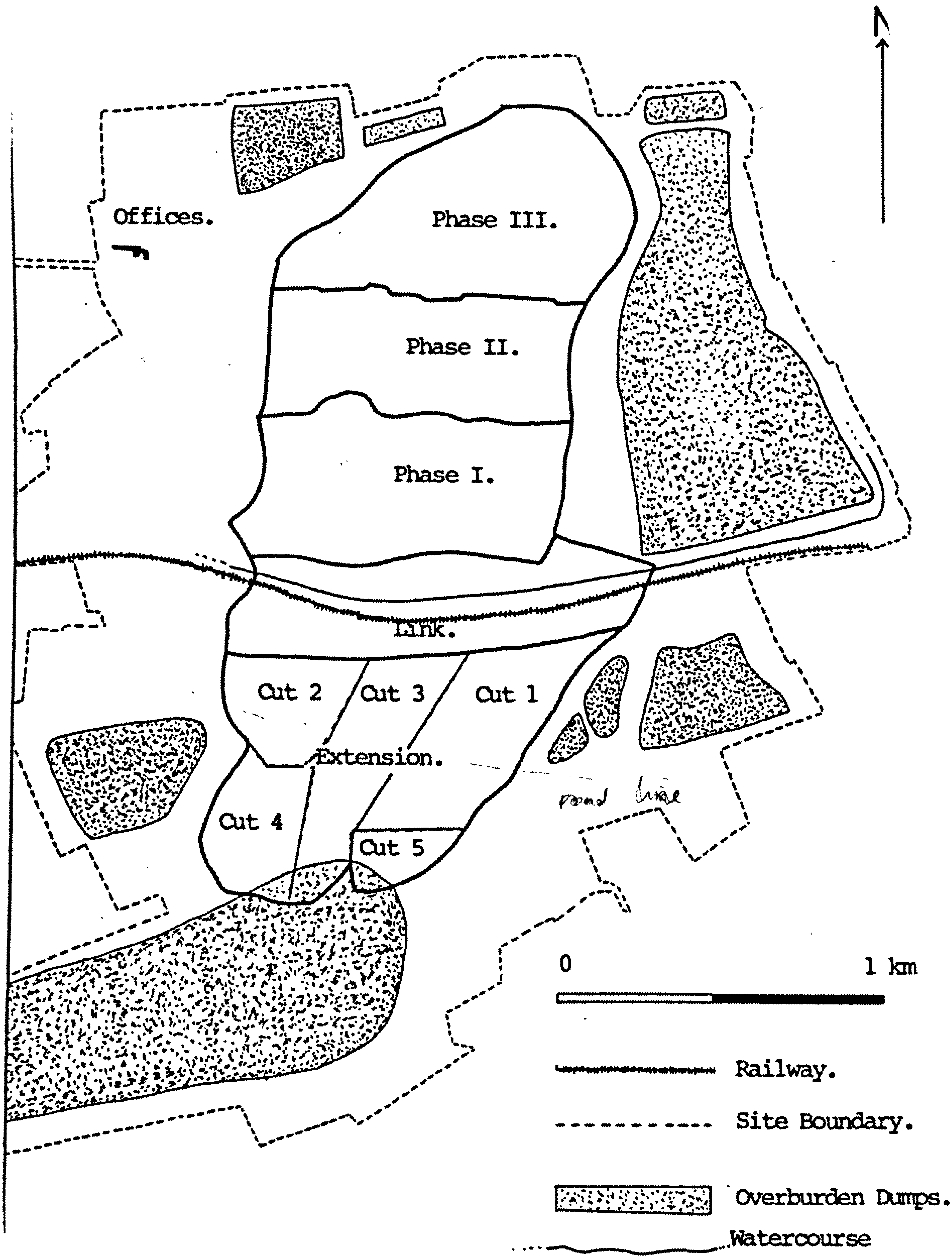


Figure 5.1 Layout of Original and Extension Sites, Site C.

The superficial deposits over the site consisted generally of boulder clay with large boulders of igneous material being common. Drift thicknesses varied from 0.60 m to 9.40 m, (including made up ground), and averaged 5.97 m in the west whilst in the east thicknesses varied from 0.65 to 8.90 m, averaging 3.69 m.

The strata rocks are a range of clays, seatearths, mudstones, siltstones and occasionally sandstones, showing a complete graduation from mudstones through siltstones to sandstones. Local concentrations of ironstone nodules occur in the excavated strata giving rise to acidic and ferruginous drainages. (Chapters 7 and 8).

The structure of the site is composed of three distinct synclinal basins with their axis trending in a north east-south west direction. The two eastern most basins were the deepest being excavated to around 60-70 metres. Fill thickness can vary from 70 to 30 to 60 metres over a horizontal distance of 100 metres.

5.3 GROUNDWATER.

Prior to working the site, piezometer instruments in the eastern area of the take indicated a groundwater level of 10 metres below the surface. During the working of the site few water problems were encountered due to the fact that the two westernmost synclinal basis drained directly into the large Phase III excavation to the North, (figure 5.1), which is not backfilled, (1986). The excavation in this region of the mine had approached 250 metres. Little water was encountered in the easternmost synclinal basin which was first to be backfilled.

It was expected that the final levels of water over the site could in certain areas recover to surface and possibly even result in flooding over parts of the restored surface. The time of recovery together with the degree however will ultimately be decided by the future use of the Phase III final void. This vast open hole, (the future of which is uncertain, but possibly for domestic refuse disposal), will obviously dictate a great deal of the final drainage patterns around the site.

5.4 INSTRUMENTATION SCHEME FOR BACKFILL SETTLEMENT MONITORING

5.4.1 The Diversion of a Minor Road.

In order to work the extension site the removal of a minor road was necessary, and a condition of the consent to work from the Local Authority was that this road should be replaced on the termination of mining. The proposed layout of the road over the fill is illustrated in figure 5.2, and in section X - X′ in figure 5.3 illustrating the variation in fill thicknesses that the road must ultimately traverse.

Figure 5.2 Layout of Road over Extension Fill Surface.

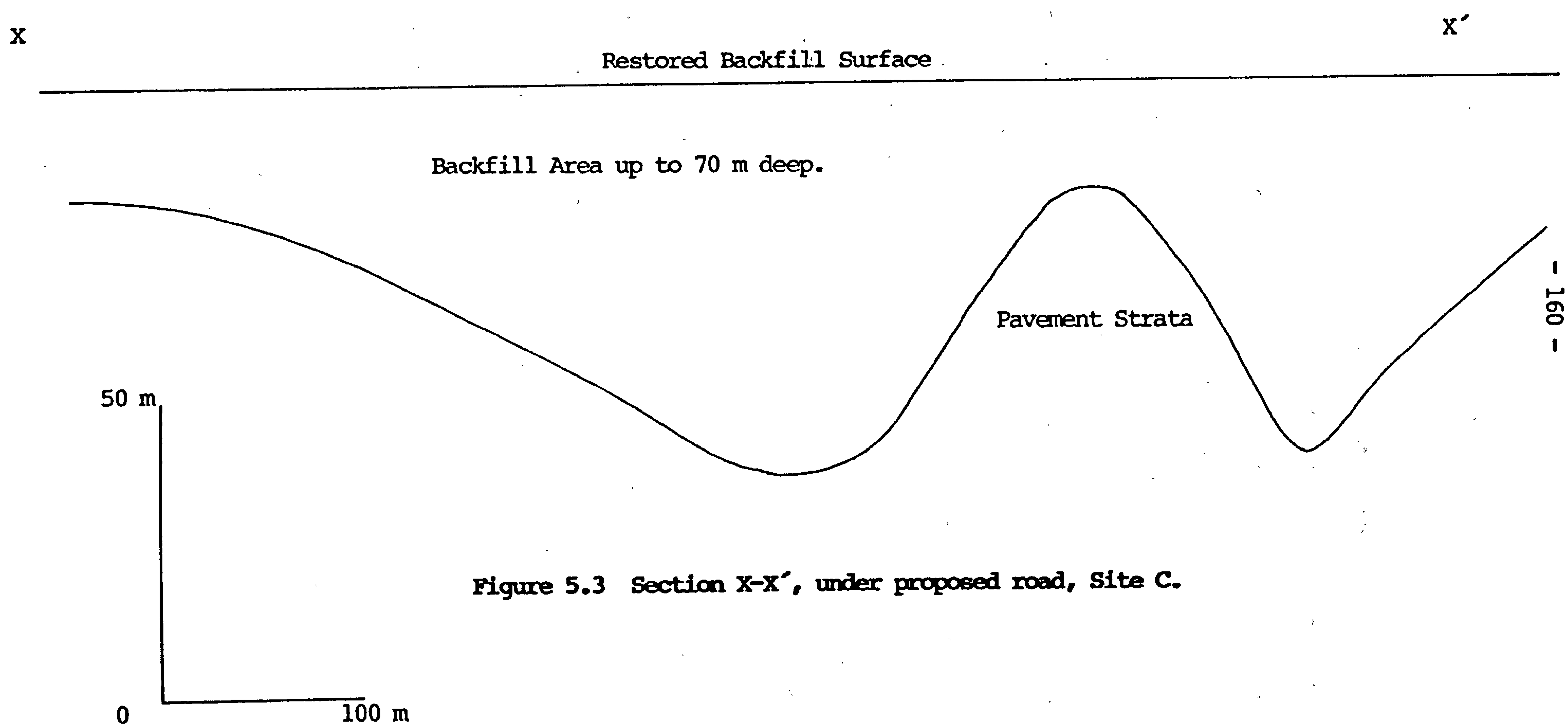


Figure 5.3 Section X-X´, under proposed road, Site C.

5.4.2 The Construction of the Minor Road.

The minor road is to be constructed over backfill of up to 70 metres depth which will be uncompacted. The standard specification regarding the design of this road is that the upper 15.5 metres of the fill is treated as shown in fig 5.4. Each layer must consist of reasonably graded rock with no surface voids. The layers are levelled by a bulldozer not less than 14 tonnes in weight and must undergo 8 passes of a single axle vibrating roller of not less than 8 tonnes in weight, 2 metres in width and with an operating frequency of not less than 2000 cycles/minute. Scrapers and other moving plant are not accepted as compactive machinery. There is however doubt to the effectiveness of this method, particularly when applied to variable thickness backfills. The specification for this site was neglected owing to the instrumentation and monitoring programme described in this Chapter. If damage to the road were to occur and was found to be directly linked to the fill movement then compensation would be paid.

5.4.3 Proposed Monitoring Scheme.

The proposed scheme involves installing four magnetic extensometers/ piezometers, in the positions shown in figures 5.5 and 5.6. The purpose of this part of the research, as in the two previous Chapters is to monitor the settlement of the backfill mass in relation to the recovery of the groundwater. The additional value of this particular scheme is that results

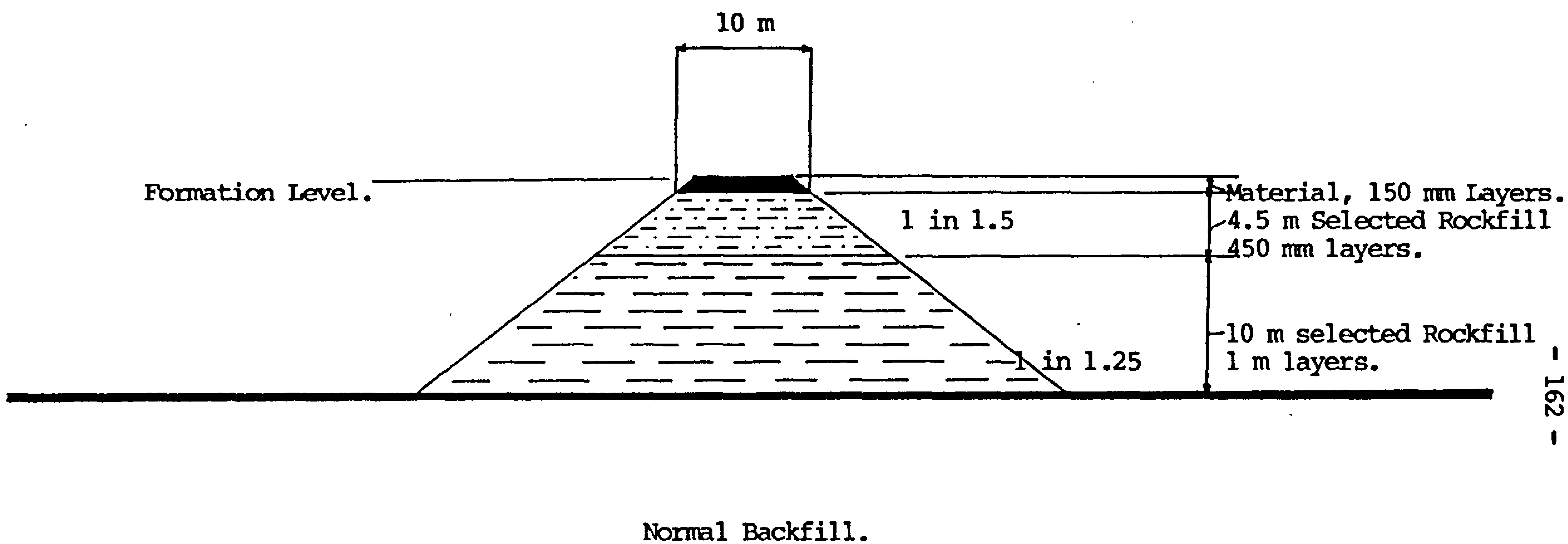


Figure 5.4 Standard Compaction Specification for Road Construction on Backfill

---------Restored Surface Contour
E1 - Position of Magnetic Extensometer

Figure 5.5 Instrumentation Plan, Site C.

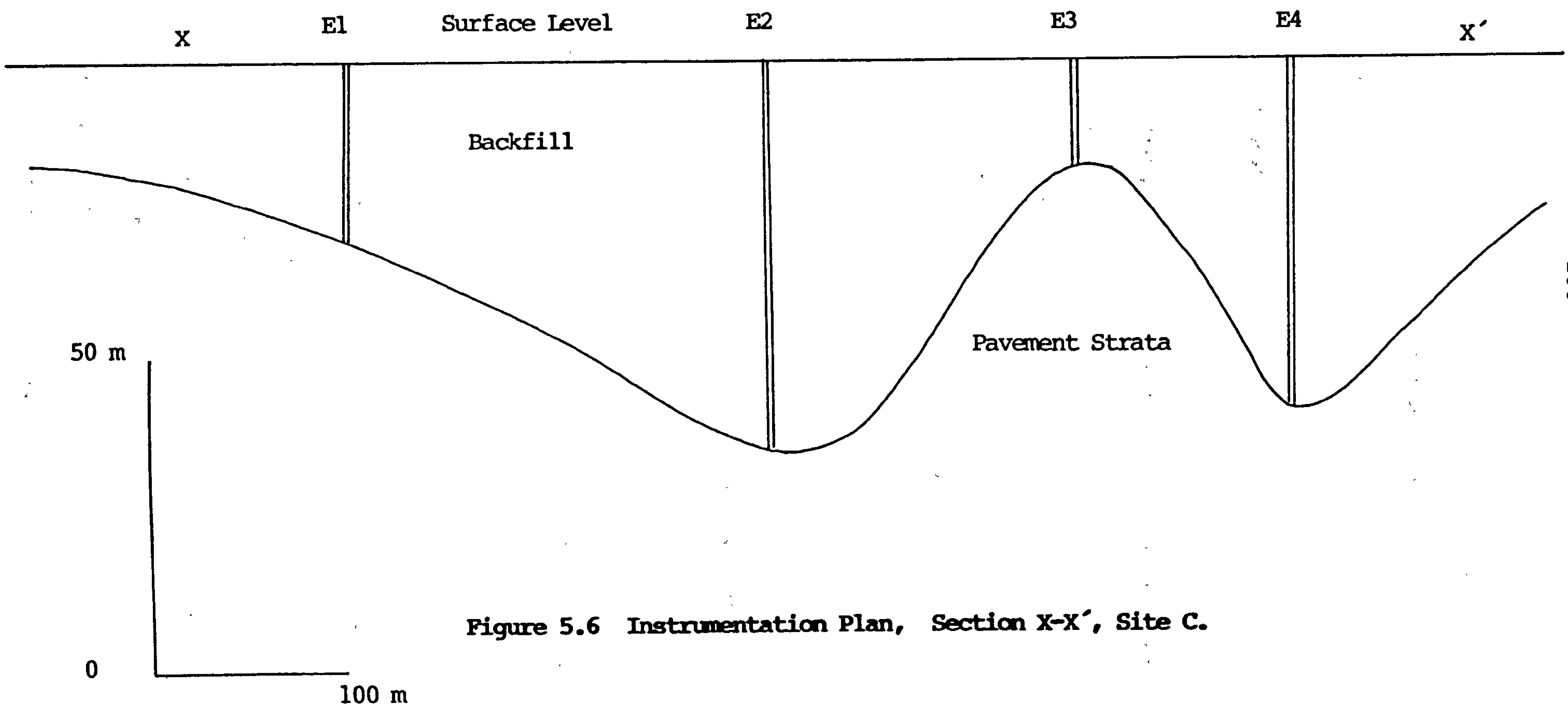


Figure 5.6 Instrumentation Plan, Section X-X´, Site C.

can be used to prove whether any break-up in the road's structure is due to the settlement of the uncompacted backfill or merely to the design of the road.

5.4.4 Instrument Installation

Four combined magnetic extensometers/ piezometers were installed in the positions shown in figs 5.5 and 5.6 between the 27 May and the 15 June 1985, to depths of 70, 60, 45 and 35 metres respectively. Installation methods were effectively similar to those conducted on Site A, with holes been drilled and cased to 149 mm, (SX size casing). Magnetic targets were separated from each other on the vertical access tubing by flexible sleeving and the magnets were fired off after the withdrawal of the casing, by pneumatic cutters. The hole was then backfilled with dry filter sand.

5.4.5 Problems encountered during Drilling and Installation.

a). Drilling.

Considering the depths drilled together with the installed casing size and type of material it was inevitable that problems would be encountered during both the drilling and casing activities. On the first, (45 m) installation a fault on the rig caused the casing to be dropped back down the hole after the pulling of only a few lengths. This casing impacted with the lower end of the instrument causing the access tubing to break at 38 metres below the surface. The drop also caused several magnets to fire off within the casing with the result that these magnets together with the flexible sleeving between then were pulled out of the hole with the casing. Fortunately it was possible to relace these magnets in the hole by pushing then down with lengths of flexible sleeving from the surface. This method utilised a length of rope attached to a length of scaffolding tubing to lower the magnets down the hole into position where they were fired off the the usual manner.

Problems were also encountered when during the drilling, a boulder in the fill was hit. On one particular occasion, the second hole, (70 m), a 3 metre boulder was encountered at 51 m depth. A total time of 4 days was lost actually drilling and casing through this boulder. (the casing diameter being larger than the bit diameter). On successfully casing off this rock it was found that beneath the boulder the fill was very weak, collapsing instantly the moment that the rods were pulled up to enable casing to continue. Thus drilling and casing operations were slowed down considerably.

The nature of the strata all over the site is such that spontaneous combustion within the backfill is a very real threat. A number of boreholes over the sites have in the past been abandoned owing to heatings at depth. Several piezometers on the Phase III part of the site could be seen to be expelling both steam and smoke as heatings have occured some time after the installation. When drilling care must be taken to use a minimum of air flushing as possible in these conditions. Foam flushing is usually the preferred treatment in unconsolidated backfill to attempt to stabilize the loose argillaceous materials, (ie prevent caving within the borehole).

b). Installation.

The instruments can be conveniently installed in 6 metre lengths whilst the rig is standing over the hole providing support, (each individual length of access tubing measures 3 metres). Nine metre lengths have been successfully handled however these are quite unwieldy and owing to the likliehood of joints on the access tubing breaking are not recommended as standard procedure.

The most important part of the installation is maintaining control over the instrument as it is lowered into the hole, particularly when installing at depth. The use of a strong rope attached to the datum magnet at the base of the instrument is essential to keeping both control as well as the weight of the instrument off the access tube joints. In addition a rope can be attached to the length of access tubing being lowered into the hole thus providing additional support to the access tubing at the surface. The presence of water in some boreholes presented a completely reverse problem, the floating of the instrument in the hole. This resulted in a slower installation process, as the rate of instrument installation was equal to the rate at which the water percolated through the tip and flexible tubing thus sinking the instrument. On the final 35 metre installation it was necessary to pour water down the central access tubing to accelerate the installation of the instrument.

The instrument design could undoubtably be improved in many ways. Of particular note were the following; the weakness of the access tube joints, the difficulty in attaching the magnets to the flexible sleeving when installing over the hole, and the problems encountered in attempting to control both the access tubing and the flexible tubing at depth. General opinion was such that it was considered possible that the magnets could be fired off accidently within the casing no matter how much care had been taken in preparation. The metallic parts of the instruments had been made from stainless steel to prevent corrosion from contact with the acidic environment of the water within the fill.

Of particular use would have been connectors which coupled flexible sleeving together rather than having to attach flexible sleeving to the magnets whilst standing over the hole. The importance of this being to reduce installation and thus rig standing times.

A common problem with all such instrumentation on active opencast mine sites is instrument protection from moving plant such as dump trucks, scrapers etc. All four of these extensometers are to be fenced off and covered with man hole covers to offer maximum protection possible.

Details of the instruments are given in table 5.1.

Table 5.1

Initial Magnet Positions and Water Levels, Site C.

Magnet No.	**Instrument**			
	E1	**E2**	**E3**	**E4**
	(Depth below top of Standpipe, metres)			
Datum	37.569*	70.829	32.478	59.792
SP1	31.670	62.197	24.275	48.694
SP2	16.389	51.718	18.572	38.407
SP3	11.346	42.204	13.462	28.250
SP4	6.593	31.860	7.136	17.968
SP5	1.338	20.599	0.782	6.662
SP6	-	15.031	-	2.479
SP7	-	8.633	-	-
SP8	-	1.242	-	-
Water Level	19.28	20.08	-	20.07

* Access Tube broken at this level

PLATE 8.

INSTALLATION OF MAGNETIC EXTENSOMETER, SITE C.

Six metre lengths of instrument are prefabricated prior to installation. Pneumatic cutters can be seen in the foreground. Drilling operations in process are using foam flushing to help stabilise the borehole.

5.5 EXTENSOMETER COMMENTS.

5.5.1 Extensometer E1.

Extensometer E1 was installed to round 48 m with rock head lying at 45.6 metres below the restored surface. Problems arose on this instrument occured when following installation the casing was being removed. The casing was actually dropped back down the hole and impacted on top of the lower end of the instrument causing the access tubing to fracture at 38 m, 4 metres above the rockhead. The resulting impact also caused three of the magnets within the casing to be fired off at to be dragged out of the hole. These magnets had to be re-located by installing them from the surface.

5.5.2 Extensometer E2.

Extensometer E2 when first dipped appeared to be blocked at 51 m, a depth corresponding to where a large boulder had been encountered during the drilling. Initial worries were that the access tubing as in E1 had fractured. However it was found that the access tubing had not in fact fractured when one week later the probe was successfully lowered to the datum magnet at 70.9 metres. The water in this hole was found to be warm and this indicates a heating within the fill.

5.5.3 Extensometer E3.

Extensometer E3 was successfully intalled in 32.5 metres of backfill. Rockhead had been anticipated at 30 m but the drillers felt that they had not reached this level. The hole was initially undipped as water was required to be poured doen the access tube to sink the instrument.

5.5.4 Extensometer E4.

Extensometer E4 was successfully installed to 60 m with no problems.

5.6 ANALYSIS OF RESULTS.

5.6.1 Groundwater Recovery.

The groundwater table had already recovered to 20 metres below the restored fill surface by the time that the instrumentation had been installed. Consequently a great degree of collapse settlement has been missed owing to rapid recovery. The fill had actually been in position for 6 months proir to instrumentation. Over the period of one year since the commencement of monitoring the water rose by an average of a further 5 metres, with most of this recovery occuring in the first six months. The water recovery appears have ceased within one year of the monitoring programme. Samples of the waters in the boreholes have been taken and their chemistries are presented in Chapter 8.

5.6.2 Settlement Results.

Over the period of a years monitoring some suprising results have been obtained. Initially it was thought that Extensometers E2 and E4 would have larger settlements owing to the deeper fill. This has however been shown to be untrue. Above all, the most suprising observation, (although from the point of view of road construction ideal), is the lack of vertical settlement recorded on all the instruments, particularly those in deeper fill. Unfortunately a blockage appeared shortly after installation in Extensometer E3, and consequently the results on this instrument have been lost. The settlement results for each of the other extensometers are presented in tables 5.2, 5.3 and 5.4.

The maximum settlements recorded on each instrument are; E1, (40 metres depth), 40 mm. E2, (70 metres depth), 55 mm, and E4, (60 metres depth), 5 mm. There has been no correlation between settlement and the position of the water table. On instrument E4 it is interesting to note that initially movements of up to 72 mm were recorded principally in the lower parts of the fill. These movements have however countered by what presumably must be heave movements at a later date. It may be possible on the second set of readings showing magnitudes of 51-72 mm settlement that the datum magnet was misread.

Magnet No.	SP1	SP2	SP3	SP4	SP5	Water Horizon.
	Net Vertical Settlement (mm)					
Date						
29.8.85	0	+6	-9	-12	+2	SP2-SP3
28.11.85	0	-18	-30	-35	-39	SP2-SP3
5.6.86	0	-14	-25	-34	-40	SP2-SP3
12.6.86	0	-15	-23	-26	-40	SP2-SP3

Original Water Level; SP1-SP2, 20.6.85.

All results referred to magnet SP1 owing to loss of datum.

Table 5.2. Settlement and Recovery Rates, Extensometer E1.

Magnet No.	SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8	Water Horizon.
	Net Vertical Settlement (mm)								
Date									
29.8.85	+6	0	-27	-33	-35	-30	-30	-29	SP6-SP7
28.11.85	+2	-3	-26	-11	-7	-18	-29	-32	SP6-SP7
5.6.86	+4	-4	-29	-14	-13	-29	-45	-49	SP6-SP7
12.6.86	0	-7	-30	-17	-17	-34	-50	-55	SP6-SP7

Original Water Level; SP5-SP6, 20.6.85.

Table 5.3. Settlement and Recovery Rates, Extensometer E2.

Magnet No.	SP1	SP2	SP3	SP4	SP5	SP6	Water Horizon.
	Net Vertical Settlement (mm)						
Date							
29.8.85	-23	-20	-24	-19	-15	-16	SP4-SP5
28.11.85	-55	-61	-72	-49	-54	-51	SP4-SP5
5.6.86	0	-2	-2	-1	-4	0	SP4-SP5
12.6.86	0	+2	-5	-3	-1	-5	SP4-SP5

Original Water Level; SP3-SP4, 20.6.85.

Table 5.4. Settlement and Recovery Rates, Extensometer E4.

+ denotes heave movement.

- denotes settlement.

5.7 CONCLUSIONS.

The following conclusions can be drawn from this study:

a). The completion of groundwater recovery within the fill occured within 12 months of placement. The present groundwater levels are approximately 5 metres below the original pre-mining levels and therefore may rise further at a very slow rate.

b). The rapid recovery has initiated collapse settlements in the fill prior to instrumentation. Since monitoring commenced no collapse settlement has been observed associated with a further 5 metres of recovery.

c). There has been no severe differential settlement resulting form the variance in fill depths. This is perhaps the most significant result.

d). The stability of the fill provides a sharp contrast to previous observations reported in Chapters 3 and 4. In particular the absence of both vertical and shear movements in deeper fill materials.

CHAPTER 6.

BACKFILL SETTLEMENT AND GROUNDWATER OBSERVATIONS ON SELECTED OPENCAST MINE SITES.

CHAPTER 6. BACKFILL SETTLEMENT AND GROUNDWATER OBSERVATIONS ON SELECTED OPENCAST MINE SITES.

6.1 INTRODUCTION

This chapter presents an analysis of backfill settlement observations conducted upon a number of opencast mine sites in the North-East of England. Recent backfill settlement phenomena on a further two opencast sites in the same region are also detailed. Table 6.1 details a summary of site descriptions. Most of these sites are in close proximity to Site B which has been discussed in detail in Chapter 4. The influence of deep mine pumping as experienced on Site B affects water levels on two of these sites.

The sites covered in this Chapter involve ones which have experienced delayed collapse settlement and groundwater recovery, secondary re-establishment, as well as ones exhibiting very small backfill movements indeed. Lateral movements are found to be the major fill displacements on one of the sites.

Settlement periods are expressed either by dates or in days, where day 100 is the 100th day after monitoring commenced.

Table 6.1. Summary of Site Investigations.

Site Description	Instrumentation Details.
Dragline Site D, 15 -30 metres depth of fill. Sandstone- mudstone.	23 Surface levelling stations and 3 magnetic extensometers/piezometers monitoring the line of a sewerage pipe constructed over the fill.
Dragline Site E, sandstone-mudstone fill. Depths- 15-30 m	3 traverses totalling 30 surface levelling stations over fill area. Correlated to local piezometers for groundwater levels.
Dragline Site F, sandstone-mudstone fill. Depths in area of instrumentation up to 35 metres.	8 surface levelling stations installed over highwall area. Correlated to local piezometers for groundwater levels.
Shallow Truck-Shovel Site G. Sandstone-mudstone fill. No water.	9 surface levelling stations monitoring vertical and lateral fill movements.
Dragline Site H, spoil heap mound.	1 tension wire extensometer monitoring settlement and shear. 1 piezometer monitoring groundwater.
Dragline Site I, sandstone-mudstone fill. Damage to Concrete line culvert and lake constructed on restored fill surface.	None
Truck-shovel Site J, on side of hillside. Shallow depth 11 m, sandstone-mudstone fill.	None

6.2. DRAGLINE SITE D.

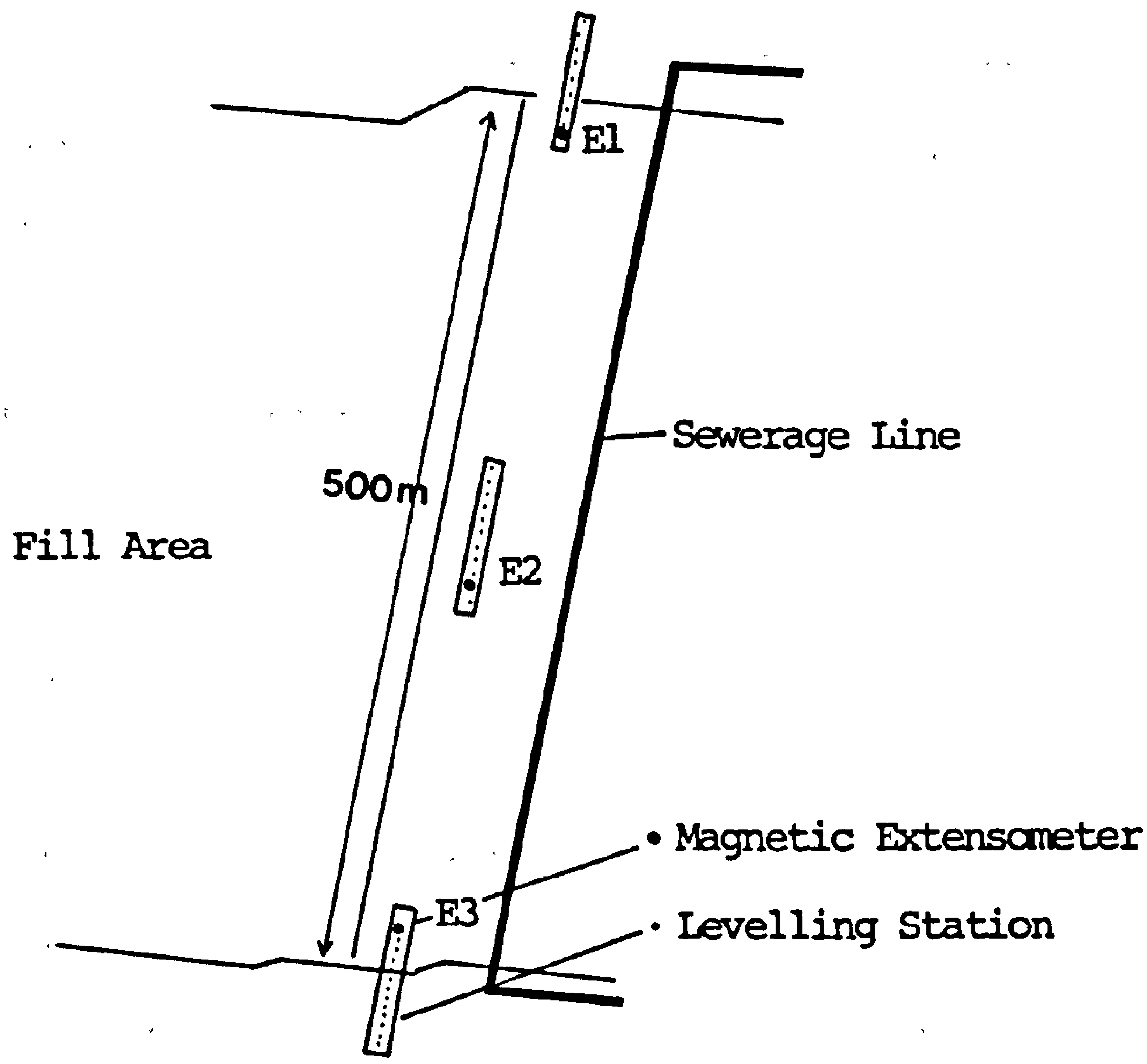
6.2.1 Instrumentation.

The monitoring scheme for Site D. was a joint Nottingham University/British Coal project which commenced in early 1982. The site, a dragline operation backfilled in mid-1974 had a sandstone-mudstone type fill typical of the area, the geological sequence worked being largely arenaceous. Two million tonnes of coal were extracted from the site at an overburden to coal ratio of about 20:1.

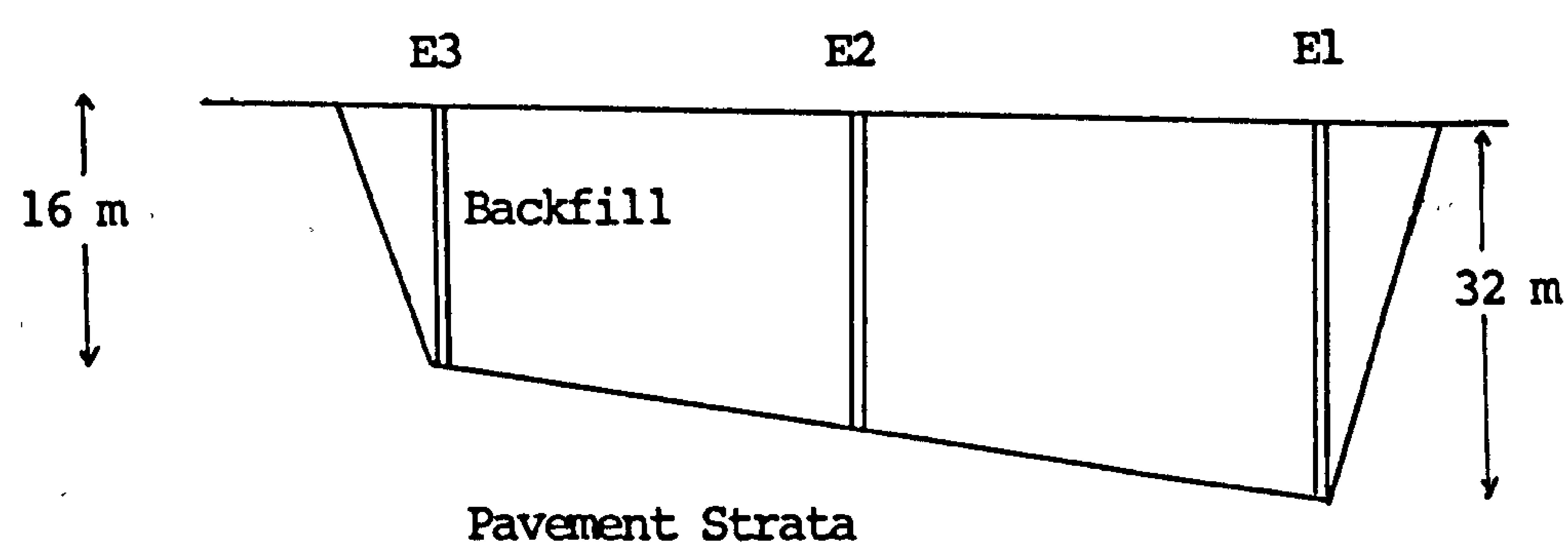
The project consisted of the monitoring of the settlement of a sewerage pipeline constructed over the mine backfill. Initial thoughts considered that the sewerage line be diverted around the highwall of the pit thus avoiding passing over fill material. The expense however that this would incur in additional pipe lengths and installation time was such that British Coal agreed to divert the line directly over the fill and introduce a settlement monitoring programme to ensure that abnormal ground movements could be detected and not adversely affect the construction of the structure.

The instrumentation consisted of the installation of three magnetic extensometers/piezometers in the fill complemented by three sets of 10 surface levelling stations. Manhole covers emplaced above the sewerage line also act as surface leveling stations. The instrumentation layout is illustrated in figure 6.1.

The design of the pipeline was such that some degree of



a). Plan of Instrumentation.



b). Section through Instrumentation

Figure 6.1 Instrumentation Plans, Site D.

settlement could be tolerated by the introduction of flexible joints between individual pipe sections. The pipes themselves were 315 mm O.D.

6.2.2. Surface Displacements.

The time elapse between the date of backfilling, (mid 1974) and the commencement of monitoring, (early 1982) of 7.5 years was to prove extremely important in the analysis of the results to the present date. Movements have been recorded of up to a maximum of 15 mm, stations have in fact shown either small settlement or heaving movements. Table 6.2 details the surface displacements recorded over a period of three and a half years.

6.2.3. Extensometer Results.

a). Piezometer Records.

Table 6.3 details water levels within the fill for extensometers E1, E2 and E3. They show that whilst E1 and E2 remained effectively dry, water levels if E3 fluctuated widely.

b). Groundwater and Settlement.

The lack of water within holes E1 and E2 is in sharp contrast to the levels recorded on instrument E3. Figure 6.2

S1	S2	S3	S4	S5	S6	S7	S8	E1	S9	S10	S11	S12	S13	S14	S15
					-5	-1	-3	-15	-14	-14	-15	-	6	4	3

E2	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	E3	S27	S28
3	3	2	2	3	2	4	4	-	4	3	5	6	4	4

S29	S30	MHD	MHE	MHF	MHG	MHH	MHJ	MHK.
-9	1	-4	-5	-8	-6	-11	0	

S- Surface Station, E- Extensometer, M- Manhole Cover.

Table 6.2 Total Surface Displacements 1982/5, Site D.

Date.	E1 (depth = 31.2 m)	E2 (depth = 27.5 m)	E3 (depth = 18.0 m)
12.01.82	28.29	27.73	10.07
05.02.82	27.94	Dry	8.10
05.03.82	28.12	Dry	13.16
08.04.82	28.25	26.73	14.46
06.05.82	28.55	Dry	15.40
02.06.82	28.97	Dry	15.70
09.09.82	29.46	Dry	14.49
14.12.82	29.47	Dry	ground level
02.03.83	29.82	Dry	5.78
09.06.83	30.05	Dry	12.21
07.09.83	30.26	Dry	17.45
07.12.83	30.30	27.70	Dry
13.04.84	30.53	Dry	9.77
07.02.85	31.20	27.74	4.11
01.08.85	31.18	27.69	1.21
Surface Levels.	93.341	96.527	100.444
Horizontal Distances.	239.36	242.22	

Water levels given in metres below the Surface.

Table 6.3 Water Level Records, Site D.

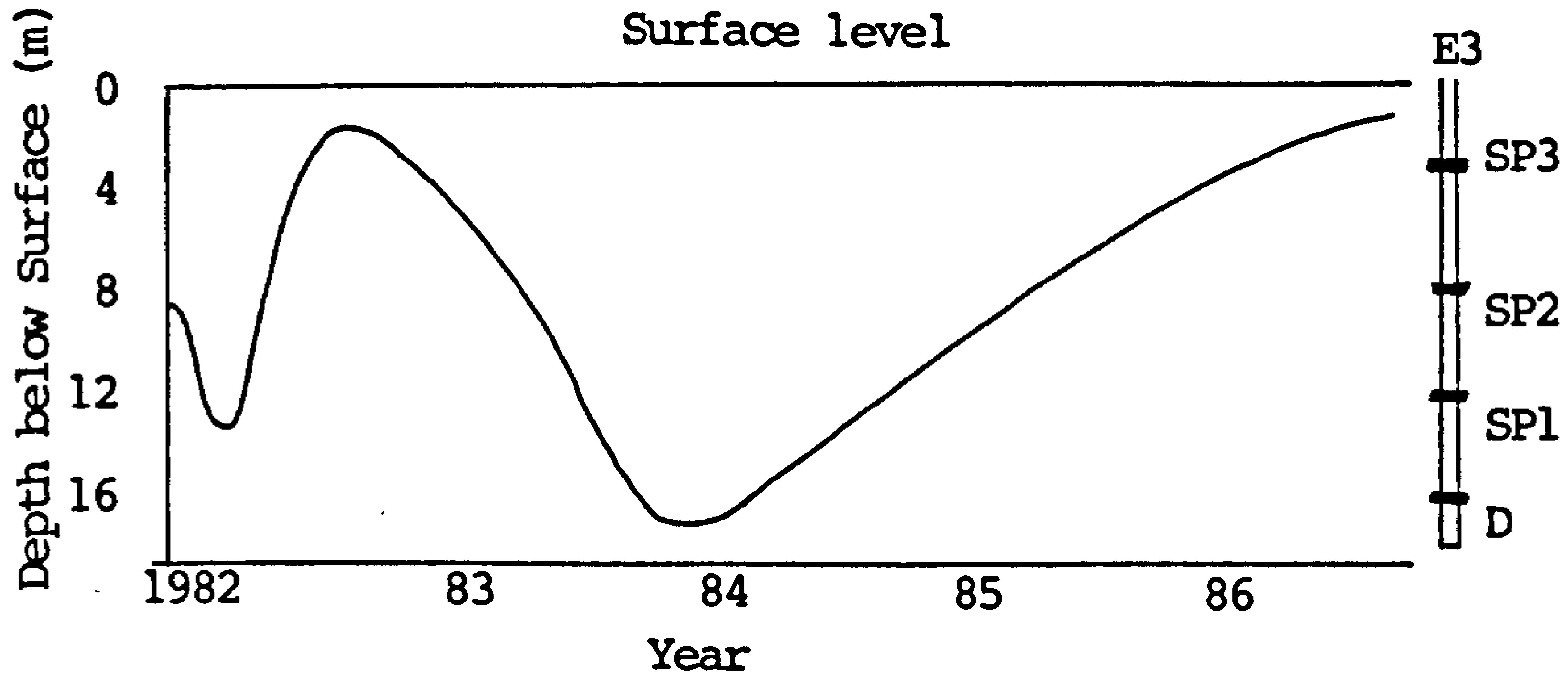
illustrates the groundwater levels and settlement characteristics for instrument E3 against time.

Whilst trends would appear to exist between magnets and water levels from inspection of figure 6.2, it is considered dangerous and probably meaningless to "over-analyse" these results further. Movements of fill in the region of ±12 mm in about 16 m of fill depth show for the purposes of this exercise that the pipeline is not being subjected to adverse differential backfill movements. No correlation can be drawn between recovery and settlement and this is in no doubt due to the fact that monitoring commenced 7.5 years after backfilling had been completed. From the E3 instrument results however it can be stated that after an uncertain time period a fluctuating water table will cease to cause further significant collapse settlements.

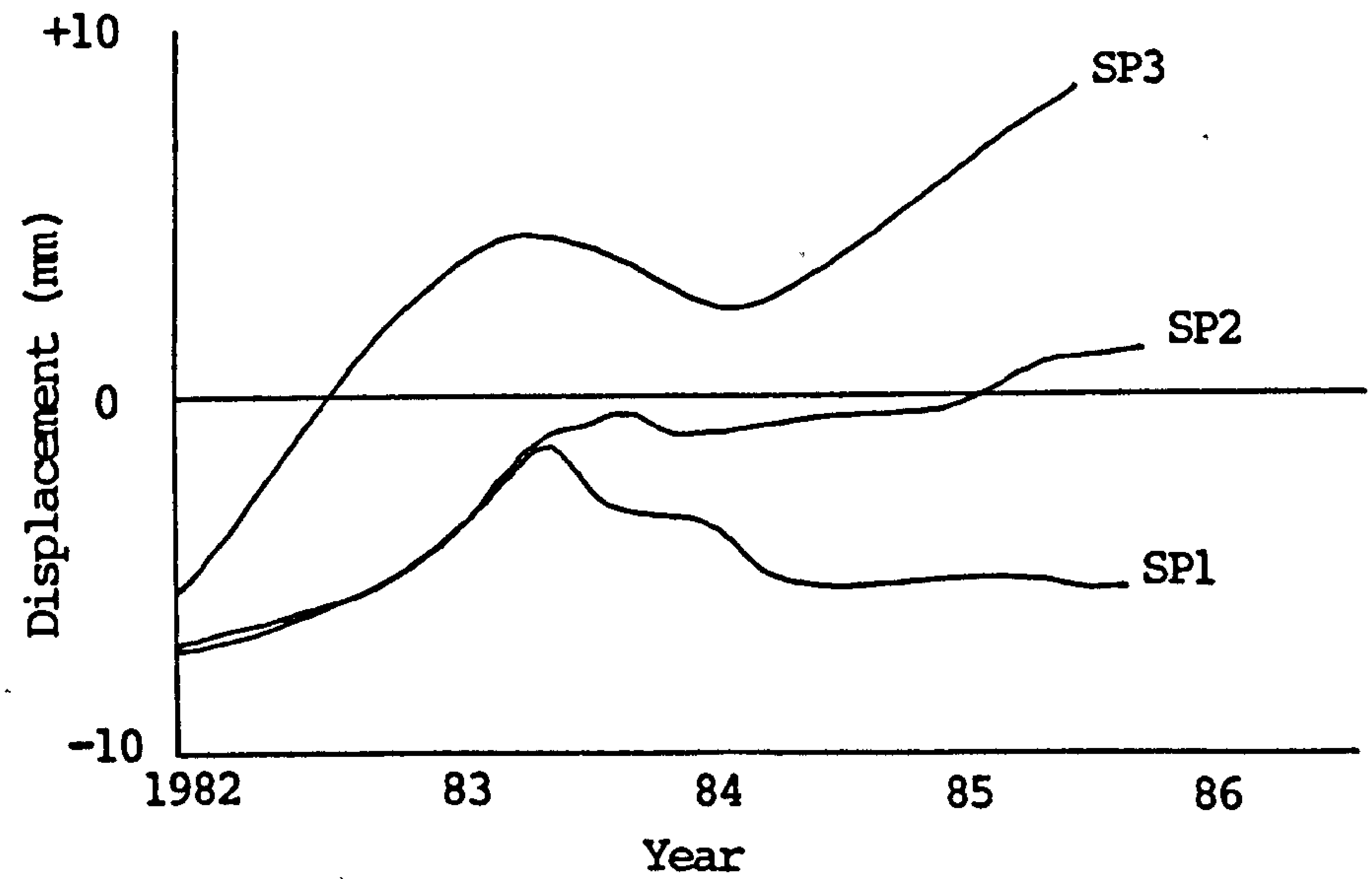
6.3 DRAGLINE SITE E.

6.3.1 Introduction.

Site E was worked between 1957 and 1973 producing about 7 million tonnes of coal from a dragline operation. The backfill is a typical sandstone/mudstone fill common in the area. On the completion of areas of backfilling, three surface levelling traverses were installed. Figure 6.3 shows the positions of the traverses together with approximate depths of fill.



Water Levels - Extensometer E3



Settlement Records - Extensometer E3

Figure 6.2. Summary of Results, Extensometer E3, Site D.

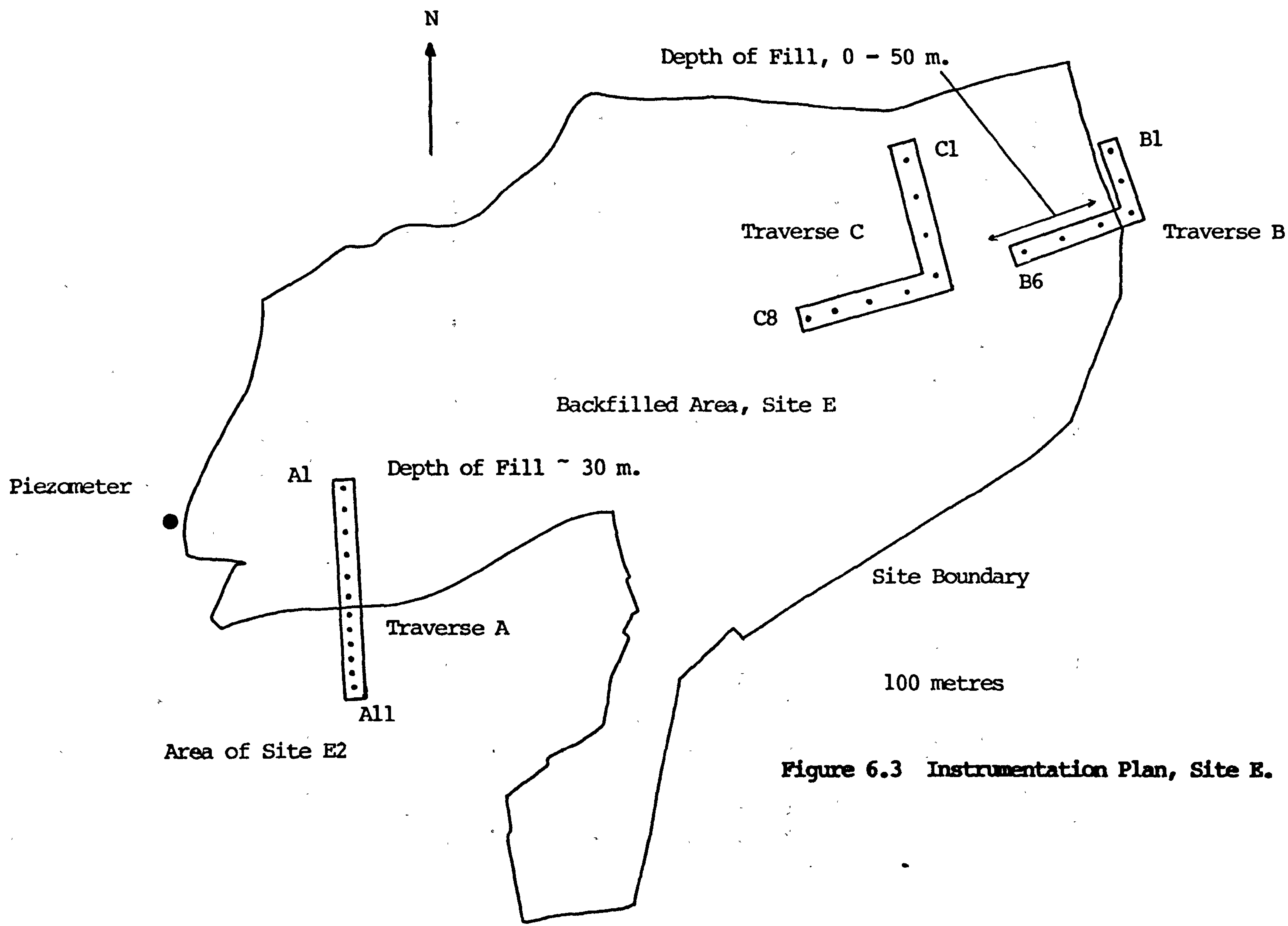


Figure 6.3 Instrumentation Plan, Site E.

6.3.2 Traverse A.

Traverse A passes over both Site E and an adjacent opencast mine site, (referred to hereafter as Site E2), which had completed coaling in 1956 just prior to the commencement of Site E. The traverse is illustrated in figure 6.3 along with the position of piezometer No. 611 from which an approximate idea of levels of water within the fill may be obtained. The water levels in this instrument are displayed graphically in figure 6.4. The figure shows that the water levels over this part of the site were recoverying slowly form the start of monitoring up until May/June 1982. In this particular area the effects of the deep mine pumping mentioned in Chapter 4, (Site B) as for Site E can be discounted owing to the presence of the relatively impermeable dyke. Figure 6.5 shows the settlement versus time curves for all the stations over the traverse. Total settlements are detailed in table 6.4.

It can be seen that settlement rates retarded around the time of the completion of groundwater recovery thus indicating that settlement and groundwater were related.

Following recovery, the groundwater levels can be seen to be dropping and this corresponds to a period of negligible backfill movements. After this period, groundwater levels again rise and settlement is seen to restart. It must be noted that the levels in piezometer 611 are higher than the restored level of the traverse, (by up to 10 m), some 320 m distant. It

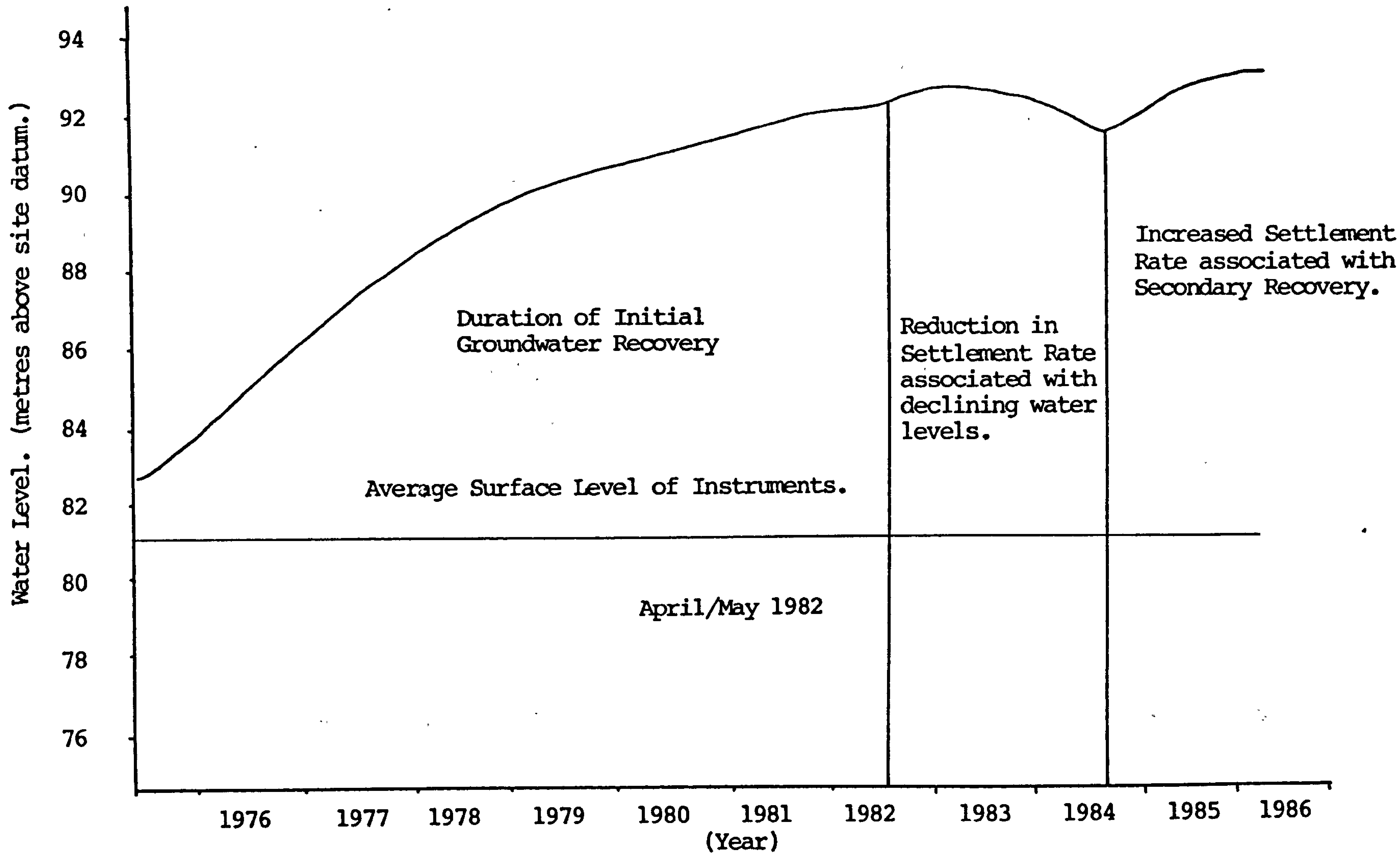


Figure 6.4. Water Levels in local Piezometer 611, Site E.

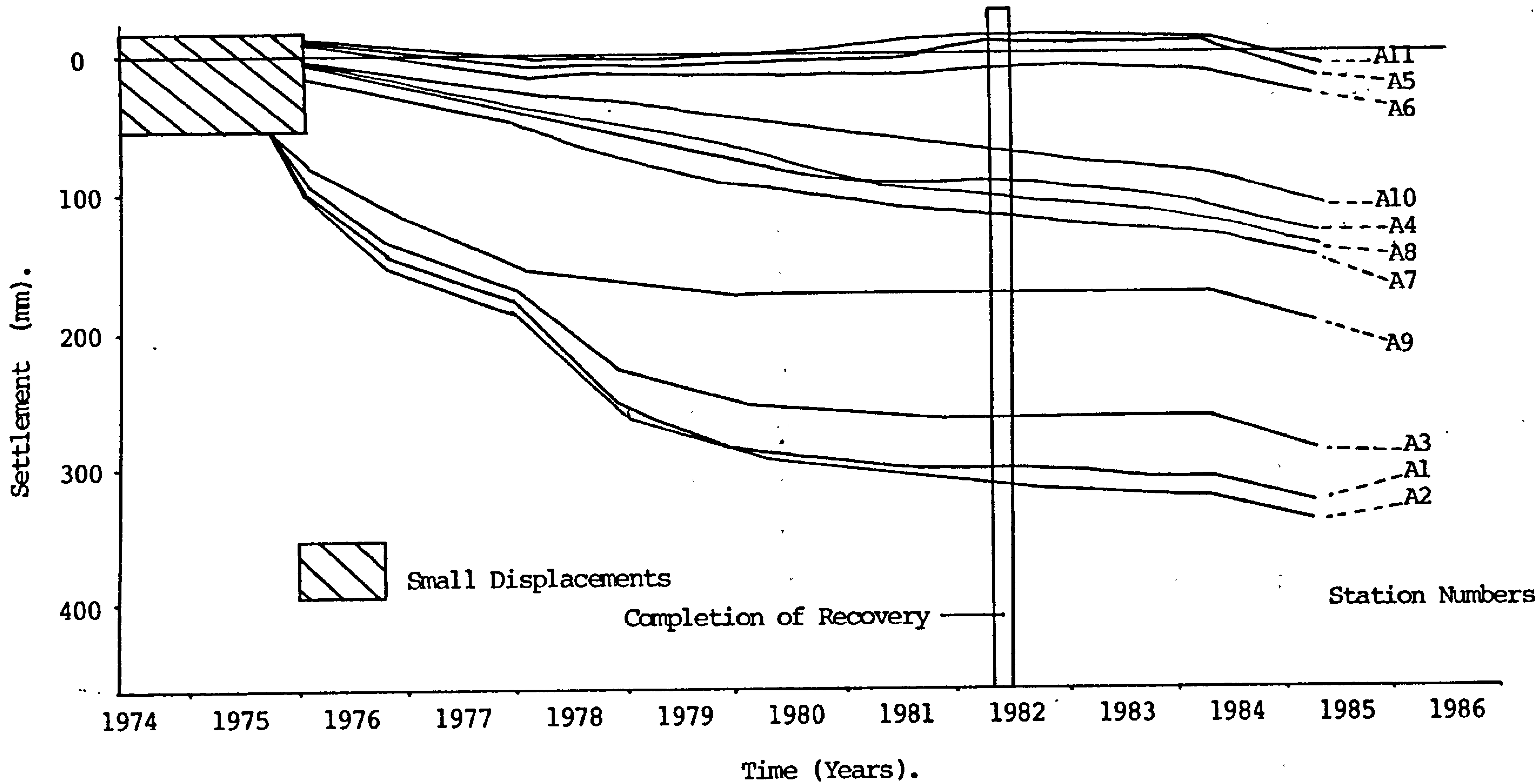


Figure 6.5 Settlement Records, Traverse A, Site E.

Station.	Approx Depth of Fill (m).	Total Settlement (mm)	Settlement, mm/m depth.	Comments.
A1	18	328	18	closest to 611
A2	21	339	16	
A3	24	290	12	
A4	21	110	5	
A5	uncertain	8	-	Border of Sites
A6	uncertain	26	-	E - E2
A7	35	148	4	
A8	18	129	7	
A9	7	195	28	
A10	7	89	12	
A11	6	+16	+3	Oldest fill.

Table 6.4 Summary of Settlement Results, Traverse A.

Site E.

is however considered that it is the trends observed that are important and that similar water level changes have occured within the fill material.

Total settlement results for this traverse are much as would be expected, ie maximum settlements have being recorded on stations 1, 2 and 3, the stations in the newest fill material. The least settlement has been recorded upon station 11 which along with stations 5 and 6 have undergone negligible movement. Station 11 is thought to be on the oldest fill in the traverse as well as being the shallowest, (c. 6 m). The depths of fill under stations 5 and 6 are thought to be shallow as well owing to this being on the border on the Dragline E and E2 Sites.

6.3.3. Traverse B

Settlement results for Traverse B are presented in figure 6.6. A summary of total settlements is given in table 6.5. The traverse is illustrated in fig 6.3 showing that 3 of the initially 6 monitored stations were positioned on solid ground. Monitoring has being performed in two stages, from 1969 until 1976 and from 1983 to the present day. As a consequence of this a great deal of the settlement data has been lost. The absence of a suitable piezometer within the area together with the loss in settlement readings has meant that the results cannot be correlated to groundwater recovery. As the trend of the settlement curves when compared to Traverse A is similar, then it is considered that groundwater

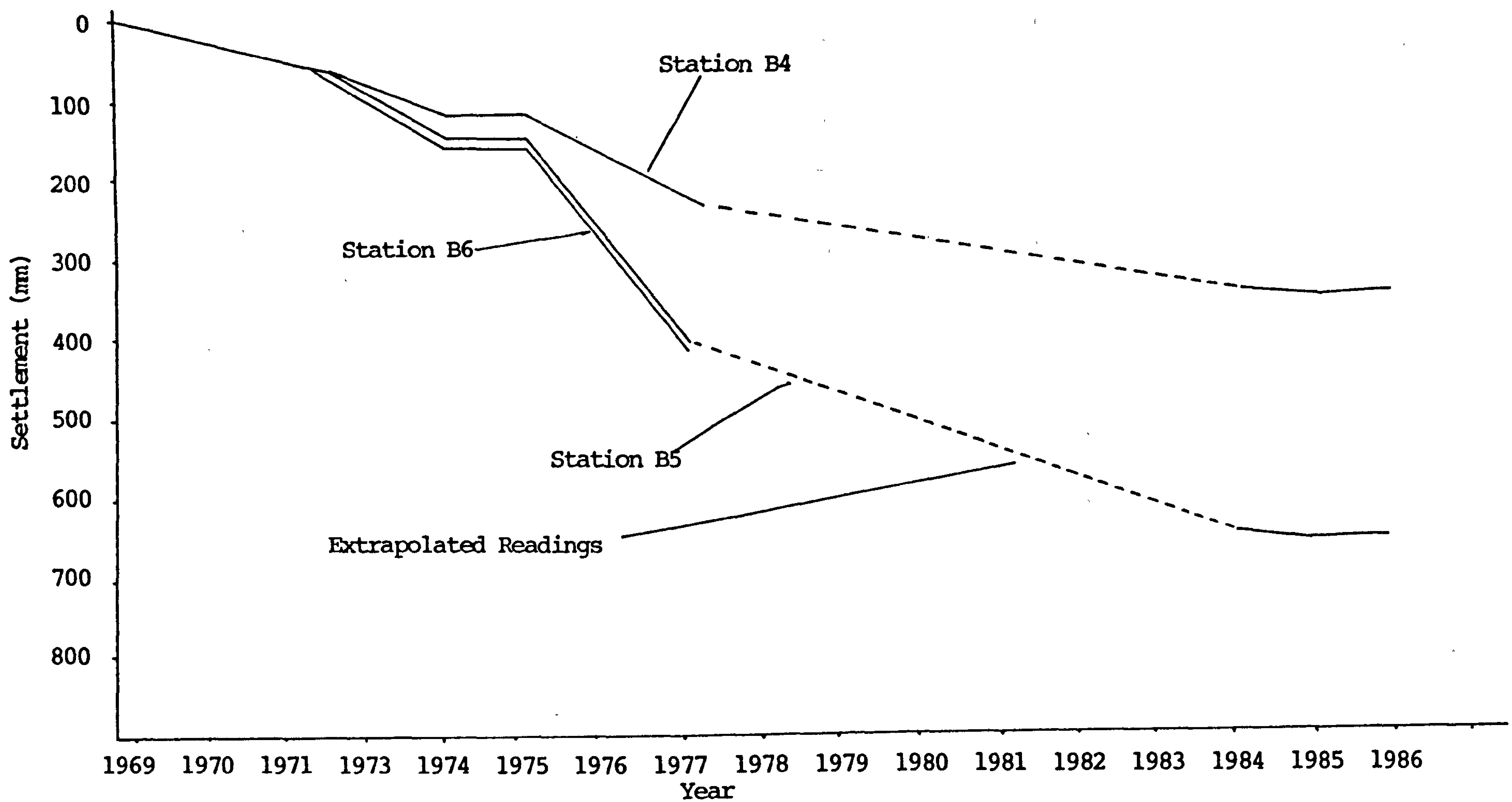


Figure 6.6 Settlement Records, Traverse B, Site E.

recovery has occured within the fill and consequently induced settlements.

6.3.4. Traverse C.

Traverse C has been monitored from 1983 until the present day and consists of 8 surface leveling stations over the fill. The total settlements are presented in table 6.6 and these show a maximum settlement recorded of 21 mm on station C7. This would appear to show that a great deal of settlement had occured prior to monitoring, and thus not recorded.

6.4. DRAGLINE SITE F.

6.4.1. Introduction.

Site F worked 2.5 million tonnes of coal in the period of 1971 to 1979, by dragline methods. The nature of the overburden being a typical mudstone- sandstone fill with an overburden to coal ratio of about 17:1. Instrumentation in the form of 8 surface levelling stations commenced in late 1975 over an area of the site. The results on this site are of particular relevance to the work undertaken on Site B , as water levels in this area are being dominated by the same colliery shaft pumping. The instrumentation scheme is illustrated in figure 6.7. Groundwater levels have been inferred from the water levels in the shaft, about 1000 m distant, and in a local piezometer 2000 metres away.

Station.	Depth of Fill. (m)	Total Settlement. (mm)	Settlement mm/m of Depth.
B1	0	0*	-
B2	0	+5*	-
B3	0	+7*	-
B4	35	347*	10
B5	55	657*	12
B6	55	402**	7

** Readings taken 12.6.69-11.2.76
* Readings taken 12.6.69-2.10.84.

Table 6.5. Summary of Settlement Results, Traverse B, Dragline Site E.

Station.	Total Settlement. (mm)
C1	-1
C2	+1
C3	-1
C4	-3
C5	-9
C6	-8
C7	-21
C8	-5

Table 6.6. Summary of Settlement Results, Traverse C, Dragline Site E. 10.1.83-2.10.84.

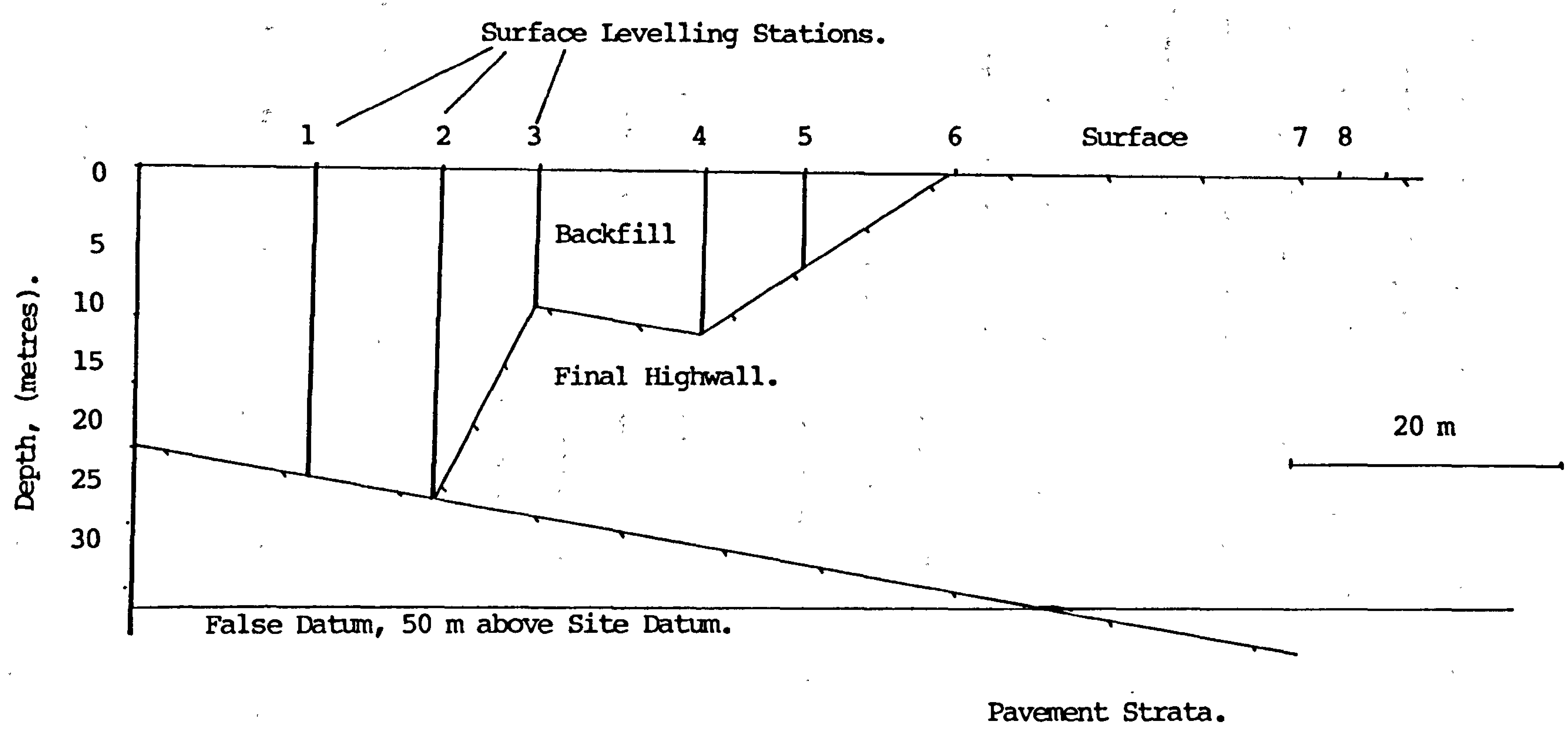


Figure 6.7. Surface Levelling Station Positions, Site F.

6.4.2. Settlement Observations.

The settlement results for the instrumentation scheme are presented in fig 6.8. Table 6.7 presents the results for all the stations expressed for the period of 3490 days of monitoring, (1975-1985) in the form of percentage of fill depth settlements. The maximum settlement recorded has been 451 mm in 18 m of fill, (2.51%), whilst the maximum percentage settlement has been 2.72%. (340 mm in 12.5 m of fill).

The total settlement results for this site have produced some interesting results summarised as follows,

i). The minimum fill settlement of 288 mm has been recorded in the maximum fill depth of 36.5 m, (0.79%).

ii). In the highwall area the degrees of settlement appear unrelated to fill thickness.

The most likely explanation for these phenomena is probably that the standard of initial compaction of the fill in close proximity to highwalls has a greater variance than say for the rest of the mine. The physical presence of the solid wall must also prevent lateral movements within the fill which can reduce in turn vertical displacements.

6.4.3. The Abnormal Phase of Settlement, Days 270-366.

An abnormal phase of settlement was found to have occured on all stations over the fill during the period of 270-361 days from the start of monitoring. This phenomena is detailed in table 6.8. Settlement rates on either side of this period

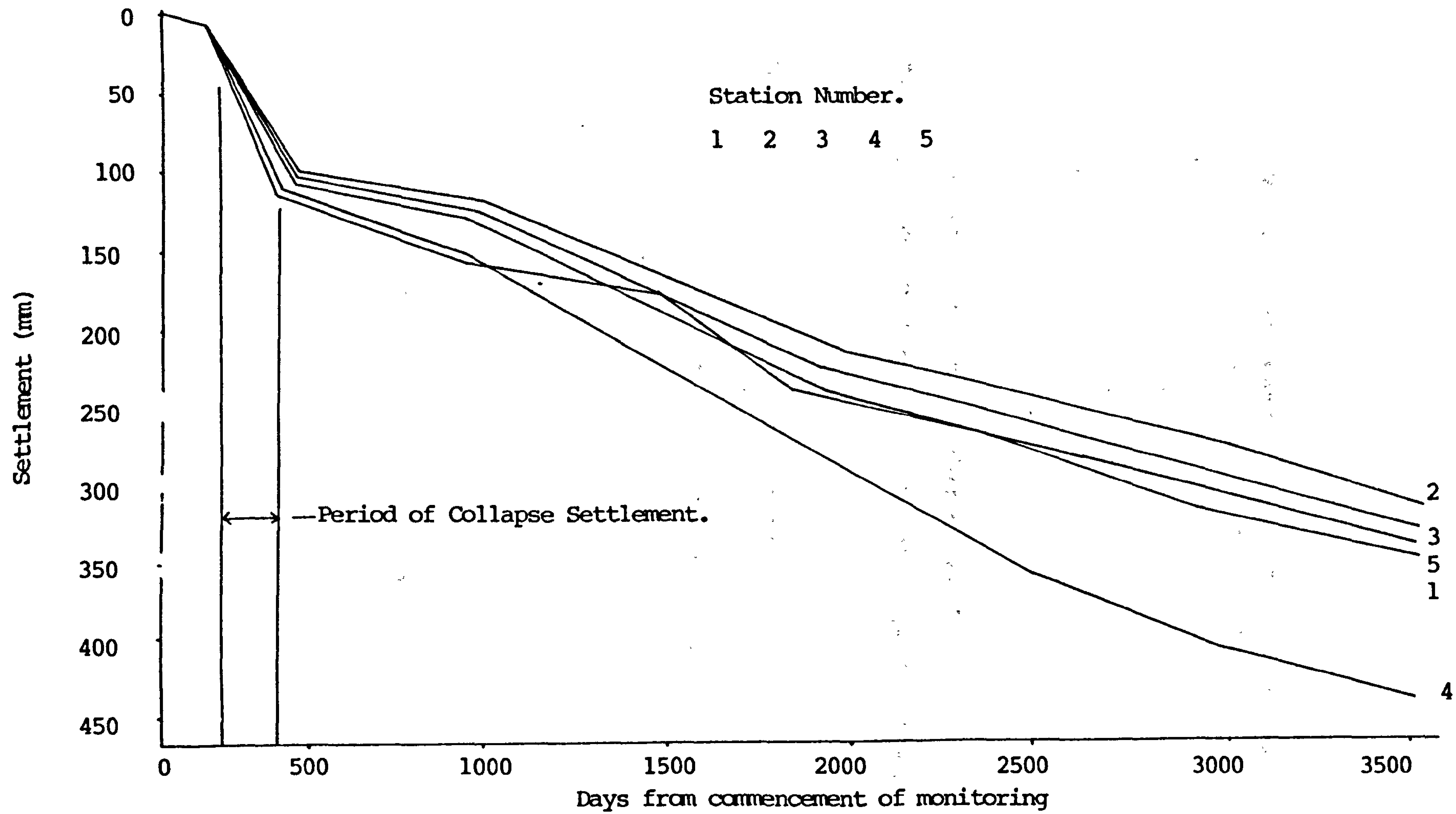


Figure 6.8 Surface Settlement Results, Site F.

Station.	Fill Depth. (m)	Settlement to Day 3490. (7.11.75-20.5.85)(mm)	Settlement as mm/m Fill Depth.
1	34	-348	10.2
2	36.5	-288	7.9
3	15	-308	21.0
4	18	-451	25.1
5	12.5	-340	27.2
6	0	+3	-
7	0	-2	-
8	0	+3	-

+ denotes heaving   - denotes settlement.

Table 6.7. Total Settlements, 1975-1985, Dragline Site F

Station.	Time Elapse since Commencement of Monitoring. (Days).				
	0-101	101-185	185-270	270-361	361-452
1	-7	-2	-	-93	-15
2	-9	-4	-1	-101	-13
3	-13	-7	-4	-103	-13
4	-12	-5	-2	-82	-9
5	-20	-10	-6	-76	-8
6	0	0	+1	-1	+1
7	+1	+1	0	+1	0
8	0	+2	0	0	+1

Displacements given in mm.

Table 6.8. Settlement Results, Days 0-452, Dragline Site F.

appear to be uniform and have continued in this uniform fashion to the present day. Of particular note is the fact that settlements on all stations over the fill are continuing at the rate of 10 mm/year, 9.5 years after monitoring commenced.

The occurrence of a sudden and dramatic increase in the rate of settlement on all stations sited over fill would appear to be akin to a phase of groundwater recovery. The fill in this area is shallow and it could be reasonable to suggest that groundwater recovery could have been completed in the period of 91 days after day 270.

Figure 6.9 details the piezometer records for piezometer 2002 on an adjacent opencast mine site, figure 6.10 illustrates the standing water levels in the colliery pumping shaft.

The piezometer results show that in the period in question, the water levels rose by about 4 metres within this hole to attain a level of 16.45 metres B.O.D, (below Ordnance Datum). The shaft water levels also show a rise in water levels which occured over this period. These results would appear to leave it in no doubt that groundwater recovery occured in the Site F fill to cause the increased settlement rates.

Following the large settlements of this period, a reduced settlement rate has continued in the fill for 8.5 years. This implies that even following the completion of groundwater recovery, significant movements can occur in shallow fills for a considerable time. It is unfortunate that this particular site was not instrumentated with magnetic extensometers and

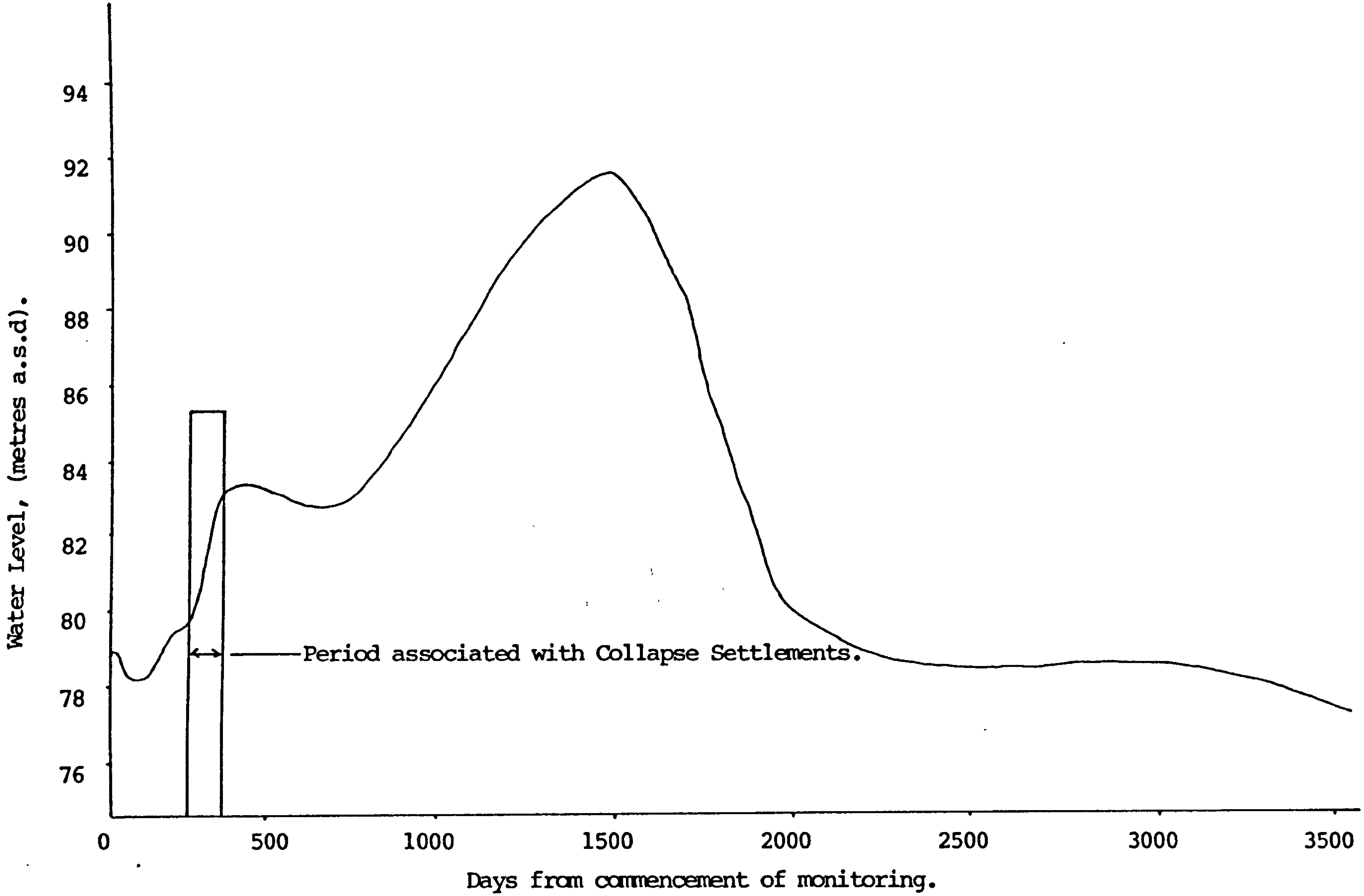


Figure 6.9 Water Levels in local Piezometer, Site F.

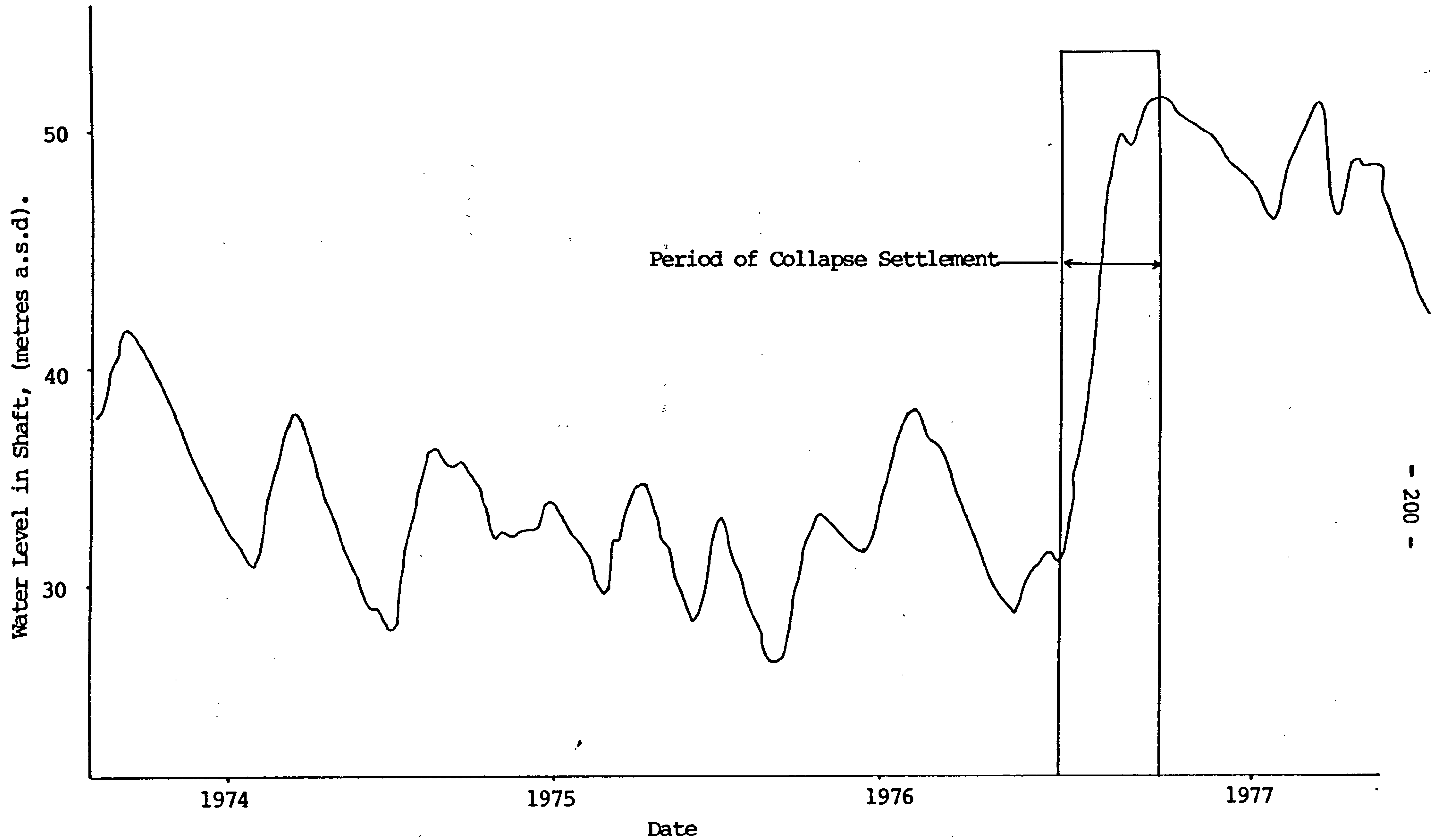


Figure 6.10 Water Levels in Colliery Shaft.

piezometers to observe whether subsequent movements have occurred in saturated or unsaturated fill materials.

6.5. TRUCK/SHOVEL SITE G.

6.5.1. Introduction.

The Truck Shovel Site G was worked between 1972 and 1973 to win about one quarter of a million tonnes of coal and 4,000 tonnes of fireclay. The nature of the fill is 10% drift, 75% sandy shale and 15% sandstones. There were no difficulties with water during excavation.

6.5.2. Monitoring Scheme.

The monitoring scheme consisted of 8 surface levelling stations installed over a highwall which were tied into a temporary Ordnance Survey Bench Mark. The scheme is illustrated in figure 6.11. Settlement observations commenced in late 1973 and continued to mid 1981. In addition to monitoring vertical displacements, changes in the co-ordinates of the stations were also recorded to derive a three dimensional view of backfill settlement. Horizontal Displacements were only recorded over the initial three years.

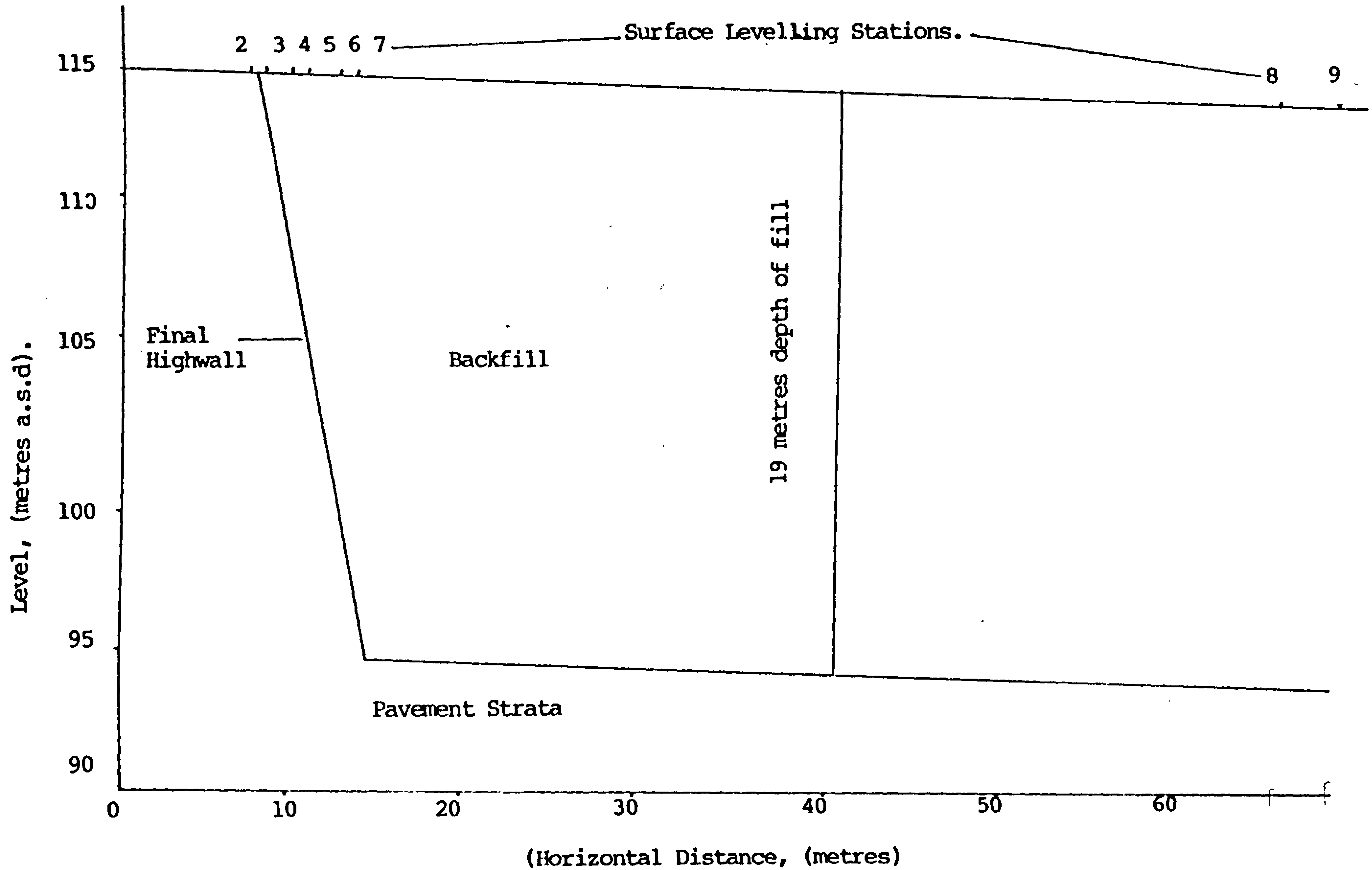


Figure 6.11 Instrumentation Scheme, Site G.

6.5.3. Results.

Settlement results are tabulated in table 6.9. Differences in Northings and Eastings are presented along with total horizontal movements in tables 6.10a, 6.10b and 6.10c.

The maximum settlement over the 8 year monitoring period was 48 mm. As no water was encountered during mining and there a no obvious settlement anomalies it is fair to state that this fill is unsaturated and that water percolation is solely due to that from surface infiltration.

Stations 6, 7, 8 and 9 are all sited in fill of similar depths, however twice the settlements of 6 and 7 have been recorded on 8 and 9. The presence of the highwall cannot be discounted from having affect, however as for Dragline Site B, to critically "over-analyse" settlement results of 48 mm maximum in 19.6 m of fill could well be misleading.

Tables 6.10a-c have detailed the horizontal surface displacements for each station. Of great importance is to note that these horizontal movements are in general greater than vertical settlements experienced. Table 6.10c shows that station 8 has displaced 62 mm up to mid 1976 whilst only 29 mm vertically. If the construction of structures is proposed then it would be this horizontal movement that would be important and not necessarily the vertical. Differential horizontal surface strains is not a subject which has been considered in previous work on backfill settlements although it is well known in subsidence work. For construction purposes however, it is essential that they be considered.

Surface Station	Total Settlement Recorded; 1973-1981. (mm)
2	0.25
3	1.9
4	5.6
5	13.2
6	23.6
7	26.1
8	44.9
9	48.5

Table 6.9. Total Settlement; Truck/Shovel Site G

	Changes in Easting, (mm). Station.							
Date.	2	3	4	5	6	7	8	9
8.11.73	0	0	0	0	0	0	0	0
13.4.75	+18	0	-6	-11	-7	-2	-29	-23
11.6.75	+19	+18	+2	-3	+10	-10	-11	-26
13.4.76	+6	+1	-8	-21	-29	-28	-56	-48

Table 6.10a. Changes in Eastings, Surface Stations, Site G.

	Changes in Northing, (mm). Station.							
Date.	2	3	4	5	6	7	8	9
8.11.73	0	0	0	0	0	0	0	0
13.4.75	-9	+6	+10	+7	+4	+8	+21	+15
11.6.75	-11	+1	+7	+1	-12	+5	+11	+5
13.4.76	-7	+6	+9	+5	+16	+9	+26	+24

Table 6.10b. Changes in Northings, Surface Stations, Site C.

Station	2	3	4	5	6	7	8	9
Movement (mm)	9	6	12	22	33	30	62	54

Table 6.10c. Total Horizontal Displacements, Site G.

Table 6.11 details the surface movements over the site as ground strains between the individual stations. It can be seen that high strain rates, the largest being between stations 6 and 7 of -26.7 mm/m generally manifest around the area of the highwall - the strains between stations 7 and 8 being generally relatively low, (0.54-0.6 mm/m). The strain values presented in table 6.11 do show that strains between two stations can change in both magnitude and direction with time. Both compressive and tensile strains have been experienced on all the individual sections.

6.6 SETTLEMENT OBSERVATIONS CONDUCTED ON AN OPENCAST SPOIL HEAP - SITE H.

6.6.1 Instrumentation.

An simple instrumentation scheme was devised in 1978 to monitor settlement and groundwater movement within a semi-permanent spoil mound. A tension wire extensometer and a standpipe piezometer were installed in two adjacent boreholes to the base of the spoil, 26 metres deep. Wires monitored displacements at levels of 10, 15, 20 and 26 metres below the surface.

A summary of total settlement displacements is presented in table 6.12. The movements are however so small, a maximum of 35.6 mm over a period in excess of 7 years that a detailed analysis would be meaningless. Groundwater levels fluctuated

Interval	Distance (m)	Lateral Strains mm/m of Interval			
		8.11.73	10.4.75	11.6.75	13.4.76
2-3	1.0	0	-21.0	+16.5	-3.9
3-4	1.4	0	-5.3	-7.5	+5.3
4-5	1.0	0	+3.6	+0.9	-7.2
5-6	1.4	0	+3.3	+7.2	-17.0
6-7	1.0	0	+3.9	-26.7	+25.7
7-8	46.0	0	-0.6	+0.5	-0.6
8-9	3.0	0	+2.8	-6.9	+7.2

Table 6.11 Lateral Strain Summary; Truck/Shovel Site G.

over the base 3 metres of the hole and had no effect on settlement magnitudes. The spoil heap itself would have been largely constructed using scraper machines which inflict a high degree of compaction to the fill.

Table 6.12

Total Settlements recorded at Extensometer Anchors, Dragline Site H, spoil mound.

Settlements after 2405 days of monitoring, (mm).

Anchor			
1	2	3	4
(10 m)	(15 m)	(20 m)	(26 m)
35.05	35.63	25.76	14.50

6.7. DRAGLINE SITE I.

Dragline Site I, worked between 1966 and 1971, extracting 2.5 million tonnes of coal in a boulder clay, sandstone, fireclay and shale overburden. The area was restored to form a country park which involved the construction of a lake with a concrete lined culvert leading to the sea. Channel excavation commenced in April 1983 and was completed complete with concrete base sections by June/July 1983. A statutory maintenance period was completed on 26 October 1984.

In June 1985, it had been reported that a section of the culvert had sunk into the fill over a 45 m length. The settlement had been of the order of 1115 to 1160 mm. The channel together with the damaged zone is illustrated in figure 6.13. The working limits of the excavation, and two of the mined seams are also indicated.

This occurrence has been of great interest as it involves a settlement delay of around 2 years after the channel had been constructed over fill that was 14 years old. The fill depth is around 33 metres and thus this represents a settlement of 3.4% expressed in terms of fill thicknesses - a much larger settlement than experienced in earlier reported observations.

Whilst no detailed investigation has been conducted the example serves to show how delayed backfill settlements can occur as a result of surface structural development.

6.8. TRUCK/SHOVEL SITE J.

Truck-Shovel Site J worked to an average depth of about 11 metres. Mining terminated in 1961, and the surface of the site now acts as a playing field for the local school.

Attention has been recently drawn to the fact that there are three or four surface depressions of irregular shape that have appeared on the fill surface. The largest of these depressions being 500 m^2 in area with a maximum depth of around 0.5 m. The depressions have only become evident within the last few years. A current National Coal Board enquiry is being conducted. These movements are of interest for the following reasons,

i). The fill has been in position for 24 years.

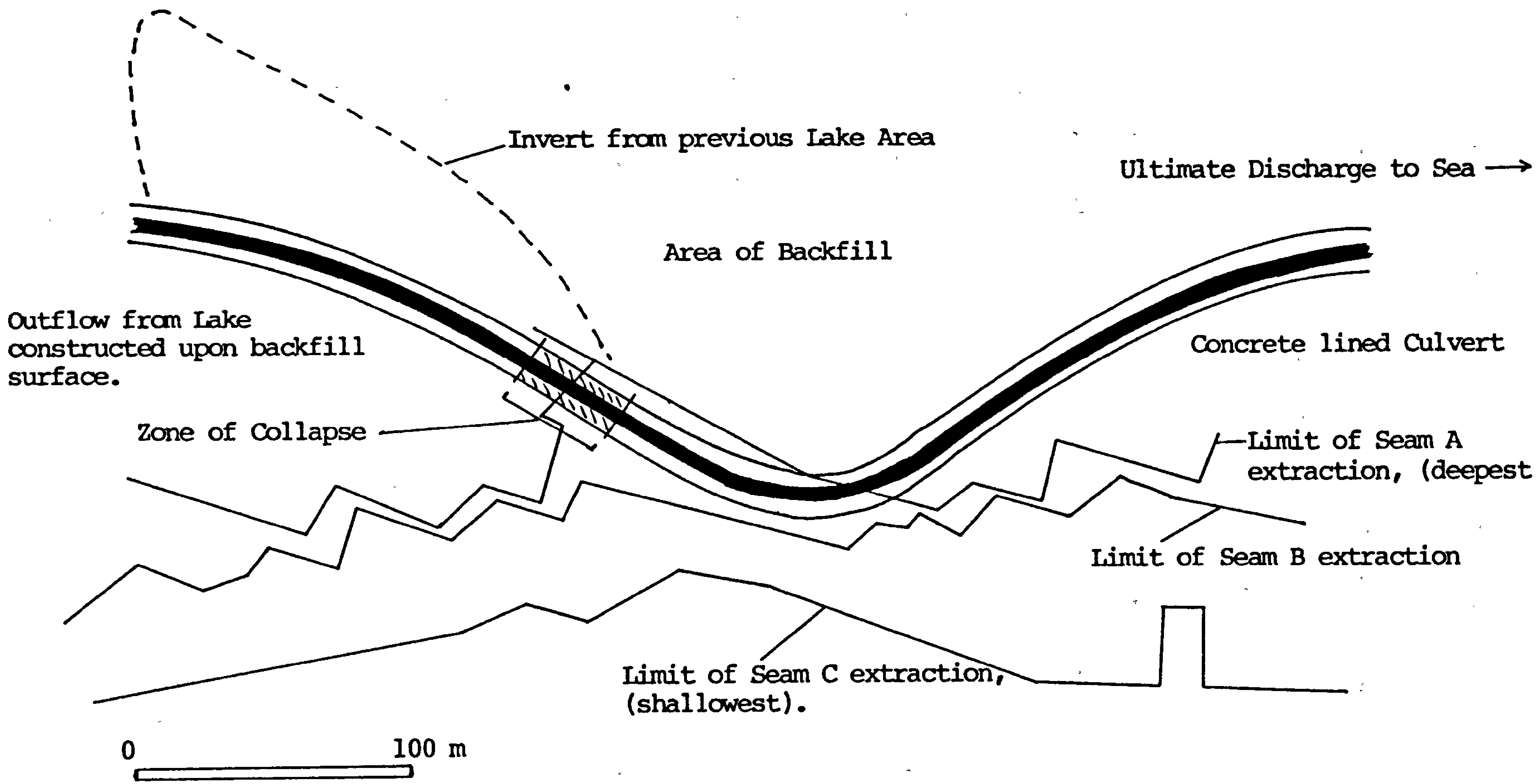


Figure 6.12 Damage to Concrete Lined Culvert constructed on Backfill, Site I.

ii). A settlement of 0.5 m in 11 m of fill represents 4.5% subsidence.

iii). Inspection shows no signs of current or previous slope failures or water issues.

iv). The last date of deep mine working was 1945, 80 m below the surface.

Akin to the observations from dragline site E there appears to have occured some exceptionally long term settlement movements. No detailed study has been conducted by the National Coal Board and any remedial technique is likely to comprise of the infilling of the surface troughs with imported material.

6.9 CONCLUSIONS

The following conclusions can be drawn from the work performed in this chapter.

i). Dragline site D.

After seven years fill movements were found to be negligible. A fluctuating groundwater table was found no longer to induce collapse settlements.

ii). Dragline site E.

Groundwater associated settlement identified. On completion of groundwater recovery there was a reduction in the rate of settlement. After a seasonal lowering of the groundwater, secondary recovery re-initiated collapse settlement in previously saturated fill iii). Dragline Site F.

Groundwater associated settlement identified. Settlement magnitudes in general were not considered a function of fill depth, more the degree of saturation. Settlement magnitudes were affected by presence of adjacent highwall, preventing lateral fill movement. Water recovery commenced in the fill 270 days after monitoring and continued for 90 days. Since completion of recovery, the settlement rate has remained steady for 9 years at 10mm/year.

iv). Truck/Shovel Site G.

Observations emphasised the importance of lateral movement prediction first mentioned in chapter 4, (Site B). Surface lateral movements exceeded total vertical settlements and were found to continue for at least three years on this site. The absence of fill saturation is considered the most important factor in the lack of total vertical settlement.

v). Dragline Site H.

Compaction by plant during spoil placement was found to be very effective in reducing total settlement. The absence of water of the monitoring period of seven years contributed to the stability of the rockfill mass.

vi). Dragline Site I.

A settlement of 3.4% was recorded in a fill 14 years old, two years after the construction of a concrete lined culvert. The settlement area occured over a 40 m length of the culvert. It is presumed a result of water leakage from the culvert into the fill.

vii). Truck-Shovel Site J.

A 4.5% settlement was recorded in a backfilled site 24 years old. It is unknown over what time scale these movements have occured. As the site comprised part of a hillside, the land was free draining and not liable to groundwater recovery although infiltration rates would have been significant.

The significance of these results along with those from the previous three chapters is presented in the General Discussion and Conclusions in Chapter 9.

CHAPTER 7.

GROUNDWATER POLLUTION AS A RESULT OF GROUNDWATER RECOVERY IN OPENCAST MINE BACKFILL.

CHAPTER 7. GROUNDWATER POLLUTION AS A RESULT OF GROUNDWATER RECOVERY IN OPENCAST MINE BACKFILL.

7.1 INTRODUCTION.

Opencast mine backfill materials can occasionally contain weathered minerals which are able to react with groundwater to produce a polluting discharge. A notable example which will be discussed in detail in this chapter is the oxidation of pyritic material to form acidic and iron rich, (ferruginous) drainages. On some opencast sites a problems can be created by the inclusion of highly pyritic colliery spoil material within the restored fill.

The resultant polluted waters are low in organic matter and high in dissolved metal salts. pH values from the presence of sulphuric acid may be as low as 2. The environmental and economic effects of these drainages are currently of great concern, and over recent years the legal constraints applied to such discharges have become increasingly severe. In the past, successful prosecutions have been made against mine operators for the pollution of watercourses as a result of emanations from both working and restored opencast mine sites, (Norton 1983).

7.2. GROUNDWATER POLLUTION ASSOCIATED WITH MINING OPERATIONS.

7.2.1 General Water Pollution.

The various types of water pollution may be divided into four categories, namely:

a). Chemical; Organic and Inorganic.

b). Physical; Colour, Turbidity, Temperature, Suspended Solids, Foam, Radioactivity.

c). Physiological; Taste and Odour.

d). Biological; Bacteria, Viruses, Animals and Plants.

Of these it is the chemical forms of pollution which give rise directly to physical and physiological effects that are of greatest importance to the environment.

7.2.2 Chemical Pollution.

a). Organic.

Organic pollutants, (carbon compounds), have three main harmful properties:

i). They interfere with natural water self-purification.

ii). They prevent re-aeration of water forming a thin surface film.

iii). Toxicity.

The natural self-purification of fresh waters consists of the oxidation of organic compounds by aerobic bacteria to form relatively harmless, stable and odourless end products.

Excessive organic pollution causes an exhaustion of dissolved oxygen and most of the organic compounds are then broken down by anaerobic bacteria - utilizing oxygen in the form of nitrates, sulphates, phosphates and organic compounds. Putrefaction results producing end products with bad odours. The reduction in dissolved oxygen levels will also have a serious effect on the fish life within a water course, with many dying at dissolved oxygen levels of 5 ppm or below.

Examples of organic pollutants include fats, soaps, waxes, rubber, coal, oil, phenol, dyes, detergents and cyanides.

b). Inorganic.

Inorganic pollutants can be subdivided into three groups;

i). Acids and Alkalis; These corrode both metals and concrete. They destroy bacteria, fish and other life forms.

ii). Dissolved Toxic Compounds; Free chlorine, ammonia and soluble sulphides are classed amongst many others as dissolved toxic compounds. Heavy metal salts are particularly toxic. As an example concentrations of 0.14 ppm copper sulphate or 0.15 ppm Zinc are enough to kill fish life. Presence of such metals as mercury, arsenic or lead constitutes a serious health hazard.

iii). Soluble Salts; the chlorides, sulphates, nitrates, bicarbonates and phosphates of sodium, calcium, potassium, magnesium, iron and manganese all induce salinity into the water. This salinity kills freshwater life, renders water hard and prevents its use for crop irrigation. Soluble iron and aluminium salts react with the natural bicarbonate alkalinity to form insoluble hydroxide precipitates in natural waters. This phenomena will be considered in detail in sections 7.4 onwards. Table 7.1 specifies the effect of dissolved salts on river usage with specific reference to chloride and sulphate anions.

7.2.3 Physical Pollution.

Physical pollution can manifest itself in one or a combination of the following ways; colour changes, turbidity, temperature, suspended solids, foam or contamination by radioactivity.

a) Colour Changes; A change in the colour of a watercourse is generally the first sign that pollution has occured. Classic examples include the ochreous deposit of iron hydroxide and the effects of kaolin and mica to turn the colour of water to white. Table 7.2 details the effect of dissolved iron concentrations on the colour of a watercourse.

b). Turbidity; Turbidity is caused by collodial dispersion inducing a degree of opacity into the water. The effects are to reduce photosynthesis and once again destroy the basis of the food chain. Deposition of mineral precipitates will rapidly lead to this effect.

c). Temperature; If a discharge is pumped into a water course at a high temperature then this will affect the environment immediately around the discharge point. Cases of temperature pollution are rare and generally unrelated to the

Table 7.1.

Effect of Dissolved Salts on Water Supplies.
(National Coal Board 1982)

Parameter	Max Concentration	Effects
Cl^-	200 mg/l Drinking	Taste, Corrosion
	70-500 Irrigation	Harmful to Crops
	100-200 Industry	Metallic Corrosion
SO_4^{2-}	250 mg/l Drinking	Laxative
	300-3000 mg/l Agriculture	Harmful to Crops

Table 7.2.

Effect of Iron Contamination on Water Courses.
(National Coal Board 1982)

Total Iron Content. ppm	Appearance	Effect on Biology.
0.5	Normal	None
1.0	Visible	Minimal
>5.0	Severe Discolouring	Severe- Food Chain destroyed.

mining industry, possibly be related to power station discharges.

d). Suspended Solids; The classification of suspended solids includes size ranges from fine clays to gravels. Suspended solids akin to turbidity diminish photosynthesis by inducing turbidity as well as smothering benthic organisms. In concentration suspended solids can also damage fish life.

e). Foam; The presence of foam on the surface of a water course is a common and unsightly feature. There have been an increased degree in foam pollution associated with mining owing to the increased use of surfactants in mineral processing plants.

f). Radioactivity; Possible contamination can arise in the use of radioactive tracers. This aspect of pollution is obviously extremely serious and stringent precautions must be taken to prevent uncontrolled radioactive leakage into watercourses.

7.2.4 Physiological Pollution.

Physiological pollution manifests itself in the form of tastes and odours. Table 7.1 has indicated the effects of chloride and sulphide on taste. Dissolved sulphur compounds invariably give rise to the presence of hydrogen sulphide within a water course producing the familiar acrid 'rotten eggs' odour.

7.2.5 Biological Pollution.

A form of pollution which is not associated with the mining industry but is included for completeness. Bacteria and viruses notably anthrax and legionnaires disease can be transmitted through water. The problem is of particular importance in the disposal of sewerage plant effluents.

7.3. LEGISLATION REGARDING WATER POLLUTION.

The legislation regarding the pollution of natural waters by mining effluents has become increasingly stringent over the past few years, with the mine operators being prosecuted and fined on a number of occasions.

Since 1951, all the groundwater pumped off a surface mine has been required to comply with various River Pollution Acts passed in that year. The most recent legislation has been the Control of Pollution Act 1974, designed to bring the law into line with E.E.C. directives on water pollution relevant to fish and drinking water abstraction.

Pumping off surface mine sites requires a discharge consent obtained from either the River Board or Local Authority. A typical example for a Scottish opencast mine is presented in table 7.3. The 1974 Act makes no exemptions to the period of abandonment of a mine and thus makes the operator liable for post-mining pollution.

Table 7.3.

Typical Discharge Consent Condition - Scottish Opencast Mine. (Norton 1983).

- Outlets to be used for discharge of Trade Effluent only.
- Temperature of Discharge must not exceed 30°C.
- Discharge must not contain more than 30 mg/l Suspended Solids.
- Discharge must not contain more than 5 mg/l Total Iron.
- pH to be maintained between 5 and 9.
- The effluent shall not contain any visible signs of oil or grease or any matter to such an extent to cause the receiving water to be poisonous or injurious to fish, fish spawn or the food of fish.

7.4. ACIDIC AND FERRUGINOUS DISCHARGES.

7.4.1. Introduction.

Iron and Sulphur minerals are widespread within coal bearing strata. Pyrite, (FeS_2) and Siderite, ($FeCO_3$) are typical sources. A severe water pollution problem in the opencast mines of Scotland has arisen from the presence of ironstone bands associated with the excavated strata, (Norton 1983, Henton 1981).

7.4.2. The Effects on Environment of Acid and Ferruginous Discharges.

The most obvious effect of an acid discharge is the deposition in a watercourse of ferric hydroxide, ($Fe(OH)_3$). The rate of hydroxide deposition is enhanced by the presence of neutral ferrous oxidising bacteria in the natural waters which oxidise ferrous salts and trap the precipitated ferric hydroxide to form a slime blanket in the bed of the affected stream around the discharge point. This blanket engulfs the plankton and micro-organisms which form the basis of the natural food chain. Fish are particularly affected by acidity with natural breeding cycles being affected at pH values lower than 5, (Scullion and Edwards 1980).

7.5. MECHANISMS OF ACID AND FERRUGINOUS WATER PRODUCTION.

7.5.1. General Mechanism.

The formation of acid mine waters occurs when sulphide minerals within the excavated strata are exposed to the atmosphere. Oxidation of these minerals has been shown to be bacterially catalysed, (Atkins and Pooley 1982). In general the pyritic material in the presence of oxygen oxidises to form a series of soluble hydrous iron sulphates. These commonly appear as yellow or white crusts on weathered rocks. When natural waters flow over these salts, hydrolysis occurs to form acidic drainages of high sulphate and ferrous iron concentrations. The ferrous iron may be subsequently oxidised to the ferric state complexing with ferrous and ferric oxyhydroxides which impart deep red and yellow colours characteristic of acidic drainages.

7.5.2. Bacterial Catalysis.

The oxidation of iron pyrites has been shown to be catalysed by micro-organisms termed iron bacteria, (Atkins and Singh 1982, Rawat and Singh 1982). Three bacterium are of importance:

i). Thiobacillus Thiooxidans.

ii). Thiobacillus Ferrooxidans.

iii). Ferrobacillus Ferrooxidans.

These bacteria are rod shaped, with rounded ends, varying from between 1.2 and 3.2 microns in length and from 0.51 to 1.25 microns in breadth, (Lau et al 1970). Oxidation may occur by either a direct or an indirect method, (Atkins and Singh 1982).

a). Direct Mechanism.

The direct mechanism entails the bacteria utilising sulphur and/or ferrous ions contained within the mineral as an energy source. The generally accepted formulae are as follows;

$4FeS_2 + 15O_2 + 2H_2O \xrightarrow{b} 2Fe_2(SO_4)_3 + 2H_2SO_4$ (7.1)

or

Pyrites + Oxygen + Water $\xrightarrow{b}$ Ferric Sulphate + Sulphuric Acid

where —b—› denotes bacterial catalysis.

b). Indirect Mechanism.

In this mode of formation, the ferric ions are considered to be the primary oxidant. The chemical procedure is as follows;

$FeS_2 + 7Fe_2(SO_4)_3 + 8H_2O \longrightarrow 15FeSO_4 + 8H_2SO_4$ (7.2)

$2FeSO_4 + H_2SO_4 + 1/2O_2 \xrightarrow{b} Fe_2(SO_4)_3 + H_2O$ (7.3)

The following may also take place;

$FeS_2 + Fe_2(SO_4)_3 \longrightarrow 3FeSO_4 + 2S$ (7.4)

$2S + 6Fe(SO_4)_3 + 8H_2O \longrightarrow 12FeSO_4 + 8H_2SO_4$ (7.5)

In this mechanism equation 7.5 is considered to be rate determining. Elemental sulphur may also be oxidised by bacteria as follows:

$$S + 3/2O_2 + H_2O \text{ — b } \longrightarrow H_2SO_4 \qquad (7.6)$$

c). **Formation of Surface Coatings.**

As ferric sulphate has a limited solubility, the compound hydrolyses to form a basic ferric precipitate;

$$3Fe_2(SO_4)_3 + 12H_2O \longrightarrow 2HFe_3(SO_4)_2(OH)_6 + 5H_2SO_4 \qquad (7.7)$$

Dependent on the acidity of the containing medium, the most commonly observed compounds formed are goethite, FeO(OH) at pH<2 and jarosites, $KFe_3(SO_4)_2(OH)_6$ at pH<1.5. The presence of these compounds may actually hinder further reaction and this concept is discussed in section 7.6.

Lau et al (1970) indicated that in the complete oxidation of iron pyrites, micro-organisms conduct a two-fold function. Firstly they secrete a phospholipid type wetting agent to remove elemental sulphur formed chemically on the surface of the sulphide particles. Secondly the bacteria directly participate either by using extra cellular enzymes or by membrane diffusion to oxidise elemental sulphur to sulphuric acid.

The mechanism of acid and ferruginous formation is a matter of debate amongst many investigators, (Singer and Stumm 1968). Some authors suggest that the rate determining step in the oxidation of pyrite is the oxidation by ferric ions rather than by oxygen itself. Others dispute this fact by stating that the oxidation of the ferric ion is dependent on ferrous:

ferric ion ratios. Under normal conditions, the ferric iron mechanism has been found to be only one third of the rate of pyrite oxidation by oxygen. It is thus concluded that the oxidation of the ferrous ion is not rate determining. Which ever is the correct mechanism, if in fact one is totally correct, it is indisputable that the reaction once initiated is self-catalysing. It is considered that if the pH of affected waters falls to below 4.5 then all the acid soluble iron compounds will become available for reaction, (Henderson and Norton 1984). Contrary to this, if pH values rise above 5 then the reaction is severely inhibited.

The red, ochreous deposit of iron hydroxide previously mentioned as a classic effect of such drainages forms as a result of the dilution of ferric sulphate in a natural water course. The mechanism can be described by the following equation;

$$Fe_2(SO_4)_3 + 6H_2O \longrightarrow 2Fe(OH)_3 + 3H_2SO_4 \qquad (7.8)$$

Thus the final products of the reaction consists of ferric hydroxide precipitate and sulphuric acid.

7.6 FACTORS AFFECTING THE RATE OF BACTERIAL CATALYSIS.

7.6.1. Introduction.

The factors which affect the rate of bacterial leaching can be summarised as follows, (Atkins and Singh 1982, Granger 1984).

a). pH.

b). Oxygen and Carbon Dioxide Concentrations.

c). Temperature.

d). Bacterial Concentrations.

e). Nutrients.

f). Particle Sizes.

g). Mineralogical Factors.

h). Metal Tolerances.

i). Secondary Mineral Formation.

j). Pressure and Light.

7.6.2 Effect of pH.

The effect of pH on the rate of desulphurisation by Thiobacillus Thiooxidans is shown in figure 7.1. The rate of desulphurisation can be observed to be at its peak in pH ranges of 2.5 to 3.5. Above a pH of about 4 the reaction rate begins to fall off dramatically.

Waters emerging from old workings into the fill of a backfilled site are of particular significance as these may be of acid character already, thus forming an ideal environment for the initiation of the acid forming reaction. The degree of calcareous material within the fill is of importance as these may supply alkaline waters which will aid in the suppression of microorganism activity.

7.6.3. Oxygen and Carbon Dioxide Concentrations.

Oxygen is of vital importance to the reaction mechanism.

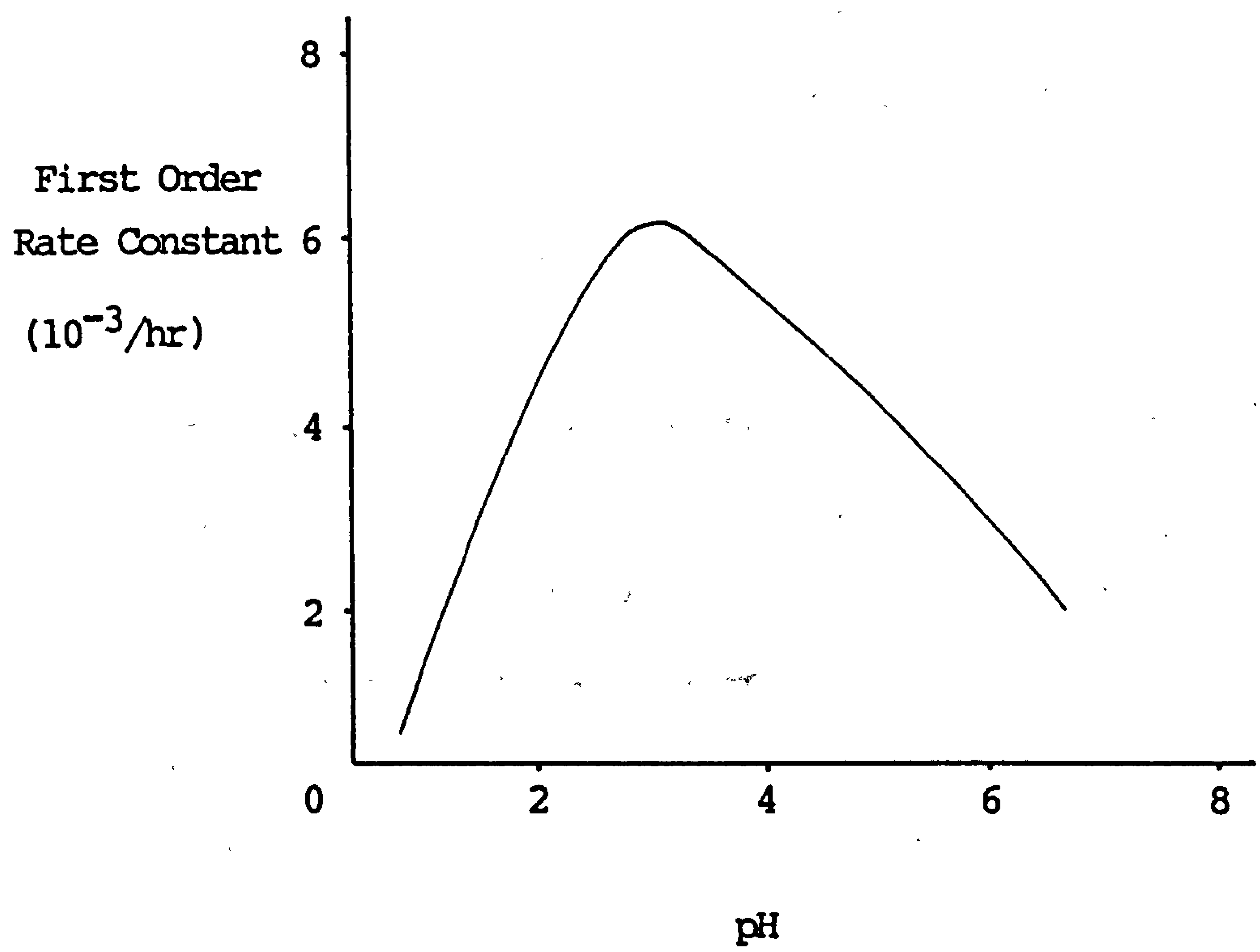


Fig 7.1 Effect of pH on Desulphurisation, (after Granger 1984).

The rate of reaction is dependent on the quantity of oxygen available to the surface of the active pyrite. Kim, (1968) states that the rate of oxidation is directly proportional to the partial pressure of the oxygen gas, i.e,

$$\text{Oxidation} \quad p(O_2)^{3/4}$$

The exclusion of oxygen from a reacting mixture is thus considered a useful control against the production of acid waters. Carbon dioxide acts as the principal source of carbon for cell growth for the micro-organisms. The exclusion of this gas would seriously inhibit microbe activity. Carbon Dioxide solubility is low in acid conditions and this could well be a reaction limiting factor.

7.6.4. Temperature.

Each individual bacterial strain have their own optimum working temperatures. For the iron bacterium the maximum rate of desulphurisation can be recorded at 28 °C at a pH of 2.3. Above 30 °C the rate deteriorates rapidly. The trends are illustrated in figure 7.2. Temperature ranges for bacterial activity can be extreme, (Granger 1984). Iron bacteria activity has been detected at 4 C in Canada and thermophilic type bacterium can exist between 60 and 80 °C.

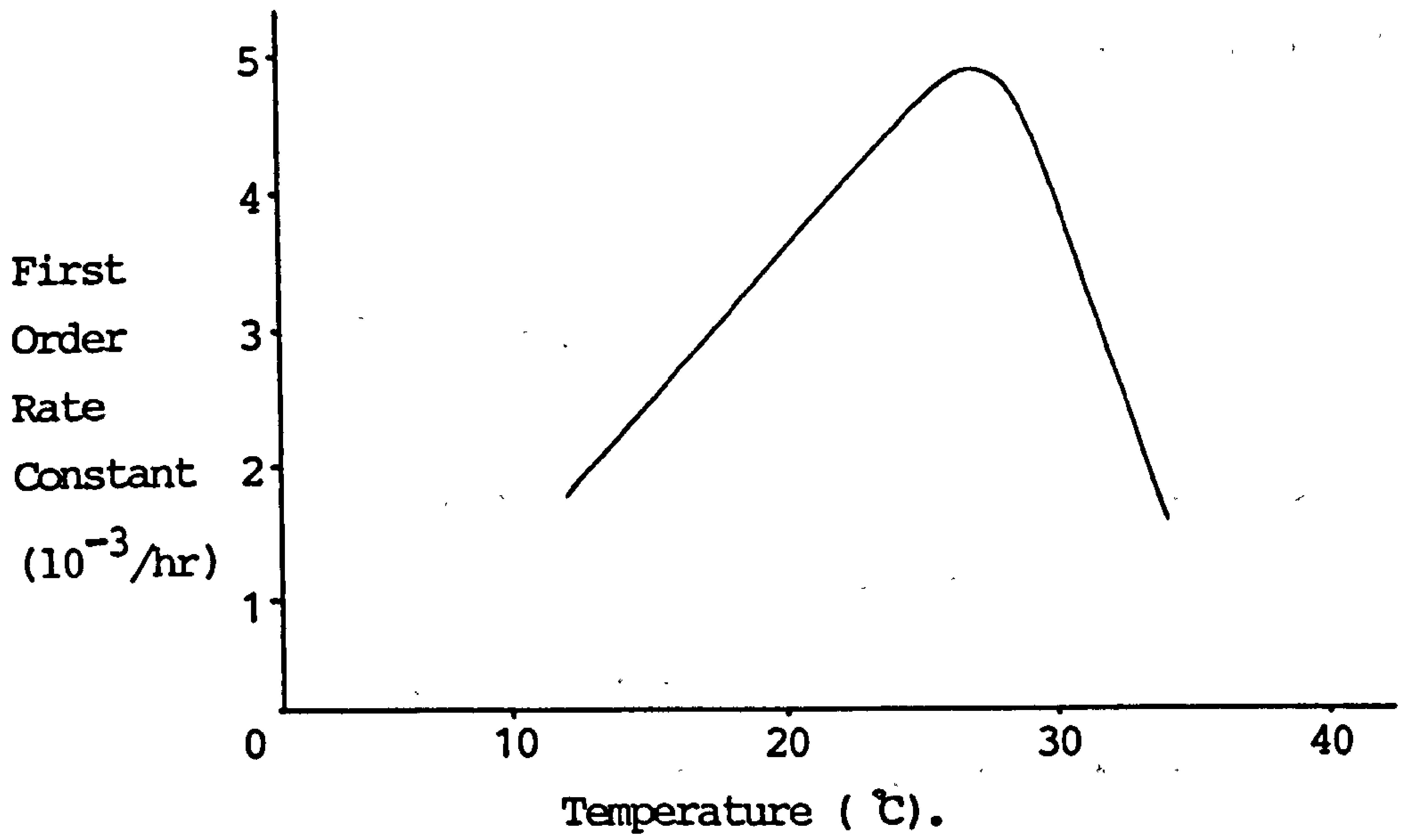


Fig. 7.2 The Effect of Temperature on the Rate of Desulphurisation.
(After Granger 1984).

7.6.5. Cell Concentrations.

Figure 7.3 illustrates the effect of bacterial cell concentrations on reaction rates. Rates of desulphurisation can be seen to increase sharply in the range of 10^8 to 10^9 cells/ml.

7.6.6. Nutrients.

All bacteria require a certain nutrient requirement in order to allow the cells to function properly. Nitrogen, phosphorus, sulphur and magnesium are all essential for the growth of thiobacillus ferrooxidans. Magnesium is necessary for the fixation of carbon dioxide and phosphorus is required for energy metabolism. Sulphur is important in the form of sulphur containing amino acids, but by far the most important nutrient is nitrogen.

Thiobacillus ferrooxidans bacteria are able to fix their own nitrogen as well as exchange carbon for nitrogen with heterotrophic bacteria. It is interesting to note that researchers have shown that significant nitrogen concentrations can actually hinder the reaction mechanism, (Kim 1968). This is may be due to reductions in oxygen and carbon dioxide concentrations rather than the presence of nitrogen.

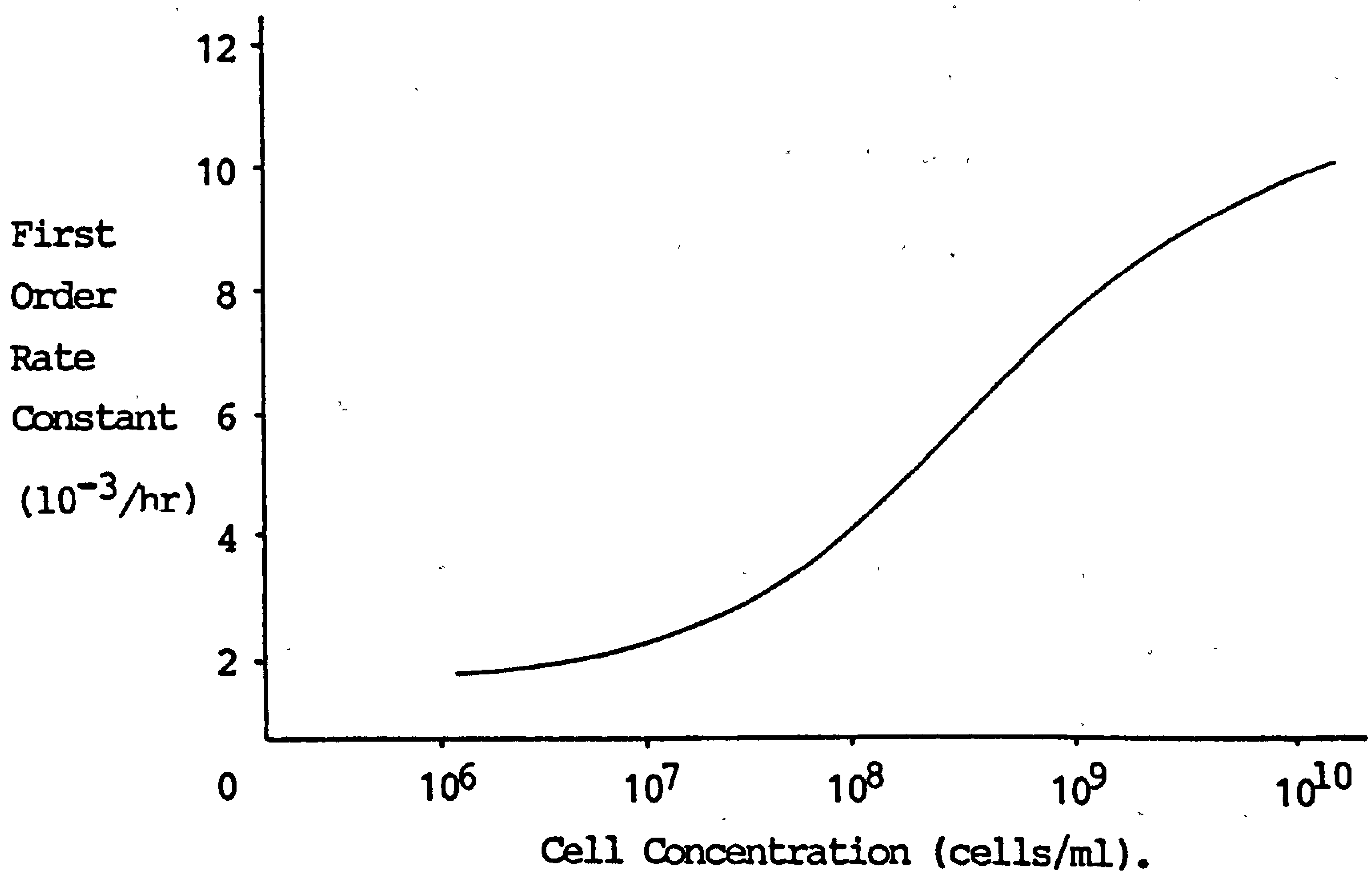


Fig. 7.3 Effect of Cell Concentrations on the Rate of Desulphurisation. (After Granger 1984).

7.6.7. Particle Size.

The size of an individual pyrite particle has been shown to be of extreme importance in determining oxidation rates, (Atkins and Singh 1982, Atkins and Pooley 1982, Caruccio 1970.) In general it has been found that the finer grained pyrites are much more reactive than their coarser grained counterparts. Figure 7.4 illustrates the effect of particle sizes on bacterial leaching rates.

7.6.8. Mineralogical Factors.

Many investigators involved in bacterial sulphide oxidation have observed that different specimens of the same material can react at appreciatively different rates under the same conditions. This is due to differences in particle mineralogy. The gangue material associated with sulphide minerals can also influence bacterial leaching rates, particularly in the presence of acid consumable materials.

7.6.9. Metal Tolerance.

Iron bacteria have a high tolerance to metals as compared with other micro-organisms. Detrimental metals include mercury, copper, nickel and uranium. Caruccio (1972) states that stable pyrites were found to contain significant quantities of titanium.

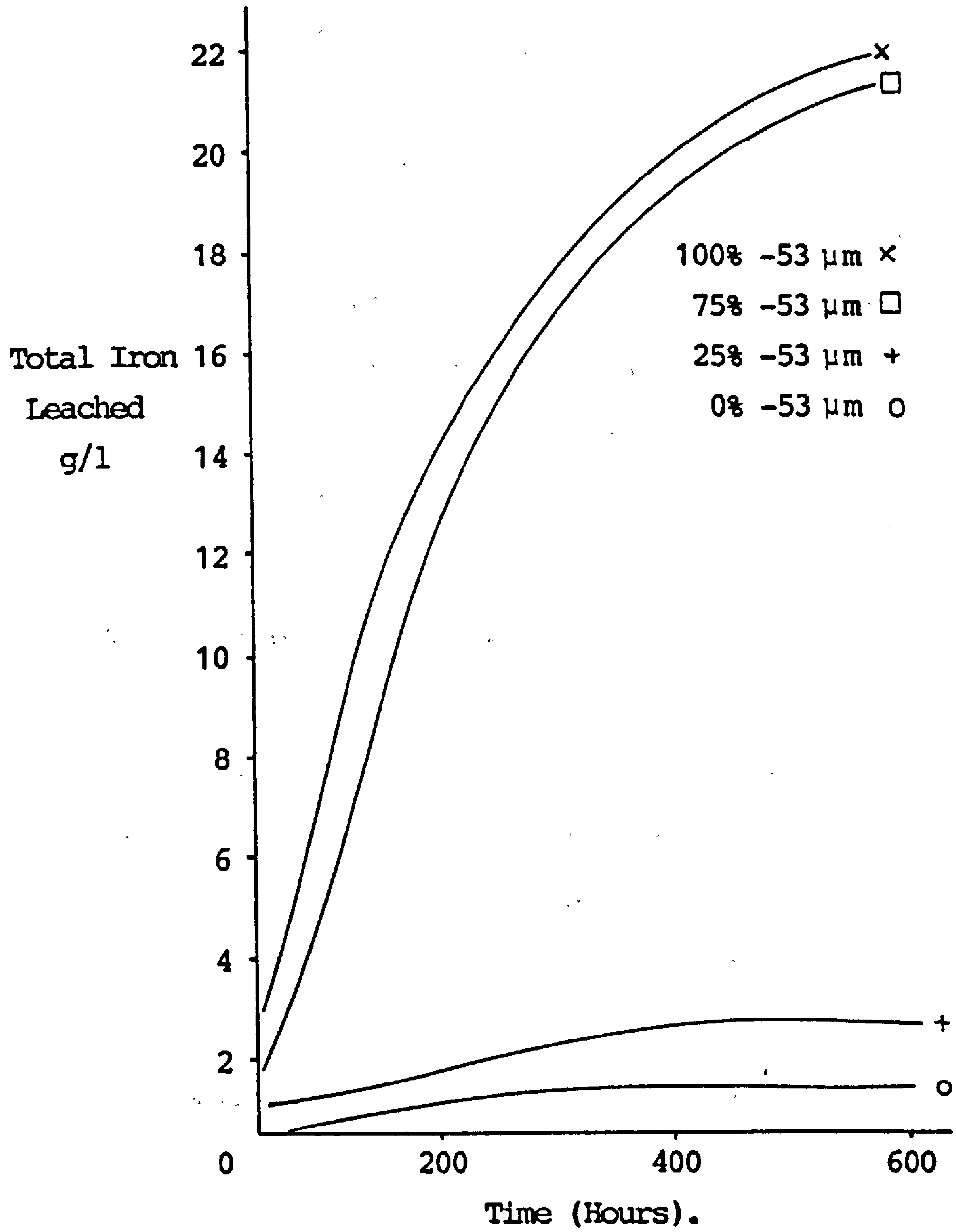


Fig. 7.4 Effect of Pyrite Particle Size on Bacterial Leaching Efficiencies. (Atkins and Singh 1982).

Percentages refer to degree of sample less than 53 μm.

7.6.10. Secondary Mineral Formation.

It has been noticed that solids may dissolve and then precipitate from solution as some other compound. The formation of goethites and jarosites have been mentioned in section 7.5.2. These minerals and others like them can form an unreactive protective coat on the surface of the pyrite particle inhibiting further reaction.

7.6.11. Pressure and Light.

The effect of pressure on the leaching process is at present unevaluated. Both visible and unfiltered light can have an inhibitory influence upon some strains of iron bacteria, notably towards the blue end of the spectrum.

7.7. THE EVALUATION OF ACID MINE LOADS.

7.7.1. Introduction.

This section examines methods for assessing polluting chemical loads which may emanate from a backfilled surface mine. A prediction of the maximum and minimum chemical loads may be made using laboratory techniques. The use of simulated weathering tests extends to the theory of degradation by attempting to model the actual field situation.

7.7.2. Laboratory Analyses.

Strata cores from initial site investigation drilling are useful in order to assess individual strata sections for acidity or alkalinity. Henderson and Norton (1984) suggest a method for determining the acid producing capacity and acid neutralising capacity for individual rock horizons.

The technique assesses pH values, moisture contents, acid neutralising capacity (ANC), Pyritic, Organic and Total Sulphur contents. Laboratory tests conducted upon coal measure rocks showed that sulphate contents were consistently low, 0 - 0.06%, and that these could be neglected if the total sulphur content of the rock type was less than 0.5%. The ratio between pyritic to organic sulphur was found to be 10:1 and thus it may be assumed for British opencast coal reserves that:

Pyritic Sulphur = 0.9 x Total Sulphur.

The overall results supply the following information on the rock strata within any one borehole;

a). The Maximum Theoretical Acid Production; this assumes that alkali contents within the rock have no neutralising effect, ie ANC=0.

b). The Minimum Theoretical Acid Production; assuming that the ANC is maximum.

The assumptions of the method are as follows;

o All Pyritic Sulphur is oxidised to Sulphuric Acid.

- o Average results are taken in proportion to sample thickness.
- o Pyritic Sulphur = Total Sulphur x 0.9.
- o Specific Gravity of the minerals are ignored.
- o No allowance is made for simulated weathering, ie the way reactions occur in the field.

7.7.3. Simulated Weathering Tests.

Simulated weathering tests are used to assess the chemical weathering attributes of strata collected from cores of overburden. The method attempts to introduce simulated field conditions specifically accounting for differences in reactivity between acid and alkaline strata.

Caruccio et al (1980) define a unit column of overburden thickness and assumes that at least 1% of the rock decomposes to a size fraction which is then utilised in the weathering test. A qualitative estimate of a minimum acid load can thus be evaluated. Extrapolating simulated weathering test data to areal distributions within a mine site, as identified by strata cores will provide a quantitative assessment. It may be of considerable importance to alert the mine operator to the possibility of a pollution hazard, especially to identify acid and alkaline materials within the overburden mass.

7.7.4. Leaching Tests.

Samples of rock of a suitable size fraction, (<4mm), are placed in an inert plastic chamber. The atmosphere within the chamber is continually purged with a humidified air flow and the sample is allowed to oxidise. An attempt is made to simulate conditions within an opencast mine site, (Caruccio and Geidel 1980).

Periodically, every 3 to 5 days the sample in the chamber is rinsed with deionised water, and the products of weathering are dissolved and collected as a leachate.

Weathering products derived from the oxidation of pyrite are readily soluble forming an acid leachate. The dissolution of calcareous material however takes place at a slower rate, and as a result the alkalinity produced during the time that the rinse water is in contact with the sample is much lower than would be expected under equilibrium conditions. Alkalinity is derived primarily from capillary and funicular water that was retained by the solid from the previous rinse. This water remains in contact with the calcareous material and with time approaches saturation with respect to calcium and magnesium carbonates. The subsequent rinse flushes out the alkaline capillary water and dilutes the entrained alkalinity. As a result alkaline loads cannot be calculated from leaching test data. Acid loads can be calculated from the leachate volume and quality, in addition to the weight of the sample under test.

The influence of acid water on the spoil material can be analysed if waters of different chemistries are used instead of deionised water. A system arrangement as illustrated in figure 7.5 could be utilised to do this.

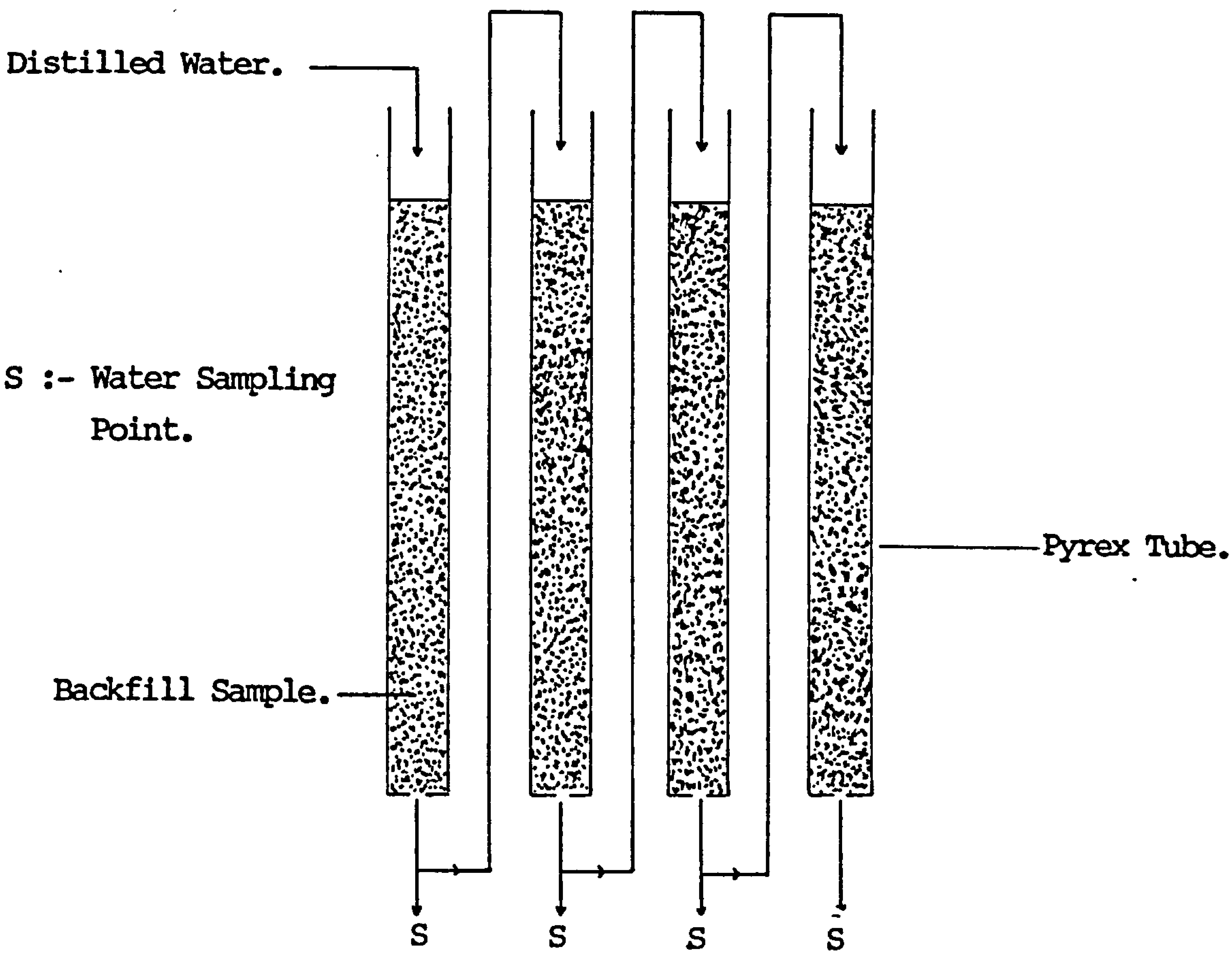


Fig 7.5 Experimental Apparatus for the Monitoring of the Effects of Different Water Chemistries on Rates of Backfill Leaching.

7.7.5. Bacterial Leaching Tests.

Column testing of a similar nature to that described in the previous section can be utilised with the addition of iron bacterium ensuring that the reaction is catalysed at the maximum rate. The method will give the maximum acid load from that particular piece of spoil in the shortest possible time.

7.7.6. Evaluation of Laboratory Test Results.

The prediction of drainage quality from overburden analyses may be rendered meaningless without accounting for a number of other important variables:

- o Kinetics of Acid/Alkali Release.
- o Groundwater Geochemistry.
- o Rain Quality.
- o Arrangement of Backfill, whether blended or segregated.
- o Mine Site Hydrology.

Overall the use of laboratory methods to predict the likliehood of acidic or polluting drainages would appear to be a convenient technique.

7.8. METHODS FOR THE PHYSICAL AND CHEMICAL ANALYSIS OF MINEWATERS.

7.8.1 Colorimetric Determinations.

The presence of many metal ions can be determined in a mine water sample by analysing the intensity of the colours that these ions can produce when reacted with suitable reagents. Colorimetric determinations rely on the fact that the more intense a specific colour in solution is, then the greater the concentration of the particular ion is present.

Colorimetric determinations require either a colorimeter or a spectrophotometer. In the colorimeter, a coloured filter absorbs most of the light and transmits only a narrow wave band which includes the required colour. The filter may be changed to suit the analysis. In the spectrophotometer, the light beam is dispersed by a grating or prism into a rainbow coloured strip from which the required spectral range is selected through a narrow slit by mechanically rotating the prism, thus sweeping the spectrum across the slit. The light beam may be modulated or ´chopped´ to reduce interference and drift, the more expensive instruments employing a double beam. The spectrophotometer allows one to select a narrower spectral range than the colorimeter so that interferences are reduced, but it requires a sensitive detector and is mechanically more demanding and thus more expensive.

7.8.2 Flame Emission Determinations.

In the Flame Emission method the sample solution is sprayed into a flame of a carefully controlled character. The ground state atoms absorb thermal energy and some electrons are raised to a higher energy level. A proportion fall back to a lower state releasing energy as a light of a characteristic wavelength, for example the yellow emission of sodium. In this work, the flux of the emitted light is measured and can be related to the concentration of the ion in the solution.

7.8.3 Determination of Conductivity.

Conductivity of water samples is a measure on the total concentrations of dissolved solutes in those samples. Differences in conductivity are reflections of differences in concentrations but also of differences in the nature of the solutes and temperature. Conventionally results are expressed with respect to 20 or 25 C. Testing is performed using a conductivity meter. The principle of such a meter is to measure the conductance of water between two rigidly mounted parallel plates of platinum or carbon. The conductance is also directly proportional to plate area and inversely proportional to plate separation.

Most instruments consist of a low voltage alternating current generator feeding a Wheatstone Bridge network, of which the test cell forms an arm. Battery operated instruments are available for field testing.

There are several satisfactory commercial models which in addition to the basic meter require a large water bath with racks in which test tubes can be kept at a constant temperature. Large Borosilicate test tubes are convenient for holding the samples. Soda glass tubes are unsuitable in soft water owing to ion exchange processes which occur. The reagents which are required are as follows;

Water; Freshly distilled and protected from CO_2 and SO_x. The conductivity of this water must be less than 2 μScm^{-1}. Potassium Chloride, (KCl), 0.01M. :- made up from 0.7456g of KCl in freshly boiled, CO_2 free water with a conductivity <2 μScm^{-1}, made up to 1000 ml.

The water should be maintained at 25 C, and if a check is being made on a complete analysis then the best procedure is to measure initially approximately and then dilute the sample so that the conductance will be around 100 μScm^{-1}. The conductance cell must have been placed in the water bath at 25 C.

Four tubes of standard KCl solution are placed in the water bath along with two samples and left for thirty minutes to allow for thermal equilibrium to be established. The standard KCl solutions must be such that their conductivity differs by less than a factor of five from the samples being tested. The testing cell is then rinsed with three of the KCl samples and the conductance is measured of the fourth. The cell is then rinsed with the first of the samples and the conductance of the second measured.

7.8.4 Laboratory pH measurement using a pH meter.

The laboratory pH meter consists of two electrodes, one glass and one calomel. A KCl salt bridge links the calomel electrode to the sample. Combined glass and reference electrodes can be obtained including the salt bridge. The reference junction is normally Ag-AgCl. Before measuring the pH of the test sample, the electrodes are washed with distilled water and then with the sample. Readings are then taken as described in the relevant instrument handbook. It is important to make readings with unstirred solutions to prevent the loss of carbon dioxide which would alter pH values.

7.8.5 Total Alkalinity and Phenolphthalein Alkalinity.

The concentrations of CO_3^{2-} and OH^- are determined by acid titration to pH of about 8.3, the end point being detected by phenolphthalein indicator. Concentrations of HCO_3^- are determined by further titration with acid to an end point pH of between 4.2 and 5.4, with methyl orange or mixed indicator as the end point detector. Table 7.4 indicates the various forms of alkalinity and their ion components.

7.8.6 Determination of Suspended Solids.

The determination of suspended solids content necessitates the filtering of the water sample. The filtrate is then dried to constant weight at 105 C.

Table 7.4

Summary of Types of Alkalinity.

Quantity	Symbol	Anions	End Point pH.
Phenolphthalein Alkalinity	PA	$OH^- + CO_3^{2-}$	8.3
Total Alkalinity	TA	$OH^- + CO_3^{2-} + HCO_3^-$	4.2 to 5.4
Carbonate Alkalinity	CA	$CO_3^{2-} + HCO_3^-$	
Total CO_2	TC	$CO_3^{2-} + HCO_3^- + CO_2$	

7.8.7 Determination of Major Ions.

The methods for the determination of the major cations, sodium, calcium, magnesium, iron, aluminium, manganese and anions chloride and sulphate are summarised in table 7.5. Detailed chemical procedures are presented in Appendix 2.

7.9 CONTROL METHODS FOR THE PREVENTION OF POLLUTION FROM BACKFILLED SURFACE MINE SITES.

7.9.1. Basis for Design.

The basis for the design of contol measures against polluting discharges is the inhibition of the pyrite oxidation mechanism. This can be direct, i.e. bacteriacides or indirect by controlling oxygen and water access to the polluting strata. Measures can either be preventative or in cases where a pollution problem already exists, remedial.

7.9.2. Preventative Measures.

Preventative methods for avoiding the formation of polluting discharges include the following;

a). Water Diversion.

b). Compaction of Fill.

c). Surcharge of Less Permeable Fill on Restored Surface.

d). Selective Overburden Placement.

Table 7.5

Summary of Methods for Determining Major Ion Concentrations

Ion		Classification of Method.	Summary
Sodium	Na^{+}	Flame Photometric	
Potassium	K^{+}	Flame Photometric	Direct comparasion against Standard Solution.
Calcium	Ca^{2+}	Flame Photometric	
Magnesium	Mg^{2+}	Titrimetric	Titrate for Total Hardness and correct for Calcium.
Iron	Fe^{2+} and Fe^{3+}	Spectophotometric	Reaction with O-Phenanthroline. Absorbance taken 510 nm, compared with standards.
Manganese	Mn^{2+}	Spectrophotometric	Reaction with Ammonium Persulphate. Absorbance taken at 525 nm, compared with standards.
Aluminium	Al^{3+}	Spectrophotometric	Reaction with Eriochrome Cyanine R. Absorbance taken at 535 nm, compared with standards.
Sulphate	SO_4^{2-}	Gravimetric	Precipitation of Barium Sulphate, ignited then weighed.
Chloride	Cl^{-}	Titrimetric	Silver Nitrate titration. Potassium Chromate indicator.
Total Nitrogen	NO_T	Spectrophotometric	Absorbance measured at 220 nm. Corrected for organic interference at 275 nm. Compared with standards.

e). Limestone Placement.

f). Biological Inhibition.

a). Water Diversion.

This method entails the deflection of surface water away from a mining excavation/backfilled mine site, by the use of surface drainage ditches around the periphery of the mine. The water is then discharged away from the mine site with normally no treatment required.

b). Fill Compaction.

The compaction of backfill into thin layers during the backfilling process produces a waste with a much lower degree of permeability. This restricts not only the quantity of water that may pass through the fill in a given time, but also the quantities of oxygen and carbon dioxide that the fill holds to perpetuate the acid forming reaction. Water flow rates are reduced, so there is an increase in contact time between weathered rock strata and water.

c). Fill Surcharges.

The final restored surface is recontoured to induce springs at selected places on the mine site using a surcharge of a less permeable fill material. The flow rate and volume through the backfill can be controlled by inducing springs to emerge outside of the restored mine area. The technique is illustrated in figure 7.6.

d). Selective Overburden Placement.

Any material within an overburden of particular polluting ability may be segregated within the backfill and sealed off from water by clay caps. It is obviously desirable to have the clay available at the mine rather than having the expense of importation, (Miller 1981). The clay cap is intended to divert the water from the material and should be constructed from a smectite type clay which will expand and contract on the processes of drying and wetting, to create a formation which tends to be impermeable when wet. If the clay source is dry then it must be irrigated in order to achieve an optimum water content of 14.6% by weight. The clay should cover the material in an umbrella shade fashion, (figure 7.7), and must be thick enough to withstand any rupture especially in the case of dragline spoiling. The noxious overburden must be buried deep enough to prevent any future contact with the surface environment and should also be positioned above the level of the anticipated restored water table.

e). Clay Seals.

On opencast mine workings in the United Kingdom it is a stipulation that old deep mine workings must be sealed by clay seals. This operation has two effects, principally water

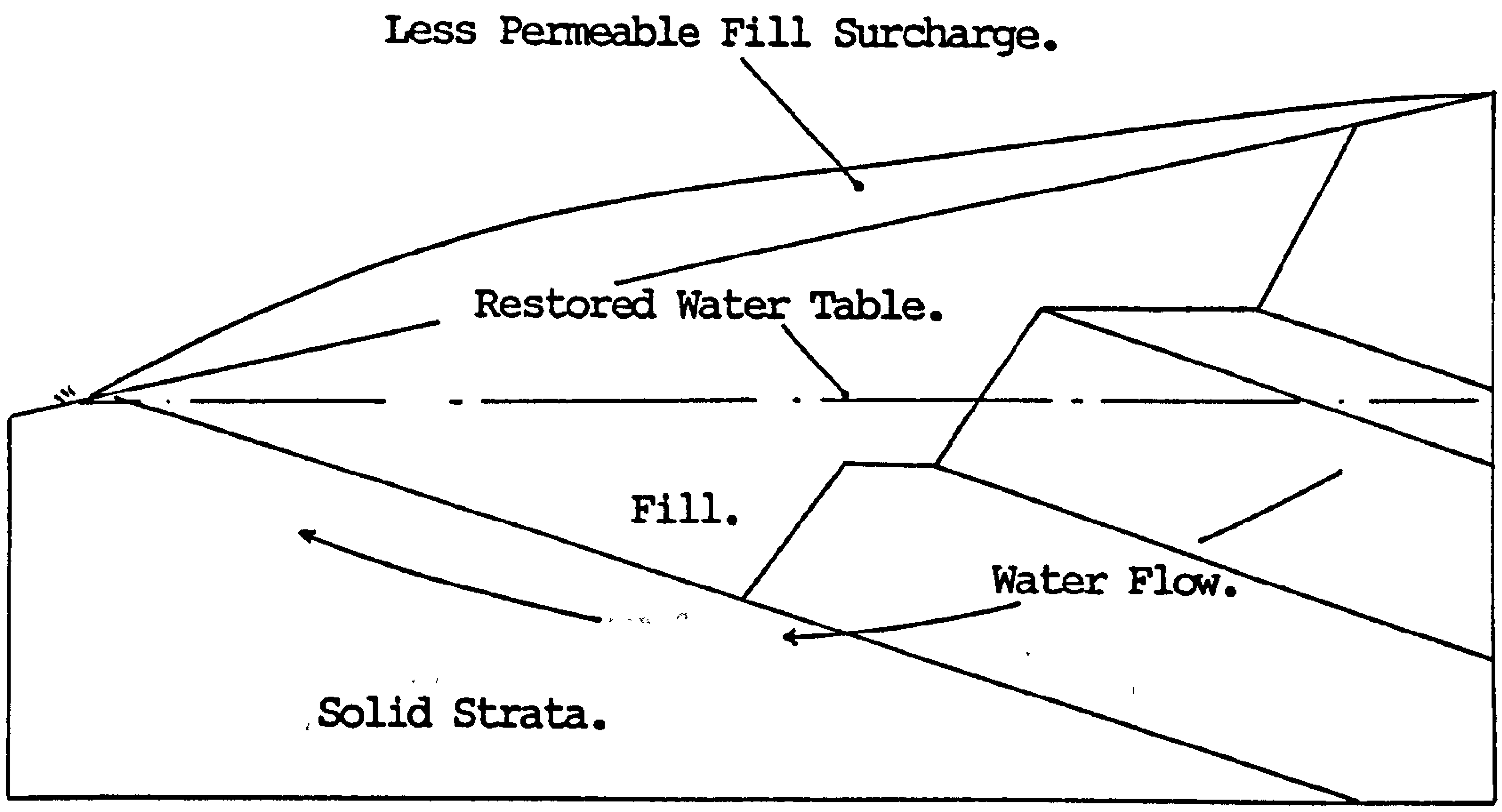


Fig.7.6 Prevention of Groundwater Pollution by the application of Fill Surcharge. (Norton 1983).

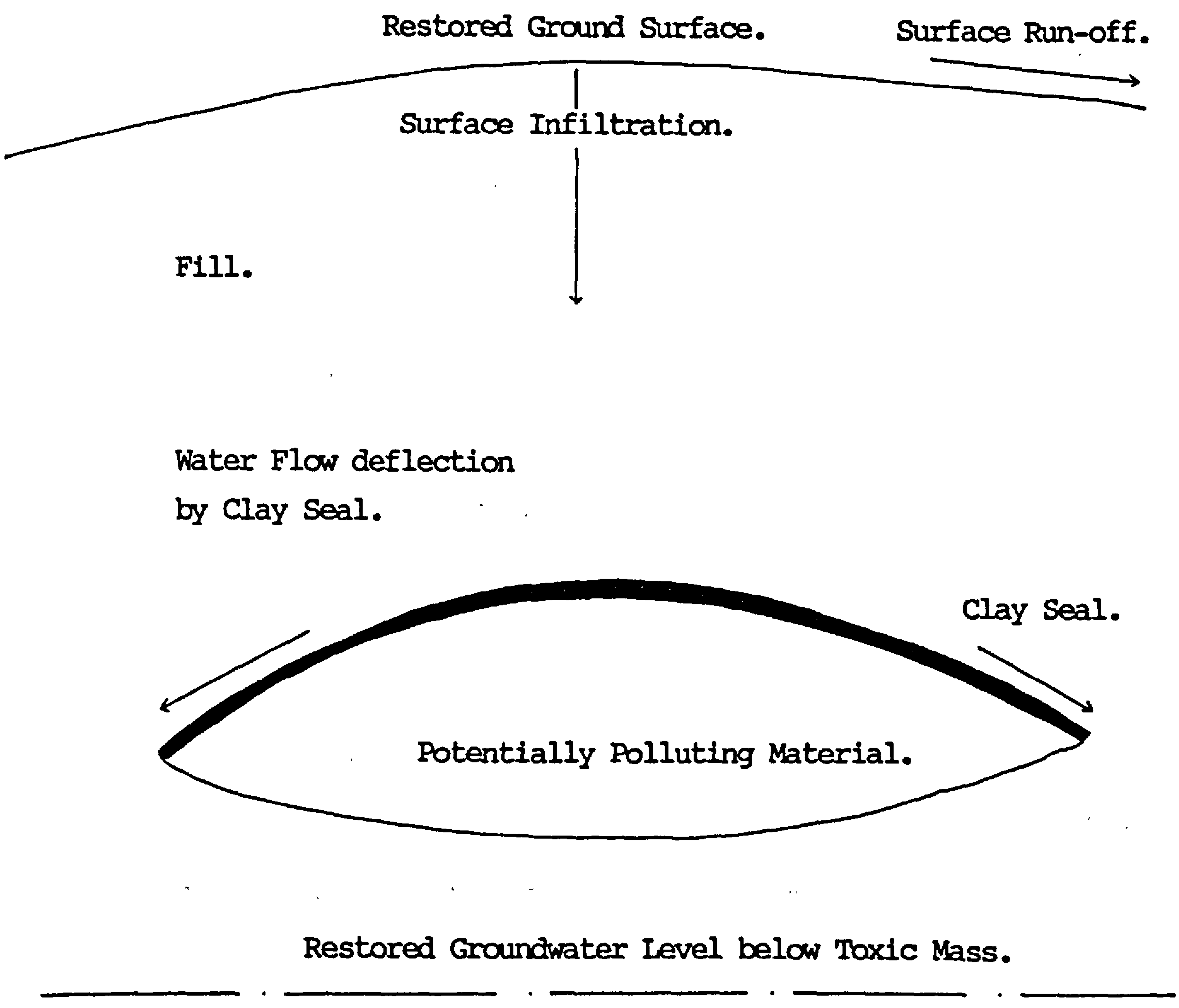


Figure 7.7 Selective Overburden Placement (Miller 1981)

cannot drain into the deep mine workings and come into contact with current extraction and secondly water cannot enter from the deep mine workings into the surface mine. This 'deep mine' water may have acid and ferruginous characteristics. Clay seals can also be used in a restoration programme to prevent water entering into a surface mine backfill, especially in cases of mines with impermeable fireclay floors. The design of clay seals are illustrated in figure 7.8.

f). **Limestone Placement.**

The alkaline nature of limestone not only inhibits the acid producing reaction but can neutralise, partially at least any acid which naturally occurs in the mine waters. The most effective limestones have been found to be those which approach pure calcium carbonate in composition. Stones with a relatively low calcium content but contain calcite and have a high surface area are equally effective. Magnesites are the least effective followed closely by dolomitic limestones, (Geidel 1980, Calhoun 1968, Ford 1970). The application of limestone into a backfill can occur in two ways as illustrated in figure 7.9.

a). Interbedding of limestones with alternate layers of fill.

b). Placement of bulk limestone at surface.

The prediction of limestone quantity is of considerable importance. This prediction may be made following an analysis of strata or backfill cores using simulated weathering tests.

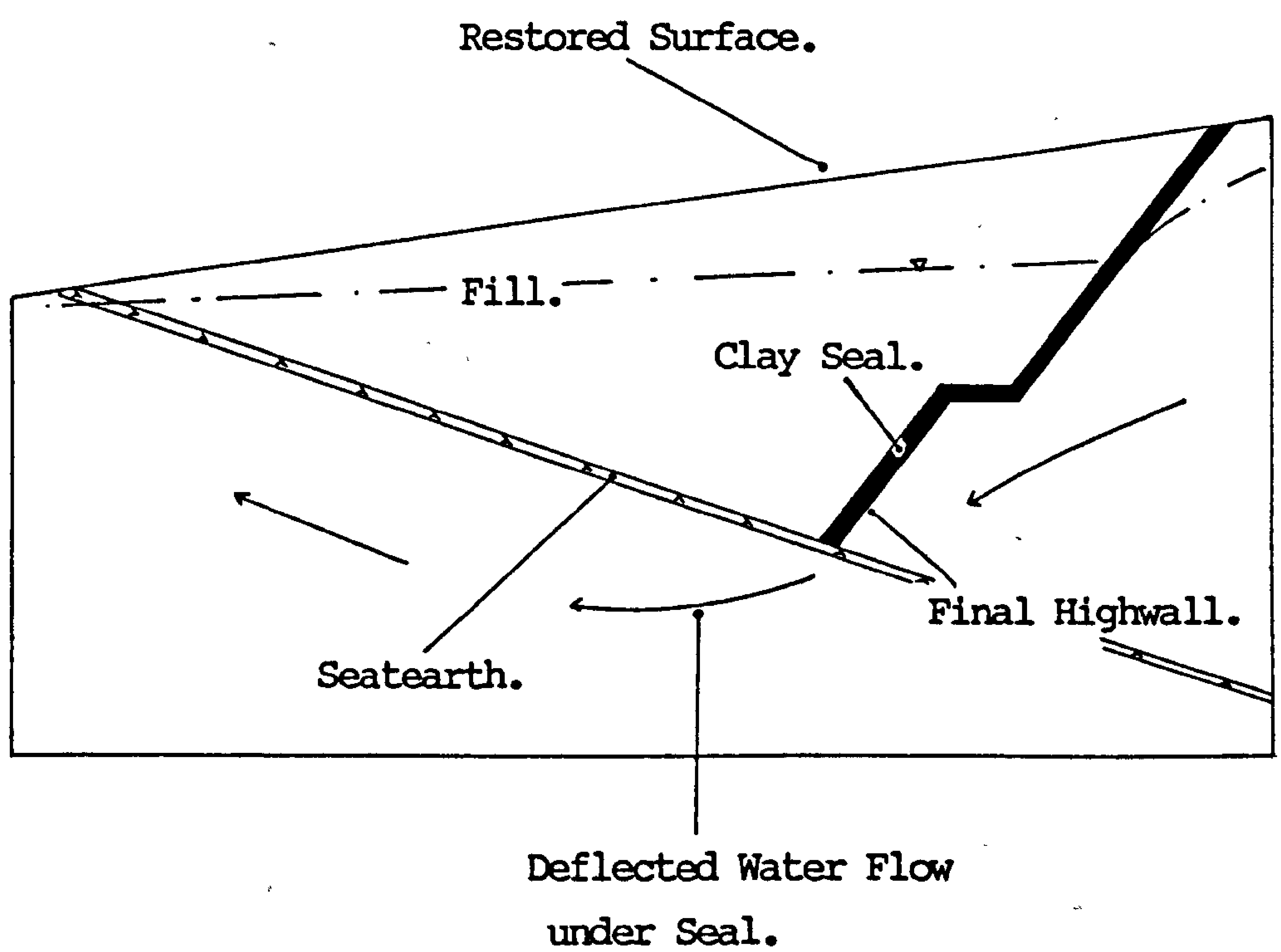
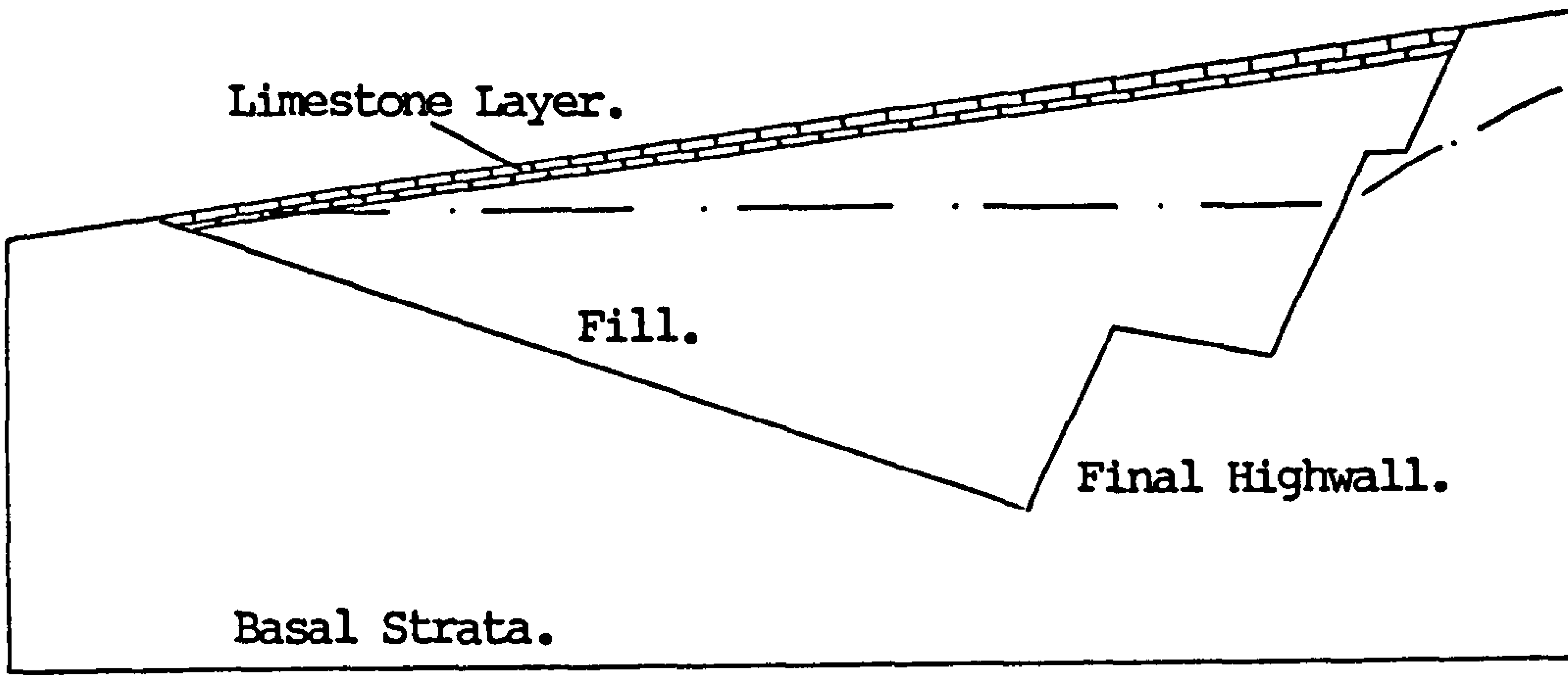
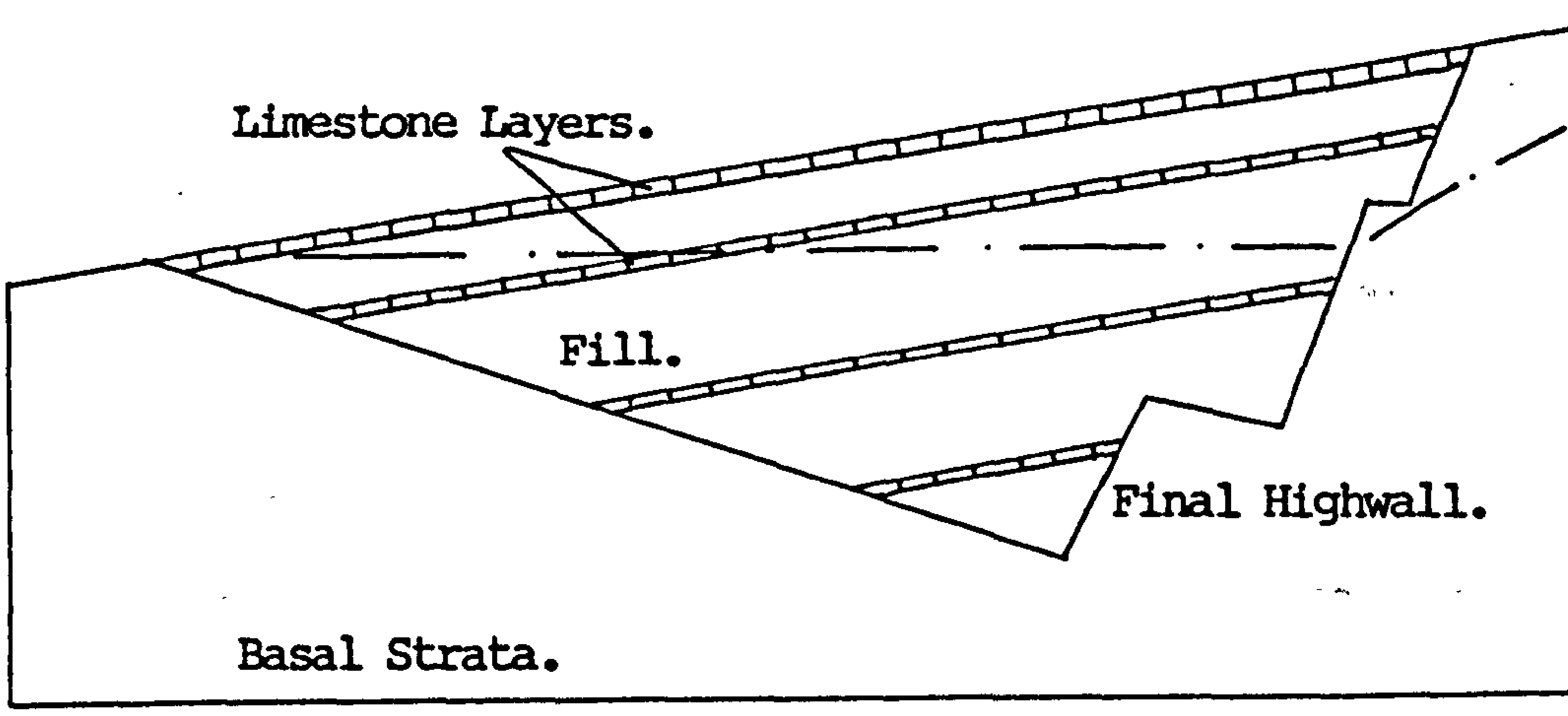


Fig. 7.8 Sealing of the Final Highwall using Clay Seals. (Norton 1983).



a). Limestone applied as a Surface Layer.



b). Interbedded Limestone/Fill Arrangement.

Fig. 7.9 Prevention of Groundwater Pollution utilising Limestone Placement.

g). Biological Inhibition.

The method of Biological inhibition relies on disrupting the catalysis of the acid reaction by iron bacterium. This can be performed by one of two methods;

a). Inhibition by other bacteria.

b). Inhibition by anionic detergents.

Electron microscopy has revealed strains of bacteria called Caulobacter in the neutral waters of certain coal mines (Shearer et al 1968). These waters were found to inhibit acid production in streams passing through pollution producing wastes. The bacteria are in fact harmless to life and have often been isolated from lakes, streams and other such watercourses. Laboratory tests have shown that the field neutralisation costs could be reduced by 5 to 10 times in successfully installed in practice.

Many biological inhibitors are unselective and could possibly cause dangerous side effects if introduced into natural waters. One class however, anion detergents are inexpensive and environmentally safe at low concentrations, (Kleinman 1980, et al 1981).

Laboratory simulations of coal refuse piles have shown that concentrations of Sodium Lauryl Sulphate of 10 - 20 ppm reduces acid production by up to 40%. At concentrations in excess of 25 ppm conditions become bacteriacidal, resulting in a 90% reduction in acid production. Anionic detergents have the further advantage of only being bacteriacial at low pH values.

The addition of such detergents to elastomer materials has enabled a control release mechanism to be devised. The detergent is slowly released from an elastomer pellet to be washed away by the natural waters. The rate of release has been shown to decrease slowly until about 60% of the detergent has been discharge. The rate then assumes an exponential decrease. The application of this technique to a backfilled surface mine site requires careful consideration - the pellets can only have a certain lifetime and may require a form of replenishment. The technique could undoubtably reduce effluent concentrations and be used to meet local discharge requirements. Means of replacing spent pellets would require investigation.

7.9.3. Remedial Techniques.

Remedial techniques are devised with an aim of controlling a pollution problem which has already manifested itself. Techniques include Limestone Neutralisation, Biological treatments and treatment by Reverse Osmosis or Ion Exchange methods. All these methods require the construction of a plant and are thus undesirable.

7.10 Conclusions.

This chapter has presented a review of the pollution of mine waters, their chemical analysis and methods for preventing polluting waters either forming or having a detrimental effect on the local ground and surface water regimes in the vicinity of a surface mine. The following chapter examines the actual geochemistry of mine waters with the opencast mining environment of the United Kingdom and evaluates the practicality of some control measures.

CHAPTER 8.

INVESTIGATIONS INTO SURFACE MINE WATER QUALITIES IN THE UNITED KINGDOM.

CHAPTER 8. INVESTIGATIONS INTO SURFACE MINE WATER QUALITIES IN THE UNITED KINGDOM.

8.1. INTRODUCTION.

Opencast coal mining in Great Britain is administered by British Coal in six geographical regions, namely; Scotland, North-East, North-West, Central-East, Central-West and South Wales. These regions are shown in figure 8.1. This chapter examines the water qualities from both current and restored opencast mine sites, and discusses satisfactory preventative or remedial techniques. For convenience the work has been subdivided into investigations in each of the above geographical regions.

Initial investigations commenced with the circulation of a questionnaire to each opencast region. The aim of the survey was to obtain some initial background information on which to base future study. The first priority was to determine how many sites undergo regular and full water analysis programmes. Information was requested on the following subjects:

a). Details of recent water samples from current working sites, with details of sampling point, e.g. sump, lagoons, discharge points.

b). Were any mines suffering from acid drainages, (however slight), and what were the forms of water treatment existing at each mine.

c). Were there any reported issues of water from restored areas or tips on mine sites which were either working or

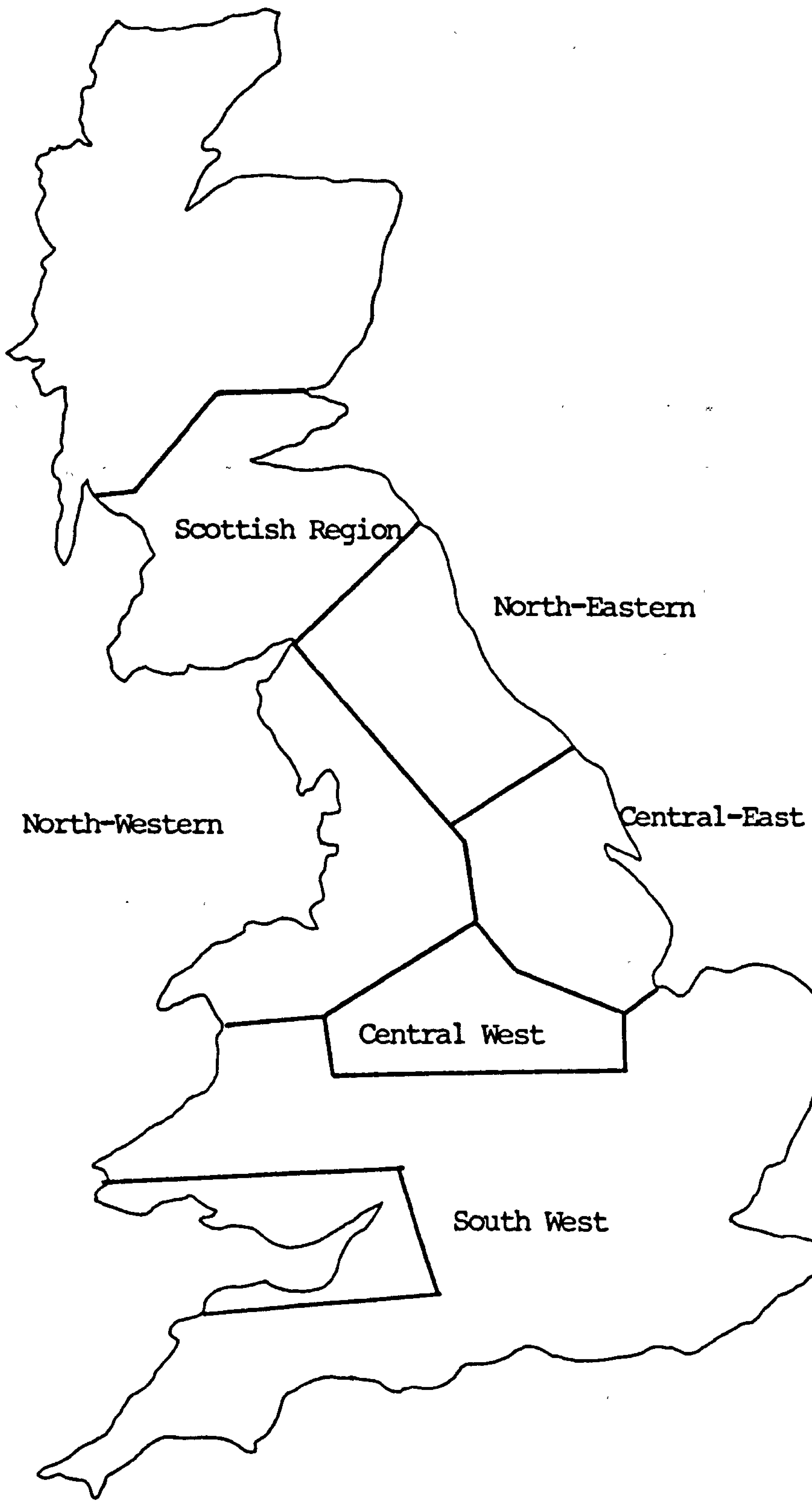


Figure 8.1. Geographical Regions of Opencast Mining in the U.K.

8.2 REGIONAL OBSERVATIONS OF MINE WATER POLLUTION.

8.2.1 Scottish Region

a). Regional Characteristics.

Opencast mine waters in the Scottish region are typified by exceptionally low pH and high dissolved iron contents forming a very real environmental hazard. Problems arise from ironstone bands interbedded with the excavated strata. These are weathered either on the surface of the exposed slope or in the backfill as broken rock. The problem of acid waters is widespread in the region and successful prosecutions have been made against British Coal for the pollution of water courses. Whilst the fines paid as a result of these prosecutions have been relatively small, (£100-200), the public image of surface mining in the region has been severely tarnished. In particular in attitudes to consents for proposed opencast mine sites.

To illustrate the type of problems which have been encountered in the region, surface springs which have emerged from underneath tip material have been recorded as having pH values of 2.8 and dissolved iron contents of 8,000 - 30,000 ppm, (Norton 1983).

Henton, (1981), reports a number of acidic emanations from restored mine sites within the Scottish Region, including the emergence of acidic water on grazing land, the flooding of church foundations by polluting waters, and recovery of acid waters to surface in a market garden. Pollution of a watercourse supplying a papermill resulted in the discontinuation of the production high quality photocopying paper.

Referring to Site C from the settlement research, which is located in this area some specific pollution problems can be detailed.

b). **Groundwater Qualities on Site C.**

The strata encountered on Site C was very argillaceous having a high degree of pyritic material. Some of the worst discharges emerged from the base of overburden dumps with analyses of pH 2.8 and 12-30,000 mg/l iron. A water sample taken from the easternmost synclinal basin, (Chapter 5), showed a pH value of 3.5 and a dissolved total iron content of 5,000 mg/l. Boreholes elsewhere installed in the backfill of the site showed waters at shallow depth of pH 3.9 with iron contents of up to 7500 mg/l. During the installation of the instruments in the road deformation monitoring scheme, (Chapter 5), it was noticed that the fill was very susceptible to spontaneous combustion. In the section of the fill just above the level of the water table, rock temperatures were very high initiating the formation of steam within the borehole. A number of other boreholes over the site were inspected and found to be on fire.

The natural water table in the area, previous to mining operations was close to surface and there is a strong possibility that streams will emerge from the backfilled area.

An analysis of the backfill mass has indicated a potential iron source of 6,600 tonnes per million tonnes of backfill, producing a possible 12,600 tonnes of ferric hydroxide. Given that the sole discharge point on the site is one small burn, the environmental effects of such chemical loads are expected to be considerable.

This site was an extension to a site which had excavated similar strata to a depth of 250 metres. The site at present has only been partially backfilled and the final void area remains empty. The coal to overburden ratio was relatively low and as a consequence there is not sufficient material to restore the site. Possibilities exist to fill the void with domestic refuge. At the base of this void is an 18 metre deep acid lake of pH of around 2. Pumping is currently keeping water levels to a constant horizon, however some time in the pumping must cease and recovery take place. The original groundwater levels around the area were as on the Extension), at or near surface, there is concern that if the pre-mining equilibrium levels are matched then spring of extremely toxic material may emanate from surface. The presence of the void will lower the natural water levels for the present and thus postpone the problems. In the meantime a solution to what may be the most potentially serious pollution problem ever encountered in the United Kingdom must be found. Table 8.1 details qualities of water sampled from the instruments monitoring the deformation of the road on Site C. Table 8.2 details an analysis of sump water from another

Extensometer Number;	E1	E2	E4
pH..................	3.56	2.83	3.60
Alkalinity to phenolphthalein, as $CaCO_3$.	0	0	0
Total Alkalinity....	0	0	0
Total Hardness as $CaCO_3$.......	4000	2700	800
Sodium.............	27	5	2
Potassium..........	98	20	8
Calcium............	83	70	20
Iron Total......	1040	48	432
Aluminium..........	1	4	3
Chloride...........	23	25	34
Sulphate...........	1206	1571	2906
Oxidised Nitrogen...	5	4	3

all results mg/l except pH.

Table 8.1 Analyses from Boreholes sites in Fill, Site C, Scottish Region.

pH..................	3.32
Acidity, as $CaCO_3$.	95
Total Hardness as $CaCO_3$.......	278
Sodium.............	9
Potassium..........	3
Calcium............	61
Magnesium..........	30
Iron Total......	81
Aluminium..........	10
Chloride...........	5
Sulphate...........	553
Total Dissolved Solids	750

all results as mg/l except pH

Table 8.2 Typical Analysis of Sump Water from a Working Mine, Scottish Region.

water by the application of clay seals to encase the fill. The impermeability of the clay would have ensured that groundwater could not percolate through the contaminating material.

It is most important that a clay seal placed on top of the fill. This ensures that the enclosed fill will not saturate with water gained over time by surface infiltration and thus produce a marshy area of land with polluting water covering the surface.

The technique of advance, (active), dewatering has been used in Scotland which results in depressing the groundwater levels during mining to below the level of the excavation. Conventional sump pumping methods rely on an in-pit pump removing water as it accumulates in the base of the mine. From an operational point of view the former technique is much more efficient for a variety of reasons in mines with large inflows of water. The initial capital expenditure is however much higher. The post-mining environmental aspects however would not seem to favour the advance methods. If the backfill remains dry throughout the life of the mine, then on groundwater recovery the full acid load may be manufactured given suitable conditions. This full load may then impinge on the environment possibly unexpectedly if no pollution was encountered during mining.

It is considered that although sump pumping suffers many disadvantages compared with the advance techniques, the acid load may be slowly released with this method in acceptable concentrations. In mines where advance dewatering is used and post mining pollution is likely then a preventative method opencast site in the region, illustrating that the problems are widespread in the area.

c). **Pollution of Groundwater from Restored Opencast Sites.**

The restoration of an ironstone tip into the void of a surface mine resulted in a local stream exhibiting pH values of 4.5 and dissolved iron contents of 650 mg/l when the groundwater recovered to emanate out of the fill at surface, (Norton 1983). Analyses of the pit heap material indicated that the potential iron source was 3,125 tonnes. The emanation of the groundwater occured practically next to the stream and thus a minimum of dilution occured prior to mixing with the clean water. The subsequent pollution led to the prosecution of the National Coal Board under the regulations of the Control of Pollution Act 1974.

Values of pH decreased drastically from acceptable levels to 3.3 after contact with the contaminating fill. Iron contents rose to 600 mg/l. An attempt to rectify the problem involved the injection of lime into the mine fill. This measure was found was only to be temporarily effective resulting in a second prosecution. To rectify the problem completely a small treatment plant had to be constructed.

The restoration plan obviously did not take into account the possible environmental impact of such an occurrence. In hindsight it is very easy to evaluate suitable preventative measures which may be taken on future similar projects.

The toxic mass could have been isolated from the passage of must be included in the restoration programme to prevent adverse environmental impacts. Care must be taken so that in addition to surface environmental protection, the protection of underground aquifers is also maintained lest contamination of the public water supply occur.

8.2.2. North-East Region.

Two restored opencast mines in the region have formed streams, one emerging out of the fill, and one emerging out of the solid ground adjacent to the mine site.

The quality of the water emerging out of the fill was not of sufficient standard for use owing primarily to chloride and sulphate contents. The pH of the sample analysed had a pH of 6.6 and the iron content was negligible.

The second stream which does contain iron emerges from the ground outside the site boundary of one restored mine in the area and is discharging into a water course. The dilution is however so great that there is practically no environmental effect. The hydrology of the site does appear to have been disrupted in that a stream which previously existed in the same area has dried up to be replaced by this new outflow.

Many sites in the North-East are excavating old deep mine workings. In the Northern area of Northumberland especially, these workings tend to drain the opencast fills as they are directly linked to a deep mine colliery pump. This obviously is temporarily reducing recovery rates and levels in a number of restored opencast sites in the area despite a standard restoration policy of applying clay seals to excavated underground workings. The pumping is expected to terminate in 10 years time and further recovery will be initiated over the entire area. This may be of importance if streams re-establish out of backfill, (although the fill is not unduly pyritic) or from the induced collapse settlement of unsaturated fills.

Table 8.3 details some water quality data measured in the Region. Table 8.4 presents some water qualities from waters sampled from boreholes installed in fill.

8.2.3 North-West Region.

No water treatment facilities save lagoons are currently being utilised in the North-West region. Samples of water obtained from sites however do indicate that the region suffers slightly from waters of poorer quality. This is a trend which has been observed over a few years, when in 1981 the compliance with water discharge consent conditions, (governing the quality of the discharged water), for the North-west was 59% compared with 66% for Scotland and a nationwide average of 75%. Samples taken on several sites showed low pH values and high iron contents with other dissolved metal salts showing high concentrations as well. Whilst the region has no where near the problems of Scotland some environmental problems may occur if voids are considered for the disposal of colliery spoil materials. Examples of analysis are presented in Table 8.5.

Table 8.3.

Typical Mine Water Samples, North-East Region.

all mg/l except pH

Full Analysis Example.

pH..................	7.9
Total Hardness as $CaCO_3$.	472
Total Alkalinity.... as $CaCO_3$.	184
Alkalinity to phenolphthalein as $CaCO_3$.......	0
Sodium..............	24
Potassium...........	-
Calcium.............	120
Iron Total......	0
Aluminium...........	0
Manganese...........	0.1
Chloride............	37
Sulphate............	273
Oxidised Nitrogen...	0

Summary of Sites Investigated.

(5 mines, 8 seams).

pH = 5.8 - 7.9 average. 7.01

Total Iron = 0 - 3.4 mg/l average. 1.15

Table 8.4.

Average Chemical Compositions of Water sampled from boreholes on Site B. (North-East Area).

all mg/l except pH

	MPP1	P2	P3	P4	Piezometer in Fill on a local site.
pH..................	8.6	8.6	8.0	7.7	7.8
Total Hardness as $CaCO_3$.	182	108	468	372	510
Total Alkalinity.... as $CaCO_3$.	78	408	507	264	326
Alkalinity to phenolphthalein as $CaCO_3$.......	0	60	36	0	0
Sodium.............	27	48	204	180	18
Potassium..........	5	89	105	82	43
Calcium............	117	166	69	345	46
Iron Total......	5	43	22	13	9
Aluminium..........	5	1	0	0	0
Chloride...........	2860	660	360	390	80
Sulphate...........	216	680	823	110	540
Oxidised Nitrogen...	0	2	1	1	0.5

Table 8.5.

Typical Mine Water Samples, North-West Region.

all mg/l except pH

	Site 1	Site 2	Site 3	Site 4	Site 5 Seam A	Site 5 Seam B
pH	6.5	4.5	6.6	7.3	7.9	7.4
Total Hardness as $CaCO_3$.						
Sodium	12	60	166	41	8	55
Potassium	8	15	18	16	4	7
Calcium	130	270	263	145	83	95
Iron Total	5	58	0	12	0	11
Manganese	0.7	1.8	1	0.5	0.3	0.4
Chloride	25	120	56	88	23	32
Sulphate	125	345	110	130	238	134
Oxidised Nitrogen	1	0.5	1	1.5	0	0.5

8.2.4 Central East/West Regions.

All sites in these regions discharge water of satisfactory nature. One site in the Central East region did however have high aluminium contents with aluminium hydroxide being deposited in a local water course. One site had water inflows arising from three seams, one of which was high in iron contamination. The iron deposits on the walls of the mine indicated that acid water was present although it was much diluted in the general pit environment. This particular site will be used to reclaim colliery spoil and thus there is a possibility that water from this seam may encourage pH values to drop in the restored fill and thus catalyse the acid forming reaction. Table 8.6 details some example analyses.

8.2.5 South Wales Area.

The geotechnical settings of opencast mine sites in the South Wales region are such that many sites form parts of hillsides or may be adjacent to restored colliery spoil heaps. No water pollution has been so far recorded from opencast sites although recently a water treatment plant with lime neutralisation facilities has been constructed at a new site. It has proved almost impossible to trace water flow through sites owing to the extremely complicated hydrology and hydrogeology of the area. Analyses are presented in Table 8.7.

Table 8.6.

Typical Mine Water Samples, Central East Region.

all mg/l except pH

	Site 1.			Site 2	
	Seam A	Seam B	Run-off	Seam C	Seam D
pH..................	8.3	7.2	8.1	7.5	7.5
Total Hardness as $CaCO_3$.	350	752	680	536	556
Total Alkalinity.... as $CaCO_3$.	148	6	120	74	136
Alkalinity to phenolphthalein as $CaCO_3$.......	14	0	14	0	4
Sodium..............	707	359	23	856	115
Potassium...........	27	19	17	22	23
Calcium.............	114	205	145	173	165
Iron Total......	0.3	15	0	2	0.7
Aluminium...........	0	0	0	0	0
Chloride............	4000	3850	220	3230	370
Sulphate............	422	232	440	130	550
Oxidised Nitrogen...	2	1	3	1	2

Table 8.7.

Typical Mine Water Samples, South Wales Region.

all mg/l except pH

	Site 1	Site 2		Site 3		
		Seam A	Seam B	Seam A	Seam B	Seam C
pH..................	8.4	6.2	8.2	7.5	5.9	6.8
Total Hardness as $CaCO_3$.	680	2000	920	1200	1480	840
Sodium..............	28	8	13	51	77	104
Potassium...........	7	10	16	19	5	5
Calcium.............	115	172	155	140	195	112
Iron Total......	2.6	1.8	1.4	4.5	2.9	3.1
Manganese...........	1.4	0.8	1	0.1	0.2	0.2
Chloride............	64	44	50	52	40	40
Sulphate............	182	230	215	225	142	150
Oxidised Nitrogen...	1	1	1	0	0	0.5

8.3 DISCUSSION ON PREVENTATIVE/REMEDIAL TECHNIQUES.

The application of clay seals to noxious overburden within the backfill of a mine is considered the most effective and reliable method of water pollution control. Other techniques such as limestone placement/ injection have been found to be too speculative and unsatisfactory. The key to pollution prevention lies in either reducing water flow or oxygen supply to the backfill mass. Clay seals will prevent both, however fill compaction may be considered as this will lower oxygen supply and reduce water flowrates, thus inhibiting the acid forming reaction. A case for the investigation of bacteriacides may exist, if these could inhibit the reaction until a rich vegetative cover could be established. Once this is done then the vegetation would again deprive the spoil of oxygen. This use of bacteriacides, providing the initial dosage and application to the fill was successful would not require bacteriacide replenishment.

Studies throughout the United Kingdom have shown that the Scottish region has a severe problem with the acidity of waters associated with pyrite oxidation. The technique of advance dewatering has been used successfully to enable mining in dry conditions with the advantages of increased slope stability, lower blasting costs etc, with the minimisation of groundwater pollution during mining. Great care must be taken on all sites however to evaluate likely stream re-establishments and the possible qualities of the discharge.

The quality of waters being pumped to settlement ponds elsewhere in the U.K. appears to be quite acceptable. What has been noticed is that as the mines tend to use passive (sump) pumping techniques, the water pumped from the base of the mine may be a mixture of waters from two or three sources, (old workings, run-off etc). The net quality of these waters may well be acceptable but in cases where one small discharge from and old workings horizon is acidic then figure 8.2 illustrates the problems which may occur as sites throughout England and Wales are selected for the disposal of the more pyritic colliery spoil.

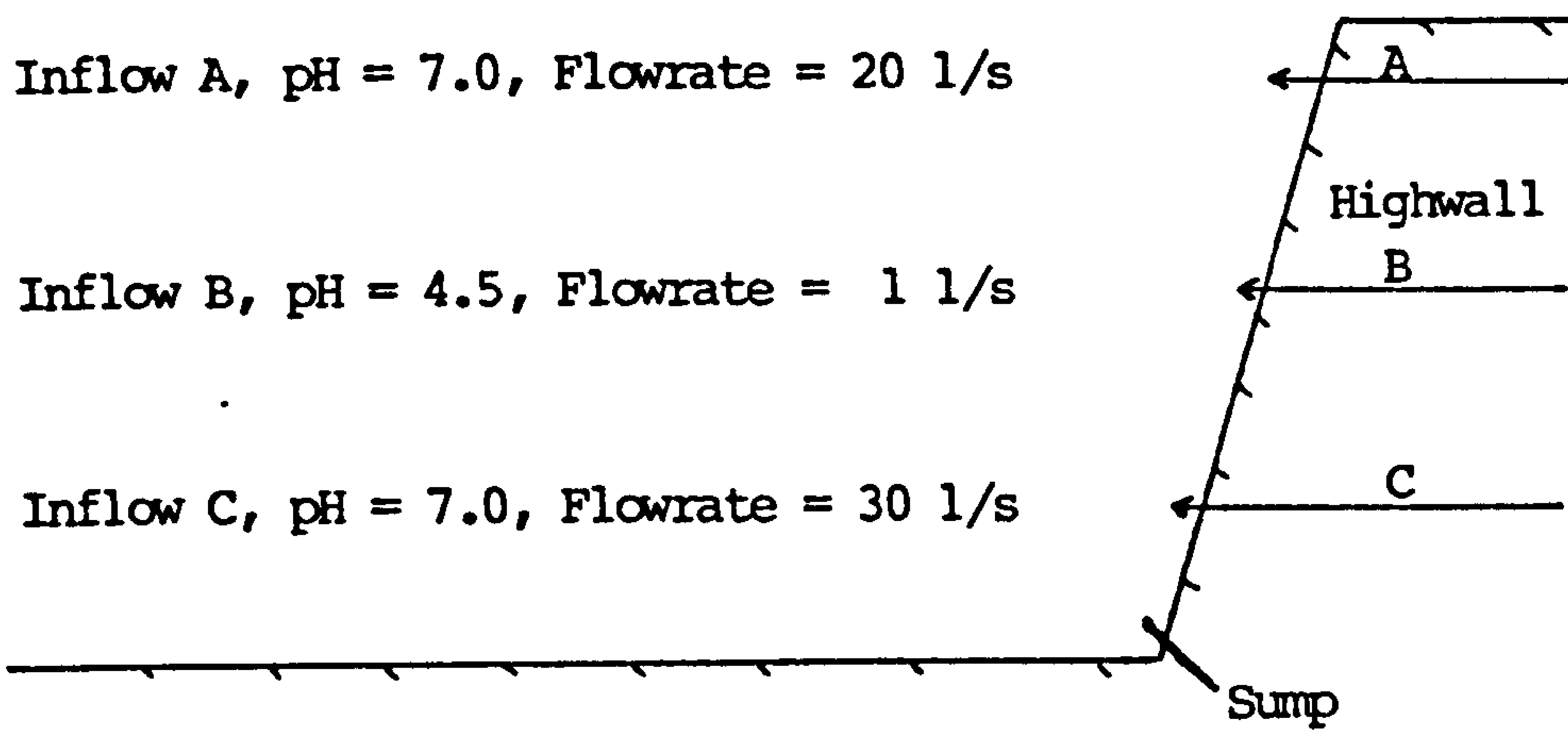
8.4. CONCLUSIONS.

The following conclusions can be drawn from this Chapter.

a). A serious acidic mine water problem exists in the Scottish Region of British Coal. The presence of ironstone bands associated with the excavated strata giving rise to waters of low pH and high dissolved iron contents.

b). Other Regions of opencast mining are free of serious mine water pollution problems. Acidic waters have been observed to exist, but in general they blend naturally with more alkaline waters to produce a drainage of acceptable quality.

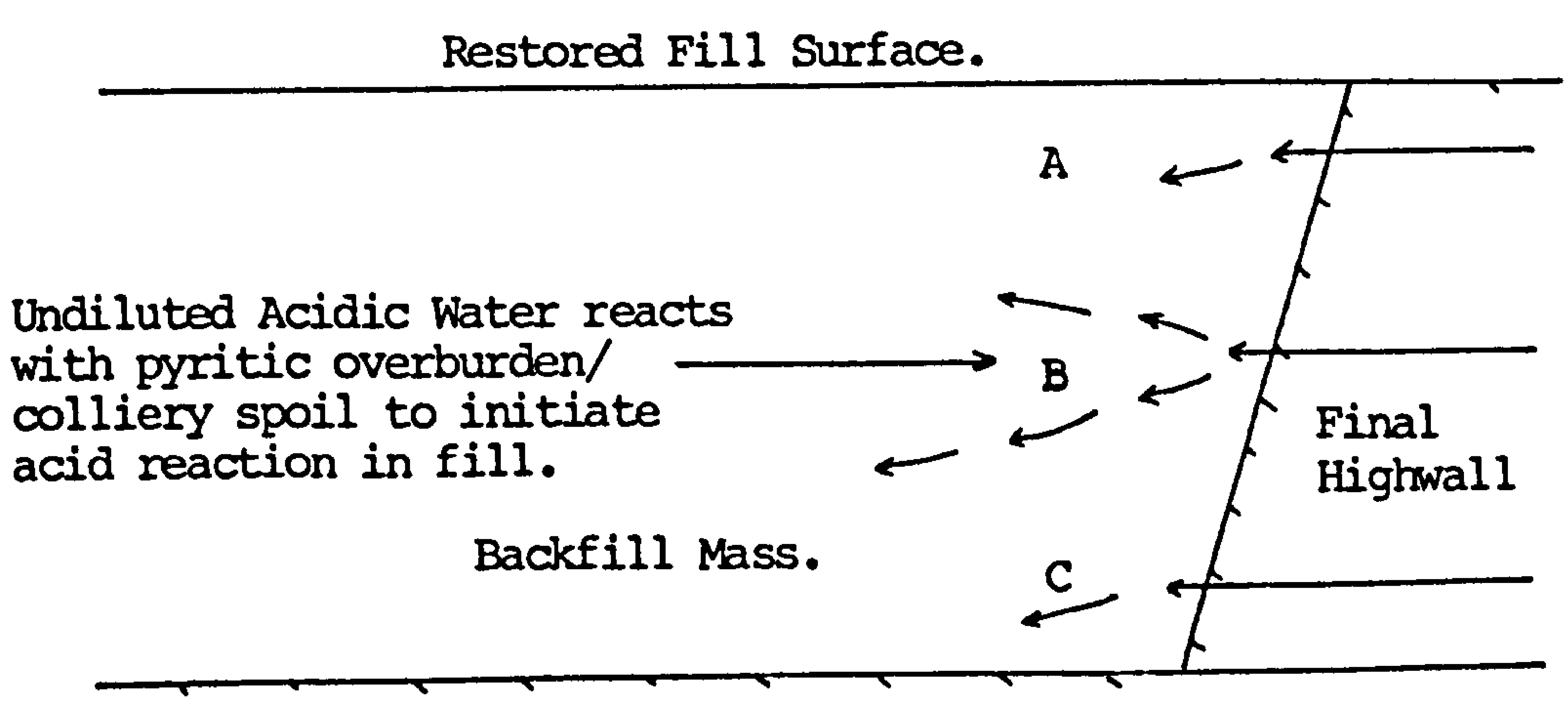
c). Groundwater pollution may be at least reduced by careful planning prior to the working and restoration of a site. Strata samples can be analysed for polluting loads, and if need be certain areas of backfill should be sealed off from



Overall Pumping Requirement = 51 l/s

Overall pH of Pumped Water = 6.14.

a). Dilution of Acid Drainage in Natural Mine Environment.



b). Dilution effects removed on Restoration.

Figure 8.2 Possible Scenario for Acid Mine Water Production following Restoration in a Mine previously immune to Water Pollution

water percolation with clay seals. If a prediction of groundwater quality and likelihood of emergent streams from backfill masses were to be made prior to restoration, then a potential environmental problem may be averted.

Further conclusions and recommendations are presented in the following Chapter.

CHAPTER 9.

DISCUSSION, GENERAL CONCLUSIONS AND RECOMMENDATIONS.

CHAPTER 9. GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS.

9.1. SUMMARY OF RESEARCH.

The project's initial objectives were to evaluate two specific problems associated with the recovery of groundwater in backfilled opencast mine sites;

a). The collapse settlement of opencast backfills, and

b). The pollution of groundwater.

Research has consisted of field investigations, the acquisition of data, and data analysis. Settlement observations have been conducted on 10 opencast mine sites, which have resulted in an analysis of a wide cross-section of site conditions and diverse observed phenomena.

Research into the pollution of groundwater from weathered backfill materials has involved the geochemical analysis of the surface mine waters throughout the United Kingdom. Owing to environmental claims, the nature of such an investigation is extremely delicate. Consequently access to information was limited, and the investigation could not be carried out to its fullest. An assessment of preventative and remedial techniques has been presented.

9.2. RESEARCH INTO BACKFILL SETTLEMENT.

9.2.1. Summary.

The evaluation of backfill settlement associated with groundwater recovery has involved the following aspects;

a). Selection, design and appraisal of individual monitoring instruments.

b). Planning and appraisal of field monitoring schemes.

c). Collection and interpretation of results.

d). Formulation of factors to be taken into account when considering or predicting the settlement of backfill associated with groundwater recovery.

9.2.2. Assessment of Field Instrumentation.

Table 9.1 presents a summary of the instrumentation used in for this research. The table details the purpose of each instrument together with comments concerning possible improvements and suitability for backfill monitoring.

a). The Magnetic Extensometer/Standpipe Piezometer.

This instrument was found to be suitable for the monitoring of vertical backfill settlement and groundwater recovery in shallow backfill environments. The instrument has also worked successfully in deeper backfills, up to 70 metres depth. One failure of an instrument installed to 80 metres depth, however

Instrument.	**Purpose**	**Comments**
Magnetic Extensometer/ Standpipe Piezometer.	Monitoring vertical settlement in soils and rockfills. Also indicates groundwater level.	Relatively straightforward to install in cased borehole. Several design improvements could be made to facilitate installation, (see text). Components expensive to purchase "off the Shelf" Accurate readings of settlement and water level. Easy to read, requiring two probes, dip meter and Reed Switch. Interpretation of readings straightforward. Unsatisfactory in fill prone to shear movements.
Tension-Wire Extensometer with modifications for conduction of pumping tests.	Monitors consolidation and shear in rock, soil and rockfill masses. Installation of discrete compartments within the borehole enables the conduction of pumping tests, thus evaluating permeability values.	Complicated installation and testing procedure. Taking of readings and conduction of tests are time consuming. Interpretation of results are complex. Results show a more informed picture of backfill movement. Requires local piezometer to measure water levels. Preferable to the above instrument in deep fills, prone to shear.
Multi-Point Piezometer.	Monitors water levels and pressure differences in rock, soil and rockfills.	Simple to install and read, requiring a dip probe. Unsuitable for deep fills subject to shear.
Standpipe Piezometer.	Monitors free groundwater level in rocks, soils and rockfills.	As for Multi-Point Piezometer.

Table 9.1. Summary of Instrumentation, Backfill Settlement Research.

was sufficient to cast doubts about the overall suitability of the instrument. The instrument had been damaged by lateral fill movements shearing the central access tubing, initially at a depth of 50 metres below the surface, and subsequently at 20 metres below the surface. The installation was in proximity to a final void which was in the process of being backfilled. Lateral movements where thus supposed to be acting towards the open void area.

The magnetic extensometer/piezometer instrument is bought "off the shelf" from geotechnical instrumentation companies. A number of improvements to the instrument to ease installation were rapidly found during instrumentation, and it is considered that the University could construct the components for such an instrument, (e.g. magnets, pneumatic cutters, connecting pieces), at a much cheaper price than the instrumentation companies supply for. One of the most inconvenient aspects of the installation was that the flexible sleeving linking the magnets had to be connected as that part of the instrument entered the hole. A very difficult operation when it is considered that at the latter points of the installation a significant weight of instrument must be supported in the borehole. In addition, the elastic nature of the flexible sleeving tends to pull downwards into the hole, with work being carried out in close proximity to a spider magnet which is been held in its retracted state by fishing twine. A simple solution to the inconvenience and danger which may result from an unexpected release of a spider magnet near the installer´s face, would be the manufacture of flexible sleeving-flexible sleeving connectors. In this way linking operations may be performed without the danger of spider magnet pre-release causing injury.

Manufactured Reed-Switch Probes tend to be far bulkier than need be. In deep holes the fiction between the wall of the access tubing in combination with the buoyant effect of water within the tube occasionally lead to problems in dropping the probe to the depth of the datum magnet. The problem would be remedied by a more compact, shorter probe with a heavier lead weight tip.

The borehole backfill must also be considered carefully. On three instrumentation projects in this thesis, grout, gravel and sand have been used to backfill the borehole after installation. The view of the author is that for any such installation, either extensometer or piezometer, the use of fine filter sand as a backfilling material is by far superior. Pea gravel is notorious for forming bridges in the borehole, which if not controlled by slow gentle application will result in the instrument improperly backfilled. Grouts used to backfill the borehole must be weak, (bentonite grout), but when poured into a borehole drilled in fill have the tendency to flow out of the borehole into the surrounding backfill. The process of grouting is also a lengthy one, owing to prolonged setting times for weak grouts.

The results obtained are considered accurate from this instrument and have been confirmed by surface levelling operations. The instrument is easy to read, needing no specialist knowledge, and thus can be read by site staff after an initial demonstration. Calculation and interpretation of the results are straightforward requiring a sole assumption that the datum magnet installed in the pavement strata below the fill is stable.

b). The Tension-Wire Extensometer with modifications for permeability testing.

The tension wire extensometer instrument was introduced to monitor both settlement and shear movements following the failure of the 80 m deep magnetic extensometer instrument. The instrument had previously been used by the University in both surface and underground mining projects. Several underground research projects had investigated changes in permeability associated with shear movements by modifying the standard tension wire instrument. These modifications were included into this research as it proved an opportunity to monitor changes in backfill permeabilities with both time and depth.

The instrument was very complicated to install, requiring a large amount of drill rig standing time. It was a very ambitious design, particularly in view of the fact that previous installations of a similar type had been designed for horizontal boreholes. The problems encountered during the installation have already been presented in chapter 4 and need not be detailed here. The instrument may have been less complicated if the combination of deformation monitoring and permeability testing had been separated and installed in two separate boreholes.

Despite the complications surrounding the installation of the instruments, the results obtained have appeared satisfactory. The instrument is read solely at the surface and requires no down-the-hole probe. The reading of wires is fairly simple and as for the magnetic instrument can be read by site staff after an initial demonstration. Permeability tests however can take a full week and require some knowledge of the techniques involved. They are not suitable for conduction by site staff principally because of the time factor.

Analysis of the results obtained in the field is fairly complicated. Tension wire readings give an overall settlement and shear movement combination and require some deductions and assumptions to evaluate results. It is preferable that each set of readings be taken in connection with a precise levelling survey of the instrument from a permanent levelling station. This is impossible however until final restoration levels are achieved owing to the changes in backfill/soil levels around the instrument over reading periods.

In order to conduct permeability tests, a domestic supply was used, (80 p.s.i), as the water source. This supply has been found only suitable for instruments containing smaller testing compartments, say a maximum of 3 metres length. Larger compartments require longer pumping times to reach steady state conditions, and in some cases, where the fill is fairly permeable, compartments may never reach steady state, as the water flows out of the compartment at a rate which is faster or similar to the incoming flow rate.

The calculation of the coefficient of permeability requires a number of significant assumptions, which although not precisely valid, enable a reasonable value to be attained. These assumptions can be summarised as follows;

a). The conduction of the test has a minimal effect on the permeability of the compartment under examination.

b). The dimensions of the compartment remain constant, (i.e. length and compartment diameter).

c). The ratio of vertical to horizontal permeability is 1.

The dimensions of the compartment are taken to be those originally installed in the borehole. Settlement and shear movements will obviously alter the length and diameter of the compartment under test. Specifically, the fill will tend to close in around the instrument after the initial installation reducing the diameter of the test compartment.

In order to calculate the coefficient of permeability an estimate of the ratio of horizontal to vertical permeabilities for the horizon under test is required. For intact rock strata a ratio of vertical to horizontal permeability may be significant, (Neate 1980), however for a broken rockfill mass it may be expected that the two permeabilities would be of the same order. The ratio will not be 1, as vertical loading from the self-weight of the fill will decrease vertical permeability. Taking the ratio to be one is however a reasonable assumption if the value is taken consistently.

c). Piezometer Instruments.

Both the single and the multi-point piezometers are both easy to install and to monitor. The piezometers may be prefabricated at surface, during the drilling operation, and installed in the borehole within minutes. A problem again arises in deeper fills prone to lateral movements, that the access tubing may fracture, which has in fact occured. Sand is once again preferred as a backfilling material for the reasons which have been given previously.

9.3. SITE INSTRUMENTATION SCHEMES AND OBSERVATIONS.

9.3.1. Summary of Instrumentation Schemes.

Table 9.2 details a summary of the 10 instrumentation schemes and site observations which have formed the backfill settlement research in this thesis. A summary of site instrumentation is also detailed.

9.3.2. Field Observations.

a). Groundwater Recovery.

Groundwater recovery has been monitored on 6 of the backfilled sites detailed in table 9.2. The following phenomena have been observed;

Table 9.1. Summary of Site Investigations. - Backfill Settlement Research.

Site Description	Instrumentation Details.	Observations.
Site A. Truck-Shovel Operation. Shallow mudstone fill, average depth =17 m, maximum depth = 33 m. Wet site with recharge from old deep mine workings.	5 Magnetic extensometers/Piezometers to monitor settlement and groundwater recovery in the fill. 4 piezometers monitoring recharge in the solid. Instruments in two profiles, one down-dip, one along strike.	Water recovery rapid, 24 m in 144 days. Collapse settlement found to occur directly related to groundwater position Mudstone swelling following saturation resulted in heave movements. Differential settlements resulted in ponded areas. Settlement over compacted haul road much reduced. Settlement = 1.1% of fill depth.
Site B. Dragline operation, working sandstone-mudstone overburden. Average depth of fill in instrumentation area = 70 m. Final void infilled by dump trucks.	4 Piezometers monitoring recharge in the solid. 2 multi-point piezometers, (5 tips in each), monitoring water behaviour in fill. 2 tension wire extensometers monitor settlement and shear in fill, also used for permeabilty testing of horizons within the fill.	Slow groundwater recovery, 5 m/year. Substantial vertical and lateral movements in fill over 2 years old. Average permeability akin to intact coal measure strata. Perched water tables present in fill. Permeabilities much greater with depth surface permeabilities very low.
Site C. Truck-Shovel operation working synclinal basins. Sandstone-mudstone fill, 40 - 70 m deep.	4 magnetic extensometers/piezometers monitoring deformations along the line of a road constructed on variable thickness backfill. Instrument depths of 30, 40, 60 and 70 metres. Top 15.5 metres of fill compacted.	Fill saturated to 5 metres below base of compaction at start of monitoring. Compacted zone appears unseceptible to collapse settlement. Small movements measured normally occuring in the base of the fill. Fill depth governing proportion of settlement. No severe differential vertical movement.
Site D. Dragline site, 15 -30 metres depth of fill. Sandstone- mudstone.	23 Surface levelling stations and 3 magnetic extensometers/piezometers monitoring the line of a sewerage pipe constructed over the fill.	Instrumentation commenced 7.5 years after restoration. Negligible movements in the fill. Fluctuating water table had no effect on settlement patterns.
Site E. Dragline Site, sandstone-mudstone fill.	3 traverses totalling 30 surface levelling stations over fill area. Correlated to local piezometers for groundwater levels.	Water recovery related collapse settlements were observed. Slow time period for recovery, 7 years. Secondary recovery induced secondary collapse settlements. Settlement not completely related to fill thickness.
Site F. Dragline Site, sandstone-mudstone fill. Depths in area of instrumentation up to 35 metres.	8 surface levelling stations installed over highwall area. Correlated to local piezometers for groundwater levels.	Groundwater recovery related settlement observed followed by long term creep displacments. Settlement independent of fill depth and affected by presence of highwall. 8.5 years after initial recovery, settlement still occuring. Groundwater levels still recoverying slowly.
Site G. Shallow truck-shovel site. Sandstone-mudstone fill. No water.	9 surface levelling stations monitoring vertical and lateral fill movements.	Small vertical movement observed in dry fill. Larger lateral movements recorded and found to be differential in both magnitude and direction. Highwall had significant effect on movements.
Site H. Permanent spoil heap mound.	1 tension wire extensometer monitoring settlement and shear. 1 piezometer monitoring groundwater.	Small displacements in dry spoil. Water levels slightly fluctuated at base of heap.
Site I. Dragline Site, sandstone-mudstone fill. Concrete line culvert and lake constructed on restored fill surface.	None	2 years after culvert constructed on fill 14 years old a sudden structural collapse occured amounting to 3.4% of the fill depth.
Site J. Truck-shovel site on side of hillside. Shallow depth 11 m, sandstone-mudstone fill.	None	Bowl- like depressions of up to 0.5 m occured in fill of 24 years age over an unknown period. No water issues. Settlement amounts to 4.5% of fill depth.

i). On small backfilled sites of shallow depth and limited areal extent, water recovery can be extremely rapid. Recovery may terminate after a matter of months.

ii). On deeper sites, over larger areal extent, water recovery may take years to rise to equilibrium level. Up to eight and a half years recovery period has been monitored.

iii). Delayed water table recovery has been observed associated with external pumping operations. Groundwater recovery observed to initiate on one site, almost one year after restoration.

iv). Perched water tables have been recorded in a deep dragline fill. These indicate zones of impermeability and zones of collapse settlement which may be above the level the water table is expected to recover to.

v). The presence of abandoned deep mine workings as either a source of inflowing water to the backfill or as a drain is of importance. Site A suffered large inflows from old workings, resulting in rapid flooding of the backfill. On site B despite the application of clay seals to the level of old workings on the excavated walls, the workings appear to be acting as a drain to an external pumping source.

b). Settlement Observations.

The presence of a recoverying water table has been observed to initiate collapse settlements at the surface of that water table in backfill materials.

On a shallow mudstone site worked by truck and shovel methods, the sole zone of the backfill which was undergoing movement was that portion in contact with the surface of the recovering water surface. Saturated horizons were observed to exhibit slight heaving movements associated with mudstone swelling. The "dry" horizons above the water table were found to exhibit negligible movement. Once the collapse settlement had finished giving way to heaving movements, then only small creep displacements were subsequently observed.

Collapse settlement was also associated with the site on which delayed groundwater recovery had occured owing to external pumping influences. The collapse settlement was sudden and of significant magnitude.

On two sites, a form of secondary recovery was observed, i.e. the groundwater reaching a peak level in the fill, lowering, and then re-achieving the peak level. On one site this secondary recovery resulted in collapse fill settlement for a second time, although at a much lesser magnitude. On the second, no backfill movements were observed, most likely related to the fact that the fill had been in position for over nine years.

Two very significant observations have been recorded as delayed damage to a concrete culvert constructed on backfill and long term backfill settlements affecting a school playing field. The ages of the fill concerned were approximately 14 and 24 years old respectively, indicating that backfill settlements can occur over very prolonged time-spans. On another of the monitored sites settlement is occuring at a constant rate, nine years after fill placement. Significant creep settlement over this period has resulted in the magnitude of creep settlement exceeding that of collapse settlement.

A major finding has been that the magnitude of lateral movements can exceed that of vertical settlement, being observed on two sites, one in the absence of water. Lateral movements have also been shown to be differential both in fill area and time. On one particular site the vertical settlements were recorded as being very small, (mm), and were exceeded in magnitude by lateral movements. If any construction had been placed on the fill, then damage may have been inflicted by shear movements rather than settlement. This is an area which will be outlined subsequently as an area for further research.

Site characteristics such as the compaction of a haul road have been observed to reduce settlements drastically and remove totally collapse settlement phenomena.

c). Permeability measurements.

Permeability tests have shown that the backfill increases with permeability with depth. The top layers of the fill can be very impermeable indeed, and may result in an ill-draining surface. Soil ripping will increase the permeability of the near surface layers, but over time unless a rich root structure can be developed, the soil itself may revert to a clayey ill-draining mass. Resulting flooding on the surface is often rectified by the delay in the introduction of subsurface drainage until the latter years of the restoration contract.

Decreased surface permeabilities may result in the emanation of streams from the backfill surface which may otherwise not be expected.

The large permeabilities in the base of the fill give a reflection of the larger boulders of rocks there present. The greater the permeability, the greater the rock size and hence the greater the degree of rock size breakdown and consequently settlement which can occur.

9.3.3. General Conclusions from Settlement Research.

The following general conclusions may be drawn from the field observations recorded in this thesis;

a). Water recovery rates although extremely variable can be predicted qualitatively from a knowledge of the following criteria;

i). Pre-mining piezometric surface.

ii). Depth and areal extent of site.

iii). Position of old deep mine workings and whether they are discharging or draining water, or lined with clay seals.

iv). Knowledge of external influences, e.g. adjacent opencast mines, underground mines etc.

v). Degree of fill compaction - related to backfill placement method. Less permeable fills will reduce the rate but not necessarily the total degree of groundwater recovery.

b). Magnitudes and rates of backfill settlements have been observed to be influenced by the following;

i). The recovery of the natural groundwater table. The level of the water table has been observed to be associated with collapse settlement.

ii). Backfill depth, (although often nullified in cases where significant recovery has occured or where some form of compaction or restraint, (e.g. highwall), has been involved).

iii). Composition of backfill and mining method. Mudstone fills have been observed to undergo collapse settlement followed by small non-differential settlements. Sandstone, dragline fills tend to contain larger boulders at the base of the fill than truck-shovel fills, and consequently may undergo greater magnitudes of settlement.

iv). Site features. Monitoring of settlement of a compacted haul road, (site A), showed that the fill in this area was unaffected by the presence of the rising water table. In addition, settlements were substantially lower in this area than on any other part of the site.

v). Time. The timespan of backfill settlement has been observed to be very variable. Settlements have been recorded in a fill 11 metres deep, 24 years old, for which no adequate explanation can be proffered. The data presented in this thesis are insufficient to construe any firm conclusions as to the time effect of total backfill movement.

9.3.4 Factors to be considered in the prediction of backfill settlement.

In assessing the suitability of a site for structural development the above general conclusions in addition to the observations presented in this thesis and other works must be borne in mind.

It is the opinion of the author that the following measures must be taken for any surface development on backfill material.

a). A comprehensive instrumentation scheme consisting of at least piezometers and surface levelling stations. Both lateral and vertical displacements must be measured. The scheme should commence at least one year prior to construction to enable a full picture of the fill movements to clarify.

b). A thorough investigation into the position of the water table and the determination of any external influences e.g. deep mine pumping which may result in a delayed recovery phenomenon.

c). An investigation into the location of deep mine workings from which subsidence movements may be mistaken for fill displacements.

d). Proposed structures should not be constructed over solid ground/fill interfaces, e.g. highwalls, nor over fill areas where substantial fill depth changes occur, i.e. benches or seam limits. If possible structures should lie over backfill of a uniform thickness. This suggestion may be modified for service lines which can contain flexible joints.

9.3.5. Discussion of lateral movements.

Several observations from this research have indicated the occurence of lateral, (horizontal) surface movements within the backfill with a magnitude which may be comparable with vertical settlement. Work has also shown that in the excavation of a surface mine, the excavated walls undergo a degree of stress relaxation owing to removal of a retaining rock mass.

Backfilled mine sites are increasingly being used for post-mining structural development - either by buildings, roads or other civil engineering structures. To date concern has been mainly expressed at the occurence of differential vertical movements (settlement), inflicting structural damage. Observations in the field of mining subsidence have shown that it is the surface strains, i.e. lateral movement, which are also of importance. An example of the results already achieved has been a net horizontal displacement of a shallow backfilled area of 62 mm corresponding to 29 mm vertical settlement. The horizontal movements have in addition shown to be differential over the area of the site and have tended to oscillate over the initial position of the fill. The mine in question was only 20 metres deep and it is expected that these movements may be amplified in deeper mine sites of around 70 to 80 m depth. Horizontal movements must have a relationship to vertical settlement and this becomes of importance to sites where different systems of compaction have been used. Selective compaction under roads and buildings may successfully remove vertical movements, but it is unknown if horizontal movements may not occur as a consequence in the movement of uncompacted fill adjacent to the construction.

The removal of a retaining rock mass to form a mine slope will induce some stress relaxation within the formed wall. The degree of stress relaxation will be governed in part by the depth of excavation. The phenomenon may induce horizontal displacements at surface in the area surrounding the edge of the wall. A number of mines at present have at least one boundary adjacent to a public road or railway, and there have been some recorded instances of damage to such structures which may be attributed to local slope instability or in turn this phenomenon of stress relaxation. In addition to damage to roads many opencast sites must divert public services such as gas lines, electricity cables, water mains around the site perimeter in order to work the site. Damage to these services may occur owing to differential lateral movements.

9.4. RESEARCH INTO GROUNDWATER POLLUTION.

9.4.1. Geochemical Survey of Surface Mine Waters.

Chapter 8 presented a survey carried out in all the regions of opencast mining in the United Kingdom into the qualities of water flowing into the mines. Preventative and remedial techniques have also been detailed.

The following conclusions may be drawn from the research;

a). The Scottish Region would appear to be the only area at present suffering from an acidic and ferruginous mine water problem. pH values are very low with corresponding high dissolved iron concentrations providing a serious environmental hazard.

b). The overall water qualities from mines in other Regions conducted in the survey appear to be satisfactory. Future problems may occur in South Wales where the strata does contain a significant degree of pyrite. A water treatment plant has been constructed on one site, although only as a precautionary measure.

c). A mine may be discharging a water of an adequate quality into a watercourse, which may contain an acidic discharge which has been diluted in the pit environment. This problem could be specifically highlighted in mines used to reclaim more pyritic colliery spoil. If the discharge becomes undiluted in the fill, then an acid forming reaction may initiate.

c). Advance dewatering may result in the overlooking of a potential water pollution problem from the restored site, if streams later emanate from the backfill surface. The technique however has many advantages including the reduction of water pollution during the operations.

d). The use of limestone as either an additive to a fill or as a treatment of acid drainage appears unreliable, ineffective and expensive. The most effective method to prevent post-mining water pollution appears to be by selective overburden placement, sealing noxious material on all sides with clay material.

A growing opinion exists that if an acid forming reaction within a fill can be controlled until a rich vegetative growth is established, then the subsequent deprivation of oxygen within the fill will inhibit the bacterially catalysed reactions. Control may be gained by compaction, (reducing oxygen and water content), or the temporary application of bacteriacides to the fill. The use of bacteriacides is an untried technique in the United Kingdom, and may form the basis of a line of research.

9.5. SUGGESTIONS FOR FUTURE IMPLEMENTATION.

9.5.1 Groundwater Pollution Research

The following ideas are suggestions for possible future implementation. They are aimed at predicting a possible pollution problem and at evaluating possible preventative or remedial techniques.

a). The conduction of a pre-mining geochemical survey to assess existing water qualities. In addition to sampling streams, rivers and lakes in the area of the mine, samples of water from exploration drilling boreholes could also be taken. On sites where a pollution problem has occurred or envisaged, than regular water sampling could occur over the life of the mine. This monitoring programme can serve as and "early warning" system against local water pollution. The results may also be able to be used in cases where a surface mine has been blamed for causing water pollution which has in fact originated from another source.

b). For sites which are to be used to reclaim colliery spoil or more pyritic overburden a full geochemical analysis of the inflowing waters must be conducted. To supplement these analyses, some form of leaching tests should be carried out on representative spoil samples in order to determine a potential polluting load. Sites containing acid inflows are considered unsuitable for reclaiming colliery spoil, as a pollution problem may manifest itself which by careful planning may have been avoided completely.

c). On surface mines which are known to have a pollution problem, an estimation should be made of the positions and chemical nature of any spring which may emanate out of the backfill on recovery. On sites where such springs are predicted to occur, the design of clay barriers should be considered in order to force springs to emerge at surface before contact with the contaminating material.

d). On mines operating with advance dewatering methods, samples of spoil should be taken for analysis for polluting materials. Thus it will be known if any serious pollution problem may occur after the water table has recovered.

e). Care should be taken when thin coal seams or ironstone bands are reclaimed into the spoil. Such measures should be examined for their pollution potential, and if need be, selectively reclaimed and isolated form water with clay seals.

f). Some work has been performed in the Scottish Region with the aim of predicting pollution potentials from exploration drilling strata cores. This technique if fully developed could prove an excellent method for determining the overall quality of the water which the mine will have to pump, as well as the final quality of the water in a backfill. These strata cores could also be used for a weathering analysis, monitoring rock degradation with time under laboratory conditions.

g). An investigation into the use of bacteriacides in both the reduction of pollution during operations and in the backfill may enable the design of a cheap and effective method of water pollution control to be devised. This work could be supplemented by an investigation into changes in groundwater geochemistry with time in a restored backfill site. Particularly with respect to the establishment of the vegetative cover.

9.5.2 Backfill Settlement Research.

a). A backfill displacement data base.

There exists a great deal of backfill settlement data both in this thesis and in other works which if amalgamated would form the basis of a backfill settlement data base. If such a data base were formed then ultimately it may be possible to introduce some form of statistical analysis to predict probabilities of backfill settlement magnitude and rate and degree of groundwater recovery. The data base would have to contain an exhaustive amount of information for each site included. Some suggestions for enclosure are presented in table 9.3.

b). **An investigation into lateral movements.**

The research approach could be based on the following distinct steps:-

i). Precise Surveying and Levelling of specific stations established around a surface mining excavation.

ii). Instrumentation and monitoring of 3-dimensional movements on the surface as well as in boreholes.

iii). Theoretical Studies incorporating numerical techniques using digital computers.

Instrumentation would consist of surface levelling stations possibly accompanied by borehole instruments such a tension wire extensometers to monitor settlement and shear movements or inclinometers to monitor lateral displacements. On backfill, instruments would be put in place as soon as practically possible after the final restored levels are achieved. The movements of the fill being monitored as the void progresses away from the initial cuts. Levelling stations would be placed around the mine excavation for the duration of

Name of Site.
Region.
Mining Method.
Method of Compaction, (if any).

Overburden Composition.
Changes in Overburden Composition with Area.
Relative Ages of Fill Materials.
Locations of Highwalls and sharp changes in Fill Depth, e.g. Benches.

Pre-Mining Groundwater Level.
Details of Pumping Operations.
Sources of Groundwater and Surface Water into the Mine.
Positions and pumping on local opencast and deep mine sites.
Estimated Final Groundwater Level after the termination of all external influences.

Depths of fill.
Positions of Spoil Mounds on backfill, (if any).
Positions of Lagoons on Backfill, (if any).
Positions of Site Haul Roads constructed on Fill, (if any).

Details of Monitoring Scheme.
Time Elapse between Restoration and Commencement of Monitoring.
Vertical Settlement Records.
Lateral Movement Records.
Groundwater behaviour.
Laboratory testing of Backfill materials.

Examples of Structural Damage resulting from Fill movements.

Table 9.3. Information Required for a Backfill Displacement Data Base.

the monitoring period, (preferably from the start of excavation). Precise levelling techniques must be used. It would be preferable to have a number of sites of different depths and geology for comparasion.

It would be preferable to have a number of sites of differing depths and geological conditions.

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APPENDIX 1.

AN EXAMPLE OF A PERMEABILITY CALCULATION FROM CONSTANT HEAD TEST DATA.

AN EXAMPLE OF A PERMEABILITY CALCULATION FROM CONSTANT HEAD TEST DATA.

The raw data obtained from the constant head tests in the field consisted of the following;

i). The steady-state constant head , P, p.s.i.
ii). The total volume of water pumped into the test compartment, V, litres.
iii). The period of each test, t, seconds.

The dimensions of each compartment, (fig A1.1), were known as;

d = diameter of compartment, m.
l = length of compartment, m.

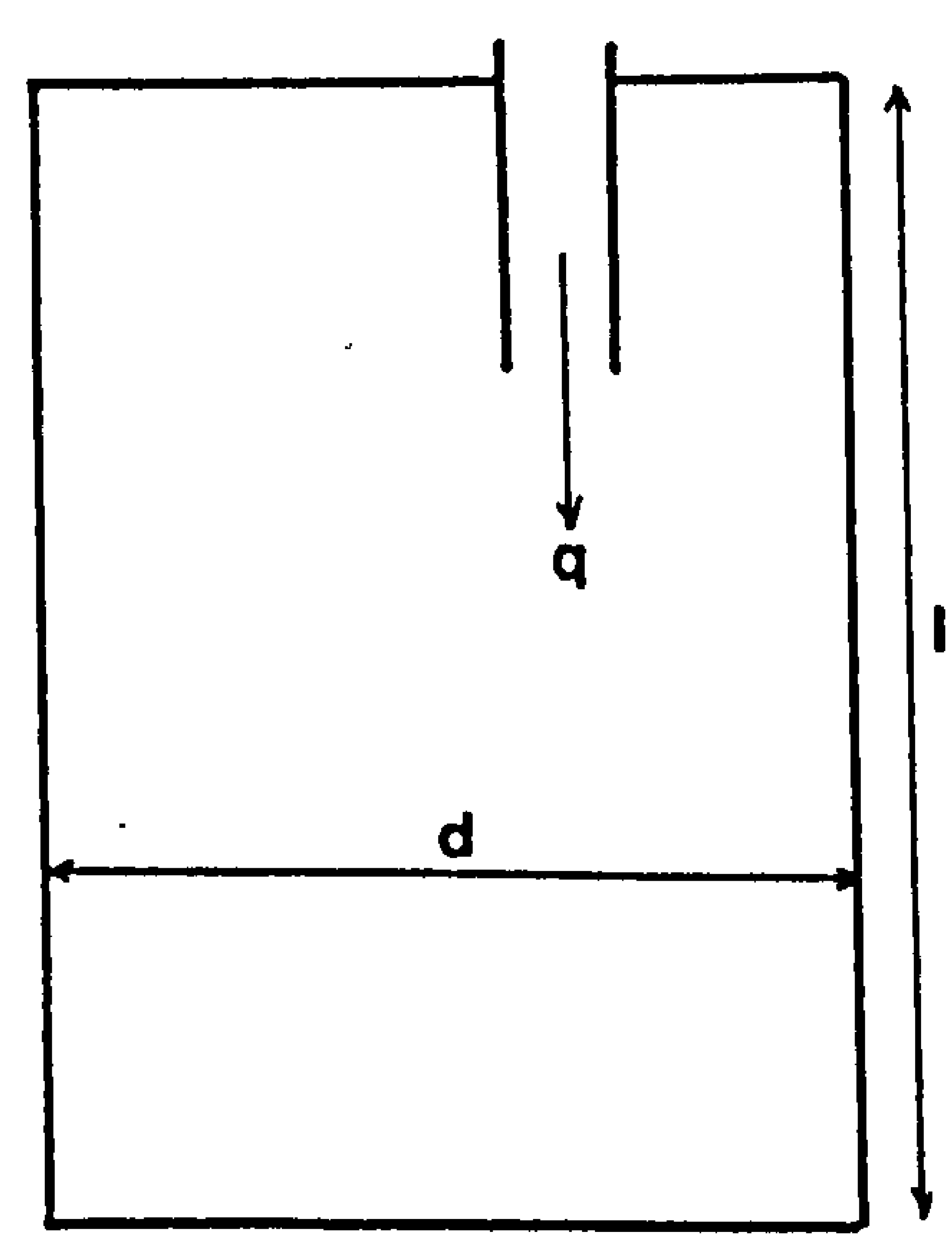

Figure A1.1 Variables used in Calculation.

The equation applicable to this type of tests is as follows;

$$k = \frac{q. \log(2.m.l/d)}{2.\pi.l.H.} \qquad A1.1$$

where;

k = coefficient of permeability normal to the compartment, m/s

k_p = coefficient of permeability parallel to the compartment, m/s

q = flowrate at constant head, m^3/s.

l = length of test cavity, m.

d = borehole diameter in test cavity, m.

$m = (k/k_p)^{\frac{1}{2}}$

H = constant pressure head of water applied during test.
(above any original groundwater value), m.

The first stage of the calculation is to standardise units.

Converting p.s.i to metres of head.

1 p.s.i = 2.307 m Water Head. A1.2

Converting total flow from litres to m^3.

$1\ m^3 = 10^3$ litres. A1.3

Giving the flow rate as;

$q\ m^3s^{-1} = V.10^{-3} / t$ A1.4

These values may now be substituted into equation A1.1.

Example

A steady state pressure of 14 p.s.i was recorded associated with a total flow of 223 litres over 20 minutes. The length of the compartment under test is 3 metres and the diameter is 0.197 m. Calculate the permeability of the horizon under test.

Converting Pressures.

$$14 \text{ p.s.i} = 2.307 \times 14 \text{ m Head} = 32.298 \text{ m}$$

Determining Flow Rate.

$$223 \text{ litres} = 223 \times 10^{-3}\ m^3$$

$$20 \text{ minutes} = 20 \times 60 = 1200 \text{ seconds.}$$

$$\text{Flow Rate } q\ m^3s^{-1} = 0.223/1200$$

$$= 1.86 \times 10^{-4}\ m^3s^{-1}$$

The ratio of horizontal to vertical permeability has always to be estimated when using equation A1.1. In intact rocks the ratio may be high e.g. 500, however in a broken rockfill mass the ratio must be much lower owing to rock breakage. For the purposes of this calculation an assumption is made that the two values are equal, i.e. m = 1. This will not be true in the natural state owing to vertical loading from the self weight of the fill. It is however a reasonable assumption.

Inserting values in equation Al.1.

$$k = \frac{q.\ \log\ (2.m.1/d)}{2.\pi.1.H.} \qquad \text{Al.1}$$

$$k = 1.86 \times 10^{-4}.\ \log\ (2 \times 1 \times 3\ /\ 0.197)$$

$$2 \times \quad \times 3 \times 32.298$$

Permeability of Horizon k = 1.04×10^{-6} m/s

APPENDIX 2.

SUMMARY OF STANDARD CHEMICAL TECHNIQUES FOR THE ANALYSIS OF MINE WATER SAMPLES.

SUMMARY OF STANDARD CHEMICAL TECHNIQUES FOR THE ANALYSIS OF MINE WATER SAMPLES.

a). ALUMINIUM

Eriochrome Cyanine R, Spectrophotometric Method.

Principle

Dilute aluminium solutions buffered to a pH of 6.0 produce with Eriochrome cyanine R dye, a red to pink complex exhibiting maximum absorption at 535 m .

Interferences

Negative errors caused by fluoride and polyphosphates.

Minimum Detectable Concentration.

In the absence of fluorides and phosphates, 6 g/l Al.

Apparatus

Spectrophotometer for use at 535 nm, utilizing a light path of 1 cm or longer.

Glassware, all glassware should be washed with warm 1+1 HCl and rinsed with aluminium free distilled water.

Reagents

Stock Aluminium Solution.

8.792 g aluminium potassium sulphate, $AlK(SO_4)_2.12H_2O$ to 1 litre distilled water.

Standard Aluminium Solution.

10.00 ml stock solution to 1 litre distilled water.

1.00 ml = 5.00 g Al. Prepare daily.

Sulphuric Acid, 0.02 N.

Ascorbic Acid.

Dissolve 0.1 g ascorbic acid in 100 ml distilled water, prepare daily.

Buffer reagent.

Dissolve 136 g sodium acetate, $NaC_2H_3O_2.3H_2O$, in distilled water. Add 40 ml 1 N acetic acid and dilute to 1 litre.

Stock Dye Solution.

A number of dyes are available for the conduction of this test, Solochrome Cyanine R/ Eriochrome Cyanine, Eriochrome Cyanine R etc.

Tests conducted have used Solochrome Cyanine R, dissolving 100 mg of dye to 100 ml distilled water. pH should be about 2.9. Stock solutions can be kept for at least a year.

Working Dye Solution.

Dilute 10.00 ml of stock dye to 100 ml, stable for six months.

Method.

Set the spectrophotometer to 535 nm, according to the manufacturers specifications. Prepare a number of aluminium solutions based on the standard in order to prepare a calibration curve. Prepare each sample to a volume of 25 ml. Include a blank sample with no aluminium present.

To each sample;

Add 1 ml 0.02 N sulphuric acid and mix.

Add 1 ml ascorbic acid and mix.

Add 10 ml buffer solution and mix.

Add 5 ml dye solution and mix.

Make up immediately the volume of the sample to 50 ml with distilled water.

Let the sample stand for 5-15 mins. (Colour fades after this time).

Read absorbance at 535 m , having set the blank sample to 0 absorbance.

Plot Calibration Curve.

Repeat procedure with unknown samples.

For samples containing high concentrations of fluorides and polyphosphates the reader is referred to the references at the end of this appendix.

b). CALCIUM

Flame Spectroscopy

Principle.

The sample solution is sprayed into a flame of a carefully controlled character, emitting a light of characteristic wavelength. At sufficiently low concentrations the intensity of the flame emission is directly proportional to the concentration of the metal.

Reagents

Calcium standard solution.

1.000 g pure calcium carbonate in 50 ml of distilled water. Cautiously add 20.5 ml N HCl and warm until solution is complete. Make up to 1 litre.

1.0 ml = 1.0 mg $CaCO_3$

1.0 ml = 0.4 mg Ca.

Method

Calibrate the flame photometer to the manufacturers specifications. By preparing samples of known concentrations determine a calibration curve.

Test unknown samples, diluting if necessary to read in the linear range.

c). CHLORIDE

Silver Nitrate Method.

Principle

Chloride is determined by titration with silver nitrate in the presence of potassium chromate indicator.

Interferences

Bromide, iodide and cyanide are returned as chloride. Orthophosphates > 25 mg/l interfere, and iron masks the end-point in excess of 10 mg/l. Thiosulphate, thiocyanate, cyanide, sulphide and sulphite also interfere.

Reagents

Silver Nitrate standard solution.

Dissolve 4.791 g $AgNO_3$ in distilled water, dilute to 1 litre. Store in brown bottle.

Chloride standard solution.

Dissolve 1.648 g sodium chloride in 1 litre distilled water.

$1.0\ ml = 1.0\ mg\ Cl^-$

The titration must be carried out without dilution.

Potassium Chromate Indicator, (bottled).

Method.

Filter the sample if necessary.

Measure 100 ml of sample into a flask on a white surface. If the pH of the sample is below 5, add a small amount of calcium carbonate and stir. If pH is above 9.5, determine on a separate quantity the volume of acid, (not HCl), required just to discharge the colour of phenolphthalein and add an appropriate quantity to the sample under test.

Add 1 ml indicator solution and titrate with standard silver nitrate until the slightest perceptible reddish colouration exists. Carry out a blank determination on a sample containing theoretically zero chloride.

$$Cl^-\ mg/l = \frac{\text{Volume of silver nitrate (ml)} \times 1000}{\text{Volume of Sample (ml)}}$$

If any interferences occur during the testing of samples, the reader is referred to the references at the end of this appendix.

d). IRON, (FERROUS AND FERRIC).

Reaction with O-Phenanthroline, Spectrophotometric Method.

Principle.

Iron is reduced in solution to the ferrous state, and reacted with Ortho-Phenathroline at pH 3.2-3.3. The reaction forms an orange-red complex which is stable for at least six months. The intensity of the colour is measured by spectrophotometer at 510 nm.

Reagents.

Stock Iron Solution.

Add slowly 20 ml conc H_2SO_4 to 50 ml distilled water and dissolve 1.404 g ferrous ammonium sulphate, $(Fe(NH_4)_2(SO_4)_2.6H_2O$. Add dropwise 0.1 N $KMnO_4$ until a faint pink colour persists. Dilute with distilled water to 1000 ml.

Standard Iron Solution.

50.00 ml stock solution to 1 litre.

1.00 ml = 10.0 g/l Fe.

Phenanthroline Solution.

Dissolve 100 mg 1,10-phenanthroline monohydrate in 100 ml distilled water. Add 2 drops conc HCl to dissolve. 1 ml solution enough for 100 g Fe.

Ammonium Acetate Buffer Solution.

Dissolve 250 g ammonium acetate in 150 ml distilled water. Add 700 ml conc glacial acetic acid to form slightly more than 1 litre of solution. Prepare new reference standards with each buffer preparation.

Hydroxylamine solution.

Dissolve 10 g $NH_2OH.HCl$ in 100 ml distilled water.

Method.

Total Iron

Prepare standard samples, 25 ml and set spectrophotometer to read maximum absorbance at 520 m .

Prepare calibration curve by treating each known sample as follows;

Add 5 ml buffer solution and mix.

Add 1 ml Hydroxylamine and mix.

Add 5 ml Phenanthroline solution and mix.

Allow 10 minutes for colour development.

Prepare calibration curve.

Test unknown samples.

Ferrous Iron

To test for ferrous iron alone, omit the addition of hydroxylamine solution.

e). MAGNESIUM

Deduction Method.

Principle.

From knowledge of the total hardness, calcium, iron aluminium, and manganese, determinations a satisfactory determination for magnesium may be made.

Method

If Hardness is known as mg/l $CaCO_3$, then

Hardness as $CaCO_3$ mg/l =

$$2.497.Ca + 4.116.Mg + 5.564.Al + 1.792.\ Fe + 1.822.Mn.$$

Where all cation concentrations are given as mg/l.

N.B. other metal ions in significant amounts, e.g. zinc and strontium will also affect Total Hardness.

From this equation the concentration of magnesium ions may be deduced.

f). MANGANESE

Persulphate Method; Spectrophotometric.

Principle.

Persulphate oxidation of soluble manganous compounds to form permanganate is carried out in the presence of silver nitrate. Absorbance is measured at 530 nm.

Reagents.

Manganese Standard Solution.

Dissolve 0.144 g potassium permanganate in approximately 100 ml of water, add 25 ml 20 % by volume sulphuric acid. Reduce the permanganic acid by dropwise addition of 20 volume hydrogen peroxide. Make up to 1 litre.

1.0 ml = 50 g Mn.

Ammonium Persulphate Solution, 10%.

Sulphuric Acid, 50% v/v.

Sodium Nitrite, 1% aqueous solution.

Silver Nitrate, 5% aqueous solution.

Method..

A set of standards to enable the construction of a calibration graph are prepared. A suitable quantity of sample, (10 mls) are placed in a 100 ml beaker. Add 5 mls of sulphuric acid and remove chlorides by evaporation to fuming. Adjust the volume of the solution to about 30 mls. Add 1 ml of silver nitrate solution and heat to boiling. Add 5 mls of ammonium persulphate solution and simmer gently for 10 minutes. Cool and make up to 100 mls with distilled water. Prepare a blank with distilled water. Compare absorbances at

530 nm.

Test unknown samples in an identical manner.

g). POTASSIUM

Flame Photometry

Principle

See CALCIUM

Reagents

Potassium Standard Solution.

1.907 g Potassium Chloride dissolved in 1 litre distilled water.

1.0 ml = 1.0 mg K

Alternatively use Calibration standard for flame photometers, 100 mmol/l K.

Method.

See CALCIUM

h). SODIUM

Flame Photometry

Principle.

See CALCIUM

Reagents.

Sodium Standard Solution.

2.542 g Sodium Chloride dissolved in 1 litre distilled water.

1.0 ml = 1.0 mg Na

Alternatively use Calibration standard for flame photometers, 100 mmol/l Na.

Method.

See CALCIUM

i). SULPHATE.

Gravimetric Method.

Principle.

Sulphate is precipitated as barium sulphate in the presence of hydrochloric acid.

Reagents.

Hydrochloric Acid, (1+1)

Barium chloride solution, 50g/l.

Methyl Orange Indicator.

Method.

Measure into a beaker a suitable volume of sample, (25-50 ml). Neutralize to methyl orange by the addition of hydrochloric acid or ammonium hydroxide solution. Adjust to 200 ml, add 2 ml HCl, (1+1), and boil for 20 seconds. Remove from heat and add 15 ml hot barium chloride solution, slowly from a pipette in the centre of the hot solution, with continuous stirring. Set aside for 1 hour and filter through ashless filter paper.

Transfer the filter paper to a previously ignited and weighed crucible. Dry the filter paper and precipitate over a low flame, gradually increasing the heat until the paper chars. Take care so that the paper does not burst into flame as this will entail losses. When charring is complete place the crucible in a well-ventilated muffle furnace and ignite at 800 C for at least one hour.

$$\text{Sulphate } SO_4 = \frac{\text{Weight of } BaSO_4 \text{ (mg)} \times 412}{\text{Volume of Sample.}} \text{ mg/l}$$

j). <u>TOTAL HARDNESS.</u>

Principle

Disodium ethylenediaminetetraacetate (EDTA), forms a chelated soluble complex when added to a solution of certain cations. When a small amount of the recommended indicator is added to a solution containing calcium and magnesium ions at a pH 10+0.1, the solution becomes wine-red in colour. The solution is then titrated with EDTA the calcium and magnesium are complexed and at the end-point the solution turns from wine-red to blue.

Interferences.

Several metal ions interfere, which may be surpressed by the use of sodium sulphide inhibitor, which precipitates insoluble sulphides.

Reagents.

Calcium standard solution.

See CALCIUM

Buffer Solution.

Add 55 ml conc HCl to 400 ml water. Add slowly with constant stirring 310 ml ethanolamine, followed by 5.0 g magnesium disodium EDTA.

The buffer solution must be adjusted before use.

Prepare a 1 in 10 dilution of calcium standard solution and a 1 in 10 dilution of EDTA. Dilute 5 ml of buffer to 100 ml water, add one or two drops of indicator and mix. The colour should be pure blue.

If the colour is blue, titrate the diluted buffer solution with dilute calcium solution. The buffer is satisfactory if 0.2 ml produces a reddish tinge, after standing a few seconds. If this is not so continue the titration, until a faint tinge is observed. Subtract 0.2 ml off the reading and calculate the amount of standard calcium solution to be added to the stock buffer, and mix. Recheck buffer.

If the colour is red, titrate with dilute EDTA and calculate the necessary additions to produce the required pure blue colour. Recheck buffer.

EDTA solution, N/50.

Dissolve 3.722 g disodium EDTA in water, dilute to 1 litre. Check by titration against standard calcium solution that;

1.0 ml = 1.0 mg $CaCO_3$.

Indicator.

Dissolve 0.5 g Solochrome Black/Eriochrome Black T in a mixture of 75 ml triethanolamine and 25 ml alcohol. The solution is stable for six months.

Sodium Sulphide Inhibitor.

Dissolve 5 g sodium sulphide in 100 ml water. Store in container with tightly fitting stopper.

Method.

Place a suitable volume of sample, 50 ml, filtered if necessary in a conical flask. Add 1 ml of buffer and mix well. Add 1 ml of sodium sulphide solution if necessary. Mix and add 1 or 2 drops of indicator. In the presence of calcium and magnesium ions the solution will be wine-red in colour. Titrate with standard EDTA with constant stirring, until the last reddish tinge disappears. Do not allow the time for titration to exceed five minutes after adding the buffer, or use more than 15 ml EDTA solution.

$$\text{Total Hardness as } CaCO_3 = \frac{\text{Volume EDTA N/50 (ml)} \times 1000}{\text{Volume of Sample}} \text{ mg/l}$$

k). <u>TOTAL OXIDISED NITROGEN.</u>

Spectrophotometry.

Principle

The analysis of total oxidised nitrogen by spectroscopic methods is one of the very few analyses which may be performed with no sample treatment, (save possible dilution). The absorbance of the solution is measured at 220 nm and interference from organic substances is adjusted by measurement at 275 nm.

Reagents

Stock Nitrate Solution.

0.361 g Potassium Nitrate in 500 ml distilled water.

Standard Nitrate Solution.

100 ml stock to 1 litre.

1.0 ml = 10 g N.

Method

A suitable range of calibration standards are constructed. No sample treatment is required. Absorbance for each sample is measured at 220 and 275 nm. The net absorbance of the nitrate/nitrite solution is given as;

$$\text{absorbance net} = \text{abs}(220) - \text{abs}(275)$$

Thus correcting for organic interference.

A calibration curve is constructed and the unknown samples tested in an identical manner. A blank of distilled water should also be tested.

REFERENCES

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