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PREDICTIVE SETTLEMENT ANALYSIS OF MINE SPOIL AT AN ALBERTA OPEN PIT COAL MINE

by

PAUL GERALD HANKINS

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
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DEPARTMENT OF CIVIL ENGINEERING

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Predictive Settlement Analysis of Mine Spoil at an Alberta Open Pit Coal Mine submitted by Paul Gerald Hankins in partial fulfilment of the requirements for the degree of Master of Science in Civil Engineering.

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ABSTRACT

This thesis analyzes the settlement behavior of instrumented minespoil at the Highvale and Whitewood Mines near Edmonton, Alberta. Patterns of settlement were observed for different spoil materials and factors influencing settlement were determined. A method to predict long-term settlement of mine spoil, called the Predictive Settlement Method, was developed. The method is based on the settlement behavior of known spoil stratigraphy and its interaction with various conditions influencing settlement such as the development of a partially indurated crust, heavy infiltration and groundwater table effects. Several examples using the method to predict long-term settlement are explained. The specifics of the method are applied to spoil at the Highvale Mine to predict long-term settlement under specified conditions. The method is also applied to the Diplomat Mine, located near Forestburg, Alberta, and the Horsley Mine in Northumberland, United Kingdom.

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1. INTRODUCTION

1.1 Background

A large area of Alberta (approximately 240,000 km^2) is underlain by coal deposits which can be exploited by surface mining. These coal resources are expected to provide thermal power generation in Alberta for at least another 50 years. In addition to coal, large quantities of oil sand and sedimentary iron-ore resources are located throughout Western Canada at depths suitable for recovery by surface mining techniques.

Surface mining techniques allow for the mining of multiple seams of coal which is not possible with underground mining. A major drawback with surface mining, however, is that the land surface becomes totally disrupted. After the resource is removed and mining operations are completed, the land needs to be reclaimed, for both environmental and economic reasons.

The analysis for this thesis was based on research carried out at the two TransAlta Utilities Corporation coal mines near Wabamun, Alberta, the Highvale and Whitewood Mines, located about 80 km west of Edmonton, Alberta. The Highvale and Whitewood Mines are in a prime recreational region with residential and light industrial development a future possibility. In similar areas throughout Alberta and Canada, the need to reclaim mine spoil for development will grow, as the demand for land grows in the future.

Before residential development begins, a thorough understanding of the properties and behavior of the reclaimed spoil should be obtained. Mine spoil is fully disturbed and has unique settlement characteristics. Factors such as the rise of the groundwater table and infiltration can greatly influence settlement.

There is limited experience related to the engineering analysis of open pit reclaimed mine spoil. This thesis should have implications for any mine reclamation where settlement is a concern.

1.2 Objective

The objective of this thesis is to derive a simplified method of predicting the long-term settlement of reclaimed mine spoil. Factors that are known to influence the settlement of reclaimed mine spoil will be identified and related to the method, termed the Predictive Settlement Method. The predictions made in this thesis are applicable only to the Highvale and Whitewood Mines. It is possible to apply the specifics of the method to other minesites with spoil material similar [illegible] that at the Highvale and Whitewood Mines, that is, [illegible]ly indurated rocks that when excavated, lose their r[illegible]ike characteristics and behave essentially a[illegible]oil. However for best results, it is suggested that the general format of the method be used at other minesites. The general format can be applied wherever sufficient settlement data are available, the spoil profile can be determined, and where movement of the groundwater table can be predicted and monitored.

1.3 Research Program

The development of this thesis involved the reworking of data from research contracts between the University of Alberta Geotechnical Group and TransAlta Utilities Corporation. These data, from field and laboratory testing, were analyzed to determine the factors which influence settlement of reclaimed mine spoil, and to formulate a method to predict long-term settlement. Numerous site visits were performed to monitor the settlement of spoil and gather groundwater table data at the Highvale and Whitewood Mines.

1.4 Scope of this Thesis

Chapter 2 is a literature review of the settlement of partially saturated fills.

Chapter 3 contains a description of the data source: what the field instrumentation involved and what testing was performed. This chapter also includes a brief introduction to the Predictive Settlement Method.

Field data and a discussion of factors affecting settlement of mine spoil are found in Chapter 4. The Predictive Settlement value Ps is explained, followed by a discussion of Ps values from twelve sites at the Highvale and Whitewood Mines. Ranges of Ps values applicable to spoil at the Highvale Mine are then presented. The chapter concludes with a brief discussion of laboratory testing data.

Chapter 5 summarizes the significant factors that contribute to mine spoil settlement, based on the field and laboratory tests performed at the Highvale and Whitewood Mines. This chapter also includes a discussion of the groundwater table and an estimation of the long-term groundwater table at the Highvale Mine. Some examples of how the Predictive Settlement Method can be applied are then explained.

In Chapter 6, the results of this thesis are applied to two other minesites, the Diplomat Mine near Forestburg, Alberta, and the Horsley Mine in Northumberland, United Kingdom.

Chapter 7 briefly summarizes the thesis and presents the major conclusions and some recommendations for future work.

Appendix A contains the design and installation procedures used for the field instrumentation. The test procedure for the large diameter consolidation experiments is found in Appendix B, and the procedure for the slaking tests is found in Appendix C.

2. LITERATURE REVIEW

2.1 Settlement of Partially Saturated Fills

When overburden is removed by dragline, a type of peak and valley topography results. This spoil material is composed of different particle sizes which are packed together, either statically by earthmoving equipment, or dynamically as the spoil is dropped from a height by a dragline.

Throughout the fill (or spoil), there exists a system of capillaries related to the size of voids in the fill. If these capillaries are fine enough, they will often be fully saturated, with a negative pore pressure, due to the relief of stress occurring during previous excavation from depth. A second system of much larger capillaries and voids also exists in the fill, which are often full of air (Cox, 1979). Variations in the moisture content of the fill during compaction and in the dry density achieved will determine the structure of the compacted soil mass. This in turn will affect the settlement that is likely to occur under any given set of circumstances, and the maximum shear strength that can be developed (Booth, 1977).

Settlement of fill can be due to self-weight, under conditions of constant stress and moisture content, (Charles et al., 1978), additional overburden loading

(Cox, 1979), or collapse of soil structure, often related to inundation or saturation (Charles et al., 1978; Nowatzki, 1980). These volume changes are related to the quantity of water present and to the quantity of air entrained in the fill.

Initially when a volume of saturated clay, for example, is excavated, it is broken up into fragments which entrain air. As the external total pressures increase as the height of a spoil peak increases, the fill is caused to compress, resulting in a reduction in void size squeezing out air (or water, if the large voids have already become saturated). This process is likely due to an adjustment of the contact area between soil particles, which is a function of their shear strength.

Volume changes that occur in saturated soils are time dependent and vary with the permeability of the fill, drainage path, and pore pressure gradients set up. Spoil, on the other hand, is most often partially saturated, and may remain that way temporarily (until inundated by a rising groundwater table, for example), or permanently, and thus has unique time-settlement properties.

Collapse settlement may be defined as the settlement that occurs in a partly saturated soil solely because of an increase in the degree of saturation (Booth, 1977). With collapse-susceptible soils, void ratio change is not due to the expulsion of pore water but to the intake of moisture by the soil and the subsequent breaking down of the weak cementation bonds that exist between soil particles. For this reason, resulting settlements are generally not time dependent and can be considered "immediate". However, unlike the "immediate" settlement that takes place during construction on dry, collapse and non-collapse-susceptible soils alike, the settlement of concern here may occur long after the completion of construction when the soil strata becomes excessively wetted. Such "collapse settlements" are then "immediate" with reference to the time such wetting takes place (Nowatzki, 1980).

If a fill is dry and has a significant overburden pressure, soil particles will be highly stressed at points of contact and be relatively unstressed around larger air voids. The addition of water, as by a rising groundwater table, causes a softening at the points of contact and a rapid decrease in volume, or collapse, which squeezes out air from the larger voids (Cox, 1979). This is a problem in earth dams when the fill is compacted too dry of optimum (Penman, 1977). The collapse mechanism involves a major rearrangement of the fill to a denser state of packing.

Barden et al., (1969), found that the collapse mechanism was controlled by three factors. The first was a potentially unstable structure, such as the flocculent type associated with soils compacted dry of optimum. The second was a high applied stress which further increases the instability, and the third was a high suction which provides the structure with a temporary rigidity, and where removal by wetting leads to collapse.

Cox (1979) found that the internal soil properties which affected the amount of collapse in a fill were the initial dry density and the initial moisture content. The external factors which affected the amount of collapse were the total applied overburden stress and the pore pressure of the water supply. Booth (1977) found that the amount of collapse settlement does not necessarily increase with increasing pressure. For any moisture content there is a pressure above which the amount of collapse reduces. This pressure is higher for soils with lower moisture contents.

2.2 Case Histories

The British Research Establishment of Great Britain investigated some open pit coal mine sites to analyze the settlement behavior of spoil material.

Great Britain has been involved in large scale surface coal mining since 1942. Excavation and placement of overburden has been done by draglines and with face shovels using trucks to end-tip the spoil into the mined out areas. The randomly dumped overburden is generally found to be "unconsolidated", with large voids.

At Horsley Village in Northumberland, both methods of excavation were used: face shovels for the upper strata, and a dragline for lower layers. When boreholes were drilled through the spoil, voids of up to 0.5 meters in diameter were encountered. Extensometers were installed in five of the boreholes and provisions were made to monitor the rise of the groundwater table through the fill. The fill, comprised of indurated sandstone and mudstone, contained rock sizes up to a meter in diameter. Further details of the spoil material are given by Charles et al., (1977 and 1984).

Pumping to dewater the mine was stopped about one year after after the instrumentation was installed. A water level rise of 29 meters was recorded at the deepest part of the pit, within two years after pumping ceased (Charles et al.,1977). Collapse settlements as large as 1.4 per cent over 50 meters were recorded. Charles et al., (1977), did not find a correlation between the age of the backfill and its susceptibility to settlement on saturation, but did find that as the groundwater level rose, settlement rates increased. Data from this reclaimed minesite will be discussed in Chapter 6.

In recent years, there have been several instances in southern Africa where deformation of road embankments has occurred, apparently due to collapse settlement within the fill. These have followed periods of exceptional rainfall, often so heavy that water has been temporarily impounded by the embankments. Though much of the evidence is also consistent with shear failure, collapse settlement is considered the more likely cause of deformation (Booth 1975).

Laboratory testing performed by Booth (1977) on collapse-susceptible soils has shown that the amount of collapse is a complex function of soil type, grading, and dry density, initial dry density being a dominant factor (the lower the dry density, the more collapse potential). However, any soil may collapse under the right conditions (Barden et. al, 1969).

3. FIELD AND LABORATORY TESTING

3.1 Introduction

This chapter outlines the field program implemented at the Highvale and Whitewood Mines, introduces the Predictive Settlement Method used to predict long-term settlement, and presents the laboratory testing performed to analyze spoil material characteristics and behavior.

3.2 Settlement and Groundwater Instrumentation - Highvale and Whitewood Mines

The field instrumentation at the Highvale and Whitewood Mines consisted of multipoint extensometers, surface settlement gauges, and standpipes. The multipoint extensometers were used to monitor the variation of settlement with depth. The surface settlement gauges, installed about 3 m deep, measured the total settlement at each site and were related to the uppermost multipoint extensometer. Standpipes were used to monitor the groundwater table, which was related to the settlement of the spoil piles. A description of and installation procedures for the above instrumentation may be found in Appendix A.

In the summer of 1982, two regions at the Highvale Mine were instrumented (Figure 3.1). One region, Highvale North, with spoil ages 1.6 to 3.3 years, was instrumented

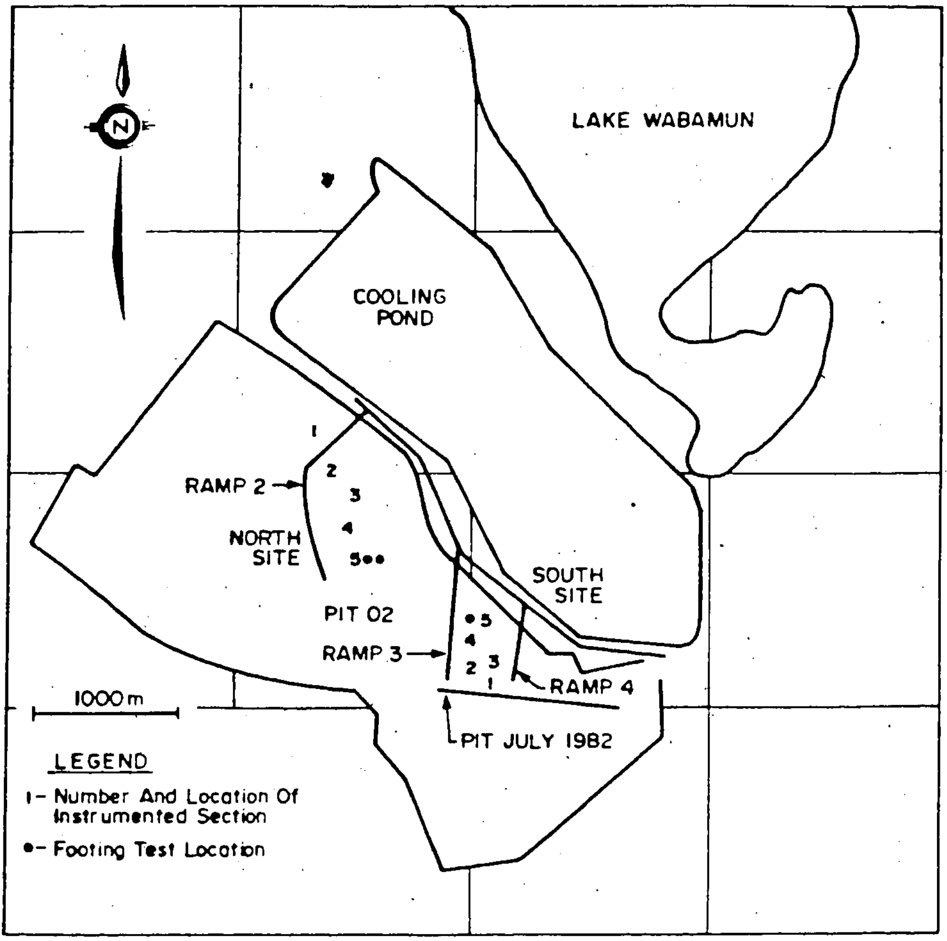


Figure 3.1 Site Plan of the Highvale Mine

in June, 1982. The other region, Highvale South, with spoil ages 1.8 to 2.9 years, was instrumented in August, 1982. Each region consisted of five test sites, and each site contained a multipoint extensometer and two surface settlement gauges. Standpipes were installed at all the Highvale sites except at Highvale North Sites 2 and 4. At the Whitewood Mine, five sites where the spoil ranged from 4.3 to 21.3 years old were instrumented in July 1982, (Figure 3.2), similar to the installations at the Highvale sites. Standpipes were installed at Sites 2, 4 and 5.

The number of extensometers per hole was determined by the depth of the spoil at each site, and were approximately equally spaced throughout the hole. All boreholes extended below the elevation of the pit floor and the lowermost extensometer was lodged in shale bedrock and acted as a reference datum. The standpipe boreholes were placed close to the multipoint extensometers and extended to the base of the spoil material.

The instrumentation installed in the summer of 1982 was placed in unreclaimed spoil pile peaks of different ages. Highvale South was subsequently reclaimed in the winter of 1982 and spring of 1983. Reclamation of the Highvale North region began in the autumn of 1983. At the Whitewood Mine, only the region of Site 5 has been reclaimed.

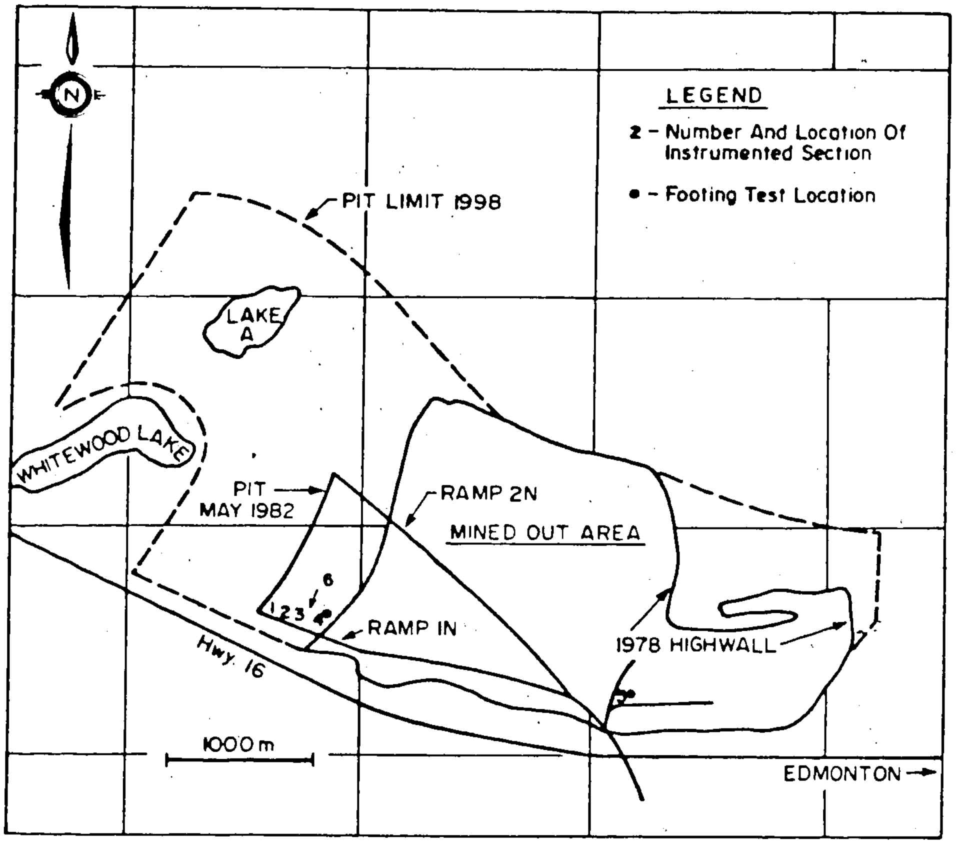


Figure 3.2 Site Plan of the Whitewood Mine

Detailed description of the recovered material, in-situ testing and sampling were carried out during the drilling of the standpipe boreholes, except at Highvale South Sites 2 and 4. Testing included standard penetration testing where Shelby tube samples were taken. These were used for the determination of in-situ densities, moisture contents, and index tests. A limited number of tests were performed.

In late June, 1983, the valley site (designated as Site 6 on Figure 3.2), between Site 3 and Site 4 at the Whitewood Mine, was backfilled with material from the peaks surrounding the instruments at these sites. The fill was about 10 m deep in the center of the valley. This site was instrumented in July, 1983. Instrumentation included a standpipe/benchmark and four deep settlement gauges, installed at various depths to allow for an analysis of settlement with depth of the fill materials.

3.3 Introduction of the Predictive Settlement Method

At each of the test sites at the Highvale Mine and at two sites at the Whitewood Mine, the spoil profile was divided into layers determined by the extensometers at the site. Throughout the following settlement analyses, a layer will define the vertical spacing between specified extensometers, and is comprised of relatively uniform spoil material. Each layer had one of the following as the major component: clay, sandy clay, or partings. Partings is a mixture of low grade coal and shale, with varying amounts of clay.

Using the extensometer settlement data, it was possible to determine the approximate settlement of each layer. Graphs were then plotted of settlement observed for each layer versus time and the logarithm of time. The latter showed that settlement tended to plot linearly with the logarithm of time. This phenomenon was also observed by Charles et al. (1977) and Knipe (1979). Because this thesis is concerned with long-term settlement, this method of plotting allowed for the extrapolation of the straight line generated on semi-logarithmic paper. The slope of the line plotted on semi-logarithmic paper, when divided by the respective thickness of the layer, gave a number which has been termed the Predictive Settlement value, or Ps value. These values could then be compared on the basis of the type of spoil material and the relation of the spoil material to the groundwater table. Although data for the method was computed from spoil less than five years of age, it is suggested that the method be best applied to sites five years after the material is spoiled, and reclamation has occurred. Young spoil (less than five years old) or spoil that has been disturbed by reclamation, may have variable settlement patterns and so this recommended delay will allow for stable settlement patterns to develop. The instrumented spoil material at the Highvale and Whitewood Mines was not disturbed by reclamation procedures and although five years had not elapsed since spoiling, the settlement data from the spoil material was reasonably consistent and was thus useful in analysis.

Ps values are not exact due to some uncontrollable variables. First, mine spoil can be more heterogeneous than homogeneous. Second, the boreholes drilled at the Highvale and Whitewood Mines were logged by different people resulting in possible differences in interpretation. Several of the holes (Highvale North Sites 1,3,5, Highvale South Sites 1,3,5, and Whitewood Site 4) were logged on the basis of soil samples retrieved while drilling. Boreholes at Highvale North Sites 2,4, Highvale South Sites 2,4 and Whitewood Site 2 were logged on the basis of the drillers estimates as the material came out of the hole. The segregation of a spoil profile into layers comprised of uniform stratigraphy is therefore fairly general. However, for spoil materials that fall more or less into the categories mentioned in the first paragraph of this section, it is assumed reasonable to analyze settlement and make calculations using the Ps values that are derived.

3.4 Laboratory Studies: Highvale and Whitewood Mines

The laboratory program related to the Highvale and Whitewood Mines involved the determination of the settlement response of soil samples when loaded and subsequently saturated, and slaking tests.

Several large diameter consolidation tests on Highvale overburden and partings material were performed. Settlement characteristics were measured while the samples were under load, and when water was allowed to infiltrate the samples. It was hoped that this process would simulate in-situ conditions, such as a rise of the groundwater table. These tests provided useful information on the settlement behavior of mine spoil.

Slaking tests were performed on overburden material from the Highvale Mine. Useful information was provided regarding the behavior of spoil material in proximity to the groundwater table.

4. PRESENTATION OF DATA

4.1 Introduction

This chapter discusses the field data and some of the factors that affect the settlement of mine spoil. An explanation of the Predictive Settlement value Ps is followed by a discussion of Ps values for twelve mine sites. Ranges of Ps values applicable to spoil at the Highvale Mine are then presented. The chapter concludes with a discussion laboratory testing data.

4.2 Field Data

4.2.1 Borehole Data - Highvale and Whitewood Mines

From the drilling done in spoil peaks during 1982, the material at the Highvale North sites was found to be predominantly cohesive with a mix of clay, silt, sand, shale and coal chips. The site plan shown in Figure 3.1 locates the various drilling sites. Borehole logs indicate that the coal content generally increases towards the base of the spoil piles. Atterberg limit tests show the natural moisture content of the material is near the plastic limit. Moisture content tests show that there is not a marked dependence of moisture content with depth, and average values vary from hole to hole.

Spoil peaks were also drilled at Highvale South in 1982. Borehole logs from Sites 1 to 3 show the spoil to be clay with varying amounts of sand, silt, coal and shale. Atterberg limits of the material indicated it was at or near the plastic limit. At Site 4 and 5, partings, coal, clay and shale fragments form the major portion of the spoil. In the partings itself, coal is a significant component. The remainder of the spoil is clay, medium to highly plastic with lenses of bentonite.

At the Highvale North and South test sites, the in-situ moisture content is close to the standard compaction optimum moisture content. Activity values from these sites show that the swelling potential of the clayey spoil is generally low, however, some of the clayey spoil has a high swelling potential. Density determinations showed that no correlation appeared to exist between settlement and density of spoil.

All N (Standard Penetration Test Blow Count) values for the spoil at the Highvale Mine are plotted on Figure 4.1 and show a general trend of increasing N value with depth. As densities in the spoil do not increase with depth but remain fairly constant, this figure likely reflects the effect of increased confining stress with depth in the overburden.

Although no large voids were encountered during drilling, voids are known to exist in the spoil piles.

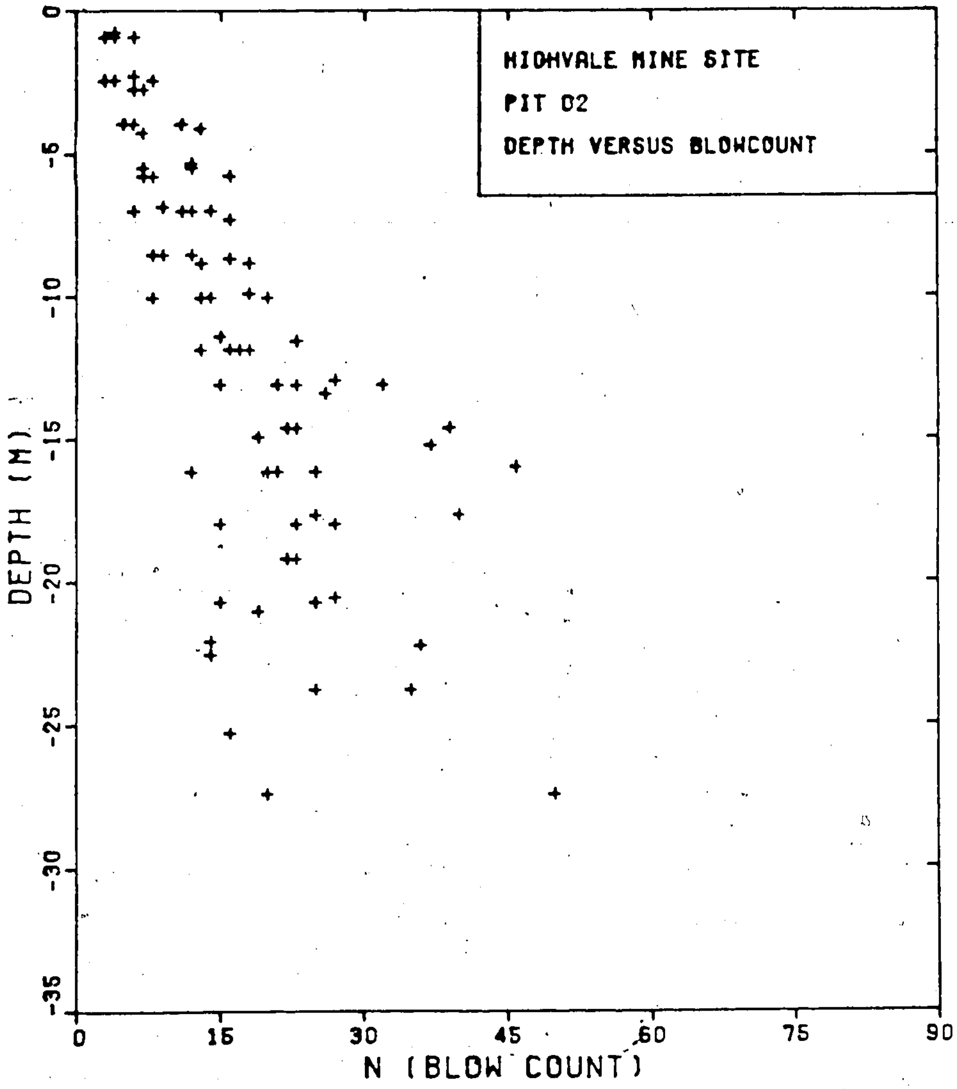


Figure 4.1 Variation of Blowcount at the Highvale Mine

This was evidenced by field technicians during a heavy rainfall in July, 1982 at the Highvale Mine. At one location at the minesite, runoff from the spoil peaks was not ponding but was disappearing into a void in the spoil.

At the Whitewood Mine, drilling was performed in spoil peaks in July, 1982 (Sites 1 - 5) and a backfilled valley was drilled in July, 1983 (Site 6). A plan of the mine showing the borehole locations is given in Figure 3.2. The material at these sites is predominantly sandy with significant amounts of clay in some holes, and varying amounts of silt, shale chips and coal chips. Coal fragments are more prevalent at Sites 4 and 5. Moisture contents vary throughout the holes, generally depending upon the sand/clay content. No definite trends were observed between blow count and depth.

Table 4.1 summarizes the soil properties of the spoil material from spoil peaks at the Highvale and Whitewood Mines.

At the valley site (Site 6) the fill is predominantly sand with a clay layer mixed with coal and rock fragments. Moisture contents tend to be fairly consistent throughout the material. Below the valley the spoil is sand with clay and coal at depth. The density of the valley fill is similar to the material below the valley, ranging from 1750 to 1820 kg/m^3 in the valley and 1600 to 1810 kg/m^3 below the valley. Blow count and dynamic cone blow count

INDEX PROPERTY	CLAY	SANDY CLAY	PARTINGS
Range of Liquid Limits w(%)	38.0-95.4	26.2-54.9	Non-plastic
Average LL w(%)	61.0	36.6	-
Range of Plastic Limits w(%)	17.8-68.7	7.0-32.5	-
Average PI w(%)	37.0	17.8	-
Number of tests	9	5	1
Range of Moisture Contents w(%)	15.0-32.8	9.2-26.4	14.4-31.2
Average M.C. w(%)	22.8	15.2	23.3
Number of tests	45	26	31
Range of density (Kg/m^3)	1140-2173	1905-2082	1028-1510
Average density (Kg/m^3)	1900	1992	1355
Number of tests	14	3	6
% Sand sizes	5-20	65-78	55
Average (%)	13	69	55
% Silt sizes	45-63	12-30	27
Average (%)	54	18	27
% Clay sizes	27-42	0-20	18
Average (%)	33	13	18
Number of tests	7	5	1

Table 4.1 Summary of Index Properties of Spoil Material From the Highvale and Whitewood Mines

generally increased with depth, particularly beyond the bottom of the valley.

4.2.2 Settlement Data

From the settlement data obtained from the multipoint extensometers at the Highvale and Whitewood Mines, it was possible to plot settlement with depth for each site monitored. These graphs show variable settlement patterns as will be discussed in Section 4.5. The older sites show considerably less settlement than the younger sites. It is of interest to note that for some of the older sites, because they have settled even a small amount, a high rate of settlement, (related to the logarithm of time), is observed. This is discussed in detail in Section 4.4. Very little settlement has occurred at the Whitewood sites over the period of observation (about 1.5 years). Less than 1.5 cm is evident at every site, with the exception of almost 3 cm at Site 2 and about 2.5 cm at Site 6 (the infilled valley site). It is seen on Figure 4.2 that the settlement at Site 6 is predominantly in the spoil material below the valley. The fill pushed into the valley has only settled a little, but the increased overburden (from the fill) has caused the material below to settle considerably. Of the five sites instrumented in July 1982 at the Whitewood Mine, only Sites 2 and 4 show consistent data that will be analyzed later.

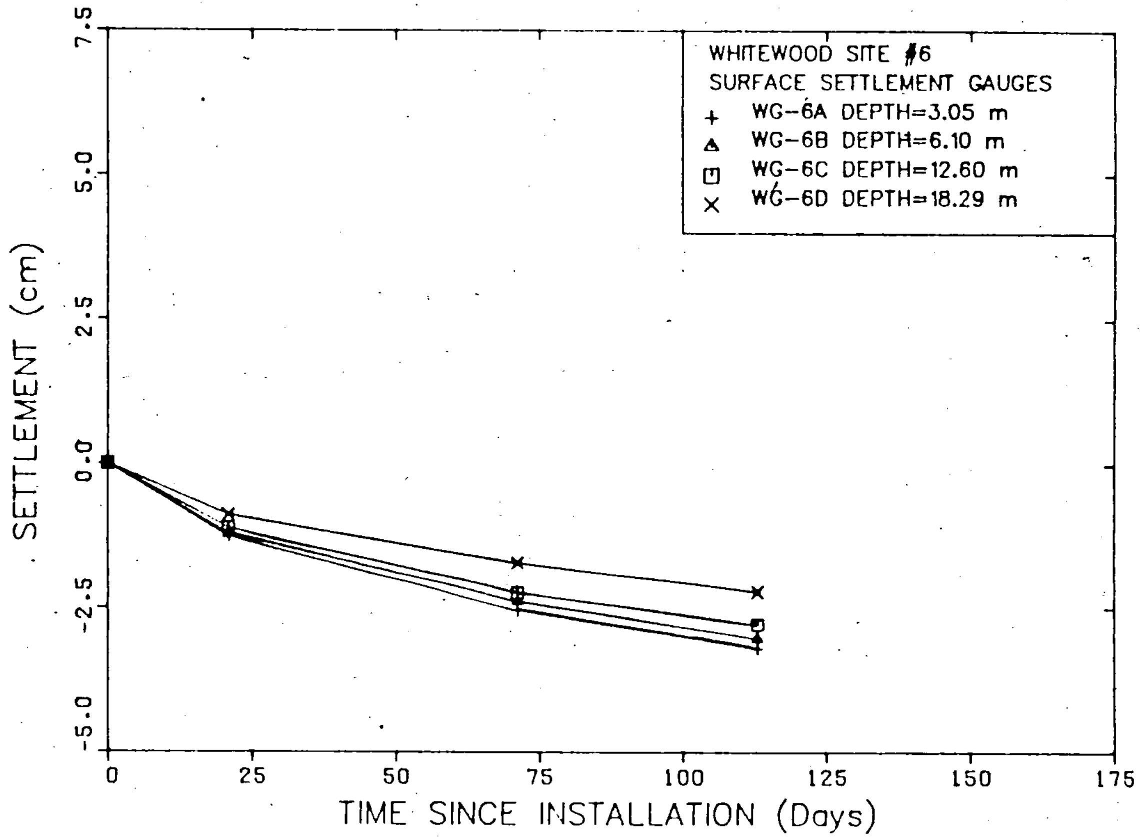


Figure 4.2 Settlement of Deep Gauges at Whitewood Site 6

4.3 Factors Affecting Settlement of Mine Spoil

There are several factors which influence the settlement of minespoil at the Highvale and Whitewood Mines. Analyzing these factors will lead to an understanding of settlement patterns of the various spoil materials at these mines.

At the Highvale Mine, an interesting correlation between meteorological data and settlement of the spoil was found. At Highvale North Sites 1-5, instrumentation was installed slightly before a period of heavy rain (18 cm in 4 days). For up to 100 days after the rainfall, large settlements were observed in the younger sites, Sites 1-3, and small settlements at the older sites, Sites 4 and 5. The instrumentation at Highvale South Sites 1-5 was installed about one month after the rainfall. These sites were still influenced by the heavy rainfall, as will be discussed later in this chapter. Figure 4.3 graphically shows the relationship between monthly rainfall and settlement rates. The high rainfall value on the graph of monthly rainfall versus time is for July, 1982. Figures 4.5 and 4.19 show how the spoil material at Highvale North Site 1 and Highvale South Site 3 responded to the heavy infiltration.

Although it is observed that infiltration from high intensity rainstorms causes settlement, their effect cannot be predicted. This is because rainstorms are random

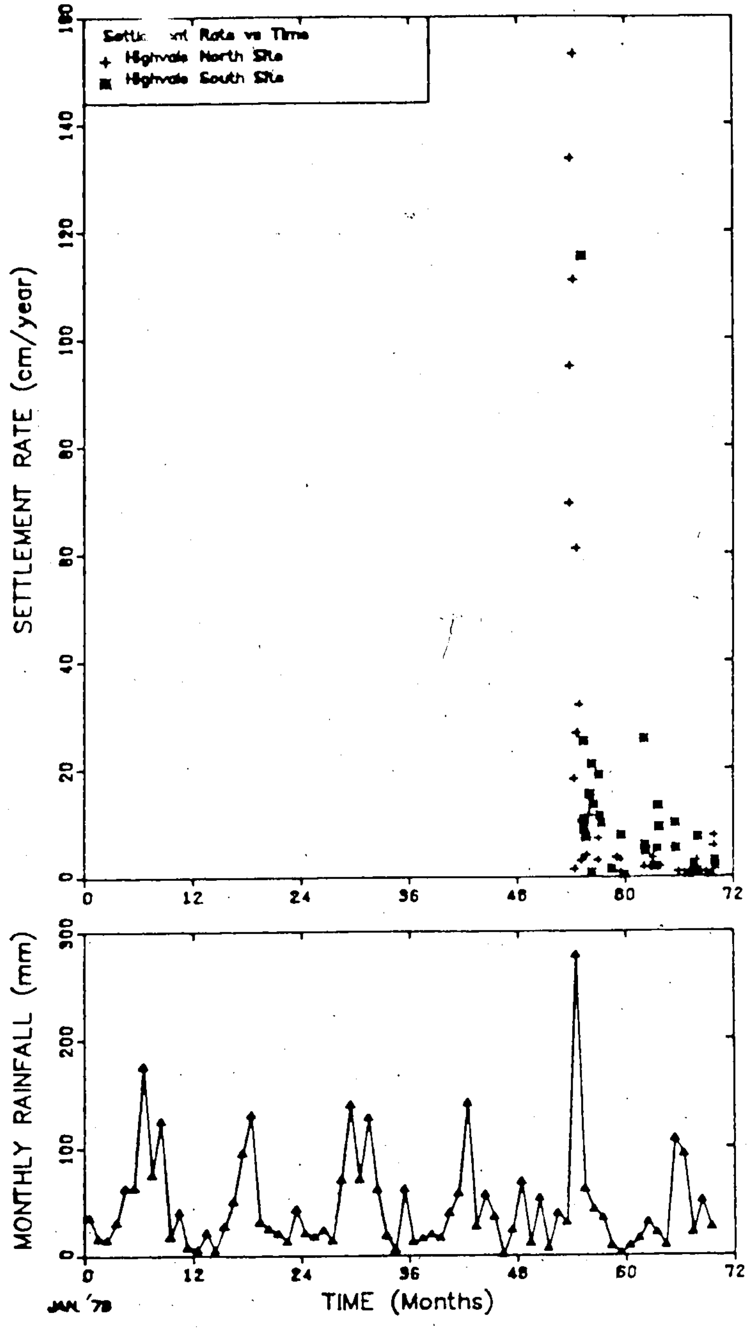


Figure 4.3 Monthly Rainfall and Settlement Rates at the Highvale Mine

in time and their intensity is variable. Due to the total possible settlement of spoil that can occur, subsequent or repeated rainfalls will have a decreasing effect on settlement. This means that applied Ps values will decrease with each heavy rainfall infiltration event. It is also thought that microtopographical effects such as the ponding of rain in shallow depressions cannot be predicted due to their random occurrence. Such variables as the amount of rainfall, evaporation, and silting of the soil under ponded water will determine the degree to which ponded water will infiltrate the soil.

A possible explanation as to why some surface layers (particularly at the older sites) are settling less than others may be related to the development of a partially indurated crust. The formation of this crust is related to a number of possible factors. One such factor may be thixotropy. The term "thixotropy" is used to describe the strength increase in soil with time, under conditions of constant moisture content and constant volume (Moh et al., 1975). The effects of thixotropy are most significant at low strains and in remolded soils having a high liquidity index (Lambe and Whitman, 1979). Terzaghi and Peck (1967) define thixotropy in the following way: Following compaction or remolding, the positions of particles of soil with respect to each other are not necessarily associated with equilibrium of the various attractive and repulsive forces. Hence, the particles may tend to rotate and assume more stable configurations, at unaltered volume. The shearing strength may correspondingly increase and the soil thus exhibits thixotropy.

Weathering is another process that may contribute to the formation of a surface crust. Large spoil particles are broken down by freeze-thaw and/or wet-dry cycles, with the result that voids in the spoil become filled by the downward migration of small particles and thus the density increases. This produces a crust that inhibits the infiltration of water.

Dessication of the surface layer of spoil may also contribute to the formation of a surface crust. Dessication is a process whereby soil moisture in clay is drawn to the surface and evaporated. During this process, the clay becomes stiffer and finally very hard. Since rain water does not expel more than a small part of the air contained in the voids of a surface soil, cohesion in the soil can survive even wet spells of long duration (Terzaghi and Peck, 1967). In other words, dessication produces a crust which prevents infiltration. As the dessication of a soft clay layer proceeds very slowly from the exposed surface in a downward direction, the crust that is formed becomes thicker with age. It is possible that this crust may have structural properties, perhaps acting like a foundation mat.

The process of cementation may also enhance the development of a surface crust. Cementation is caused by the deposition of some salts in soil when soil moisture is evaporated. These salts may form strong bonds between soil particles. Because the Highvale Mine area experiences a mean annual moisture deficit (Monenco, 1981), which means that evapotranspiration exceeds precipitation, this process could be a major factor in the development of a crust.

If a spoil pile is allowed to sit undisturbed for a period of time, it is possible that the soil structure of the surface layer can become quite stable and less susceptible to infiltration or to settlement by self-weight. If the spoil is subjected to a groundwater table rise, it would then likely soften and begin to settle. The various processes leading to the formation of a partially indurated crust, such as thixotropy, weathering, dessication and cementation, possibly explain why both loose and dense spoil has not settled, and thus why there is no correlation between density of spoil and settlement at the test sites. Throughout the remainder of this thesis, this phenomenon of a partially indurated crust will be referred to simply as a crust.

Another factor that influences the settlement of spoil is that of capillary rise, also known as capillarity. Capillarity is a phenomenon whereby a dry soil will draw water above the phreatic line, or where a draining soil mass may retain water above the phreatic line, due to surface tension effects. The height of water above the phreatic surface that a soil can support is called the capillary head and is inversely proportional to the size of soil void at the air-water interface. Because spoil has varying sizes of voids, an infinite number of capillary heads are likely to exist.

If a water supply from above (as in the case of rainfall infiltration) flows downward and fills voids above a large void that would otherwise inhibit capillary rise, these voids can remain saturated and contribute to capillary rise above the large void. This implies that a large rainfall infiltration may result in a significant capillary rise if, for example, the groundwater table had been in a zone of coarse or loose material previously.

It is difficult to ascertain the height of capillary rise in the spoil material at the Highvale Mine. This is because disturbed, unsaturated soil (such as mine spoil) will probably contain a proportion of much larger air voids than are likely in a natural deposit that has dried out slightly since deposition (Barden, 1965). Although capillary rise of 3.6 meters has been measured in silt in laboratory experiments (Lamb and Whitman, 1979), it has been suggested that it is doubtful that a capillary zone of even one to two meters could be detected in any soil because evaporation removes the water as fast as it is pulled to higher elevations (Bowles, 1979). Because evapotranspiration exceeds precipitation at the Highvale Mine, capillary rise, at least in the upper layers of spoil (when the groundwater table is at depth), is not a factor to be considered. However, any material in the vicinity of the groundwater table may be susceptible to capillary rise. This includes partings, as it contains significant amounts of clay which implies potential for capillary rise. At any site considered in this thesis where the groundwater table is in or near the lower part of a layer, capillary rise is assumed to be significant. At some of the sites analyzed, a large degree of capillary rise appears to be the factor influencing settlement. An arbitrary value of 5 m for capillary rise in the three types of spoil material, (clay, sandy clay, and partings), has been chosen for analysis in this thesis.

Based on the slaking behavior of spoil material in laboratory testing, it is reasonable to conclude that slaking of spoil occurs when it becomes submerged. Settlement of submerged spoil material, particularly partings at the Highvale Mine, has been observed. This settlement is thought to be caused by slaking of the spoil.

4.4 Explanation of the Predictive Settlement Value Ps

It was found that when the settlement of a layer of mine spoil was plotted against the logarithm of time, a straight line was generated. The slope of this line, in conjunction with the thickness of the layer, gave a value termed the Ps (Predictive Settlement) value. For some spoil, the line had two slopes, the first very steep over a short period of time, indicating settlement response to a temporary condition, the second was relatively shallow and indicated a long-term settlement pattern under constant conditions. The line for some spoil had only one slope, indicating no change in settlement pattern.

Ps is defined as follows:

$$Ps = \frac{\delta H/H}{\log(T2/T1)}$$

where:

T1 = start time

T2 = finish time (equal to T1 plus an arbitrary time interval)

H = thickness of the strata in question

δH = the change in thickness of the strata (i.e. settlement) between T2 and T1

The Predictive Settlement Method is based on the observation that settlement of mine spoil, under constant conditions, will increase at a decreasing rate, (or at a rate proportional to the logarithm of time). The equation above involves the logarithm of time, and thus considers the fact that spoil of different ages will be settling at different rates with time, or, the same rate if related to the logarithm of time. Therefore, a spoil site will have the same Ps value when it is old as it did when it was young if conditions do not change.

Ps values by themselves do not necessarily reflect the amount of settlement that has occurred (or will occur if used in a predictive capacity). Rather, the amount of settlement that has occurred or will occur is a function of the Ps value, the thickness of the spoil material in question, and when the settlement takes place. It is important to note that the total possible long-term settlement at any site will likely be the same regardless of the path or series of settlement events that occur. Thus, the amount of future settlement at a site is also a function of the amount of settlement that has already occurred. This is discussed further in Section 5.4.1.

The Predictive Settlement equation takes into account varying strata thicknesses, rendering Ps dimensionless. This means that two different plots of settlement versus the logarithm of time that have the same slope would have different Ps values, if the strata thicknesses were different.

A range of Ps values are applied when predicting settlement. This is because the materials that have defined the range may be the same, but have responded differently to settlement causing conditions. For example, if two similar materials have different moisture contents, they may respond differently to capillary rise. A range of Ps values thus accommodates variable spoil behavior and also considers that spoil subjected to heavy infiltration will likely have lower Ps values after the infiltration than before. This is discussed further in Section 5.4.1. As settlement is monitored at a site, it is possible to ascertain the approximate Ps values that exist, and thus narrow the range of the Ps values that were applied.

Settlement in a submerged layer may be due to the slaking of only a small thickness in that layer. However, it is believed that slaking may occur not only when the groundwater table comes in contact with spoil, but for a time after the material is submerged. This means that Ps values calculated from submerged layers are based on the assumption that measured settlement occurs over the entire thickness of the layer, whether it is occurring more in one part of the layer, or uniformly throughout.

During the period of monitoring the instrumentation at the Highvale and Whitewood Mines, the groundwater table rose between 0.0 and 2.5 meters per year. Presently there is no local experience of the effect of a quickly recovering groundwater table (i.e. greater than 2.5 meters per year). Further analysis would need to be performed to determine if settlement patterns change under these conditions. At one site at the Horsley Mine in the United Kingdom, the rate of groundwater table recovery was found to affect the rate of settlement (Chapter 6). This in turn influences the calculation of Ps values.

Ps is constant for a particular soil, but will change if conditions change. Besides a partially saturated soil becoming submerged due to a rising groundwater table, some changes that affect self-weight settlement and thus Ps values are a partially indurated crust, inundation by infiltration, and capillary rise.

4.5 Settlement Analysis of Twelve Mine Sites

4.5.1 Introduction

In the following settlement analyses, the spoil at each of twelve sites is divided into layers, defined by the extensometers at the site. Each layer consists of either clay, sandy clay, or partings, based on borehole logging data. Layers are numbered from the top down. The zone of spoil above the uppermost extensometer is not analyzed as no settlement data were available.

Each site has a graph showing how settlement varies with depth throughout the spoil. On the same graph, the material comprising the spoil profile is identified, and the separation of the spoil into layers is indicated. On each plot of depth versus settlement, a dark line shows the location of the groundwater table over the period of monitoring, and is dated at the beginning and end of monitoring. The term "shale bedrock" on each graph indicates the bottom of the spoil pile into which the bottom extensometer was embedded. The age of the spoil when instrumented is the elapsed time from when the overburden was spoiled to when it was instrumented.

Most sites also have a graph showing settlement versus the logarithm of time. The points on these graphs are actual data points and the lines through the points were drawn using linear regression techniques. The slopes of the lines on each graph are dashed beyond the data points, suggesting a continuation of the present settlement trend, if conditions do not change. If conditions do change, the slope of the line will change. The slope of each line is labelled with one of the following settlement condition terms related to the slopes: self-weight, capillary rise, GWT (groundwater table) in layer, submerged, and response to heavy infiltration.

Calculated Ps values are presented in each of the following analyses, derived from the settlement data of each layer. Actual numerical values of settlement for determining Ps values are from extensometer data. All values of Ps are to be multiplied by 10^{-3}. The sites and layers at the Highvale and Whitewood Mines are abbreviated in the following manner: Highvale South Site 3, layer 2 would become HVS3-2.

4.5.2 Highvale North Site 1 (HVN1)

Highvale North Site 1 is divided into 3 layers (Figure 4.4). Layer 1 is clay and had an initial Ps value of 38.7, related to the heavy rainfall of July, 1982. After a short time, as seen on graph HVN1-1 of Figure 4.5, the slope of the settlement versus the logarithm of time plot changes, the value of Ps becoming steady at 8.08. This steady value could be related to either self-weight of the spoil, or possibly capillary rise. The latter is most likely as the groundwater table is very near the bottom of the layer, although it has dropped a meter over the test period (July 1982 to November 1983, Figure 4.4).

It is a strange phenomenon for an extensometer to register less settlement than the extensometer below it. The plot of Figure 4.4 should show the line between the top two extensometers to be sloping to the right, to indicate settlement between the two extensometers, or the line should be vertical to indicate that no settlement had occurred. A possible explanation as to [illegible] this figure shows the top extensometer initially [illegible] settling less

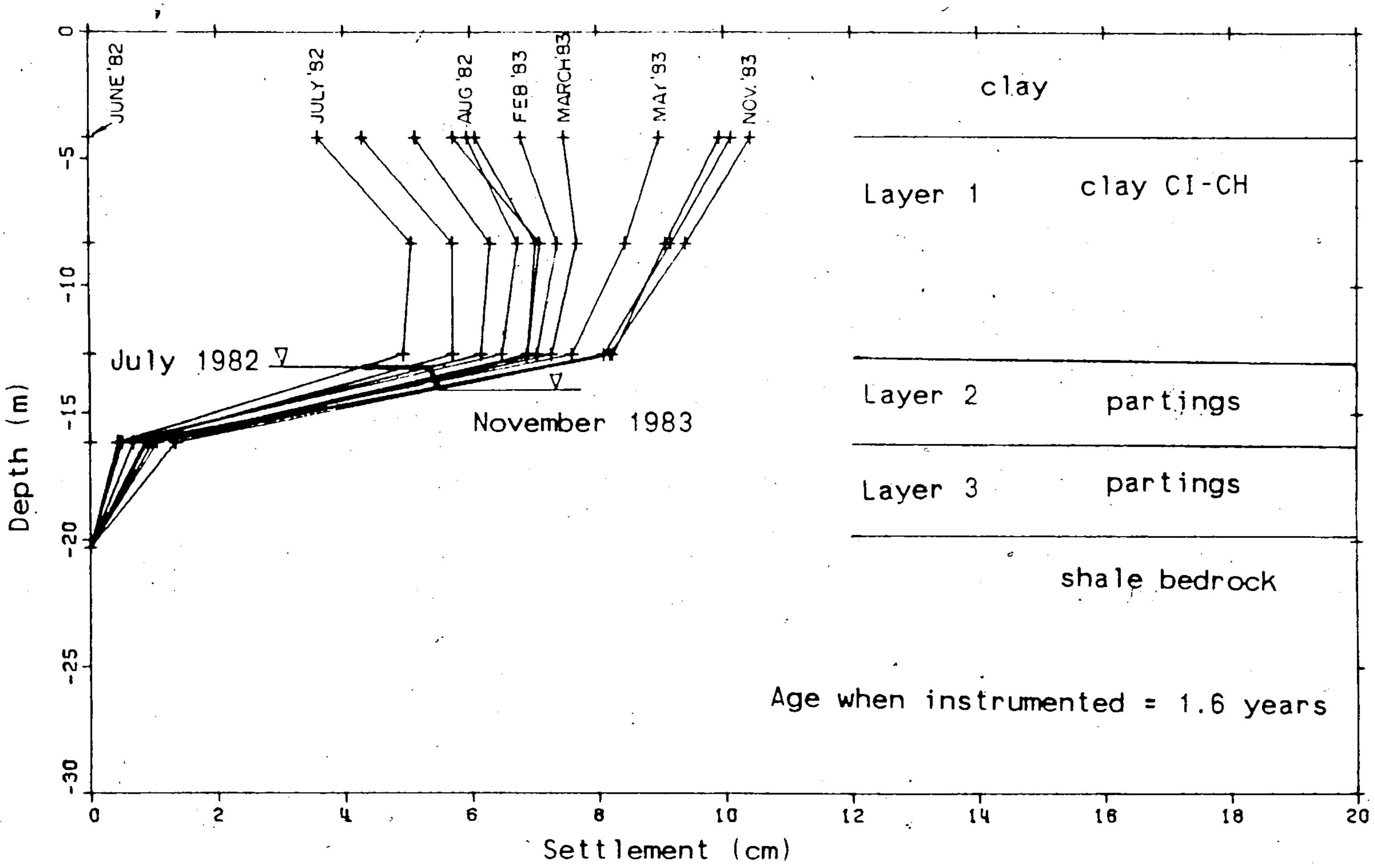


Figure 4.4 Settlement at Highvale North Site 1

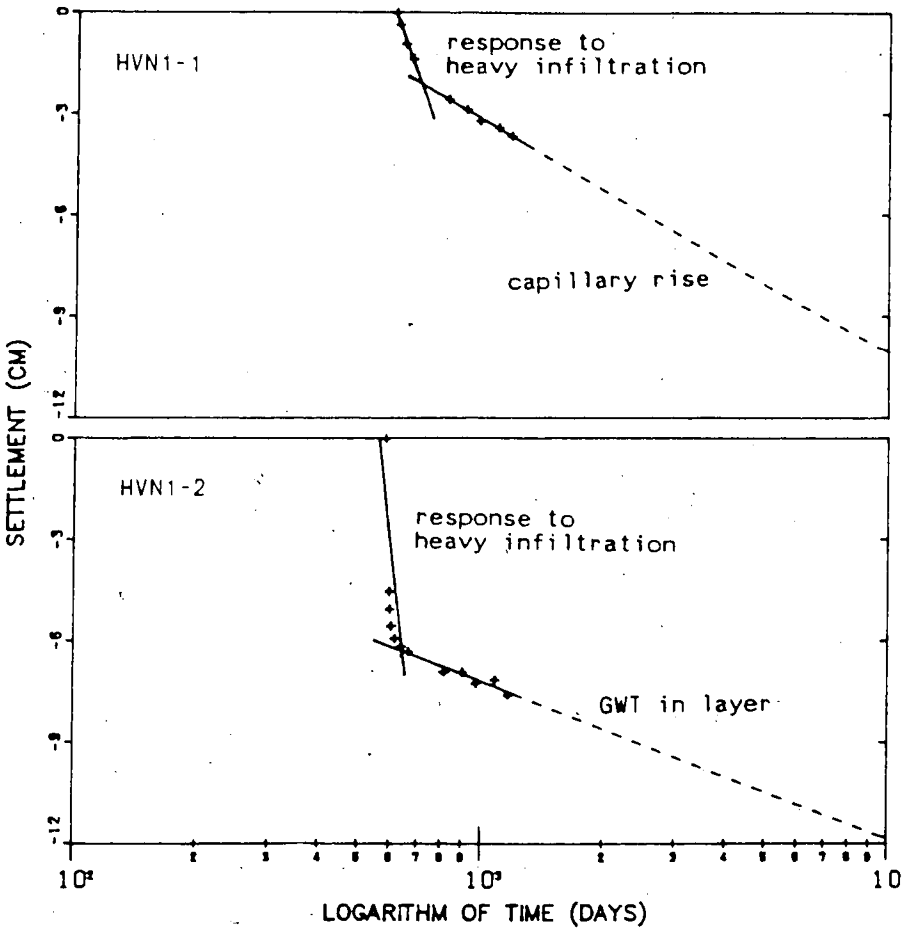


Figure 4.5 Settlement of Layers 1 and 2 at Highvale North Site 1

than the one below could be due to two things. In the region of the uppermost extensometer, either the soil in which the extensometer is embedded is very stiff, perhaps acting like a mat, or the soil is actually arching around the extensometer hole, preventing the soil of this layer from settling with the material below. It appears that this phenomenon, which is also observed at some of the other sites analyzed, deteriorates with time, and uniform settlement patterns develop.

Layers 2 and 3 at HVN1 are both partings material. Layer 3 had varying but small amounts of settlement, with the largest recorded amount of 1.33 cm, with a resulting value of Ps equal to 12.2. Because settlement was so small and inconsistent, no graph was plotted for this layer. Layer 2 initially had a very high Ps value equal to 375, related to the heavy rainfall of July 1982. Layer 3, under water before the rainfall, did not respond dramatically to the infiltration, as did layer 2. Layer 2 as seen in Figure 4.4 had the groundwater table in the layer, and a sudden increase in the groundwater table related to the heavy infiltration likely caused significant collapse related settlement. In a short time, (less than sixty days), the value of Ps for layer 2 went from 375 to 13.3. The slope of graph HVN1-2 (Figure 4.5) suggests this value of Ps (13.3) represents a settlement trend of partings, with the groundwater table almost submerging the layer.

4.5.3 Highvale North Site 2 (HVN2)

The spoil at this site is divided into three layers, layers 1 and 2 are clay and layer 3 is partings (Figure 4.6). Layer 1 is above the groundwater table. Layer 2 has the groundwater table in the layer. The heavy rainfall of July 1982 caused significant settlement in all layers as seen in the initial data points of Figure 4.7. Most settlement was recorded in layer 3 where Ps worked out to be over 2000. This value is an anomaly, especially because the layer was already submerged prior to the rainfall. The initial value of Ps for layer 1 was also high at 1100. This value is also considered an anomaly when compared with the other Ps values that were calculated for clay, which is done in Section 4.6.2. The initial Ps value for layer 2 was 395. Although this value was high when compared with the infiltration response of HVN1-1 (Ps = 38.7), it was considered reasonable for analysis.

These high Ps values meant there were large settlements at this site (almost 15 cm) due to the young age (2.0 years) of the spoil and thus its susceptibility to large settlements when inundated. It is noted that an older site with smaller settlements could have the same Ps values. The Ps value for layer 1 is presently 8.04, capillary rise a possible factor, and 19.9 for layer 2, reflecting either the effect of capillary rise due to the groundwater table in the layer, or the effect of being

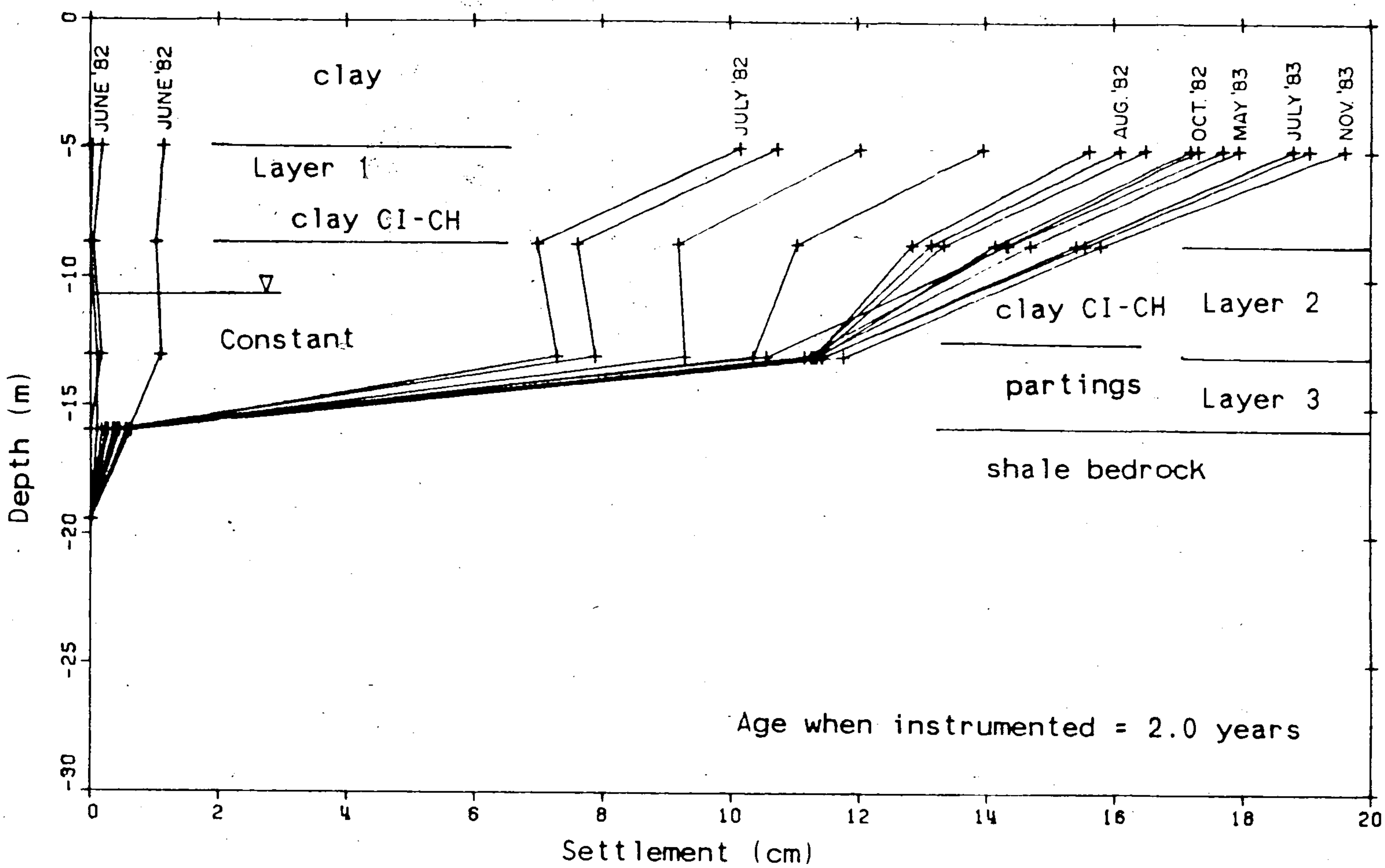


Figure 4.6 Settlement at Highvale North Site 2

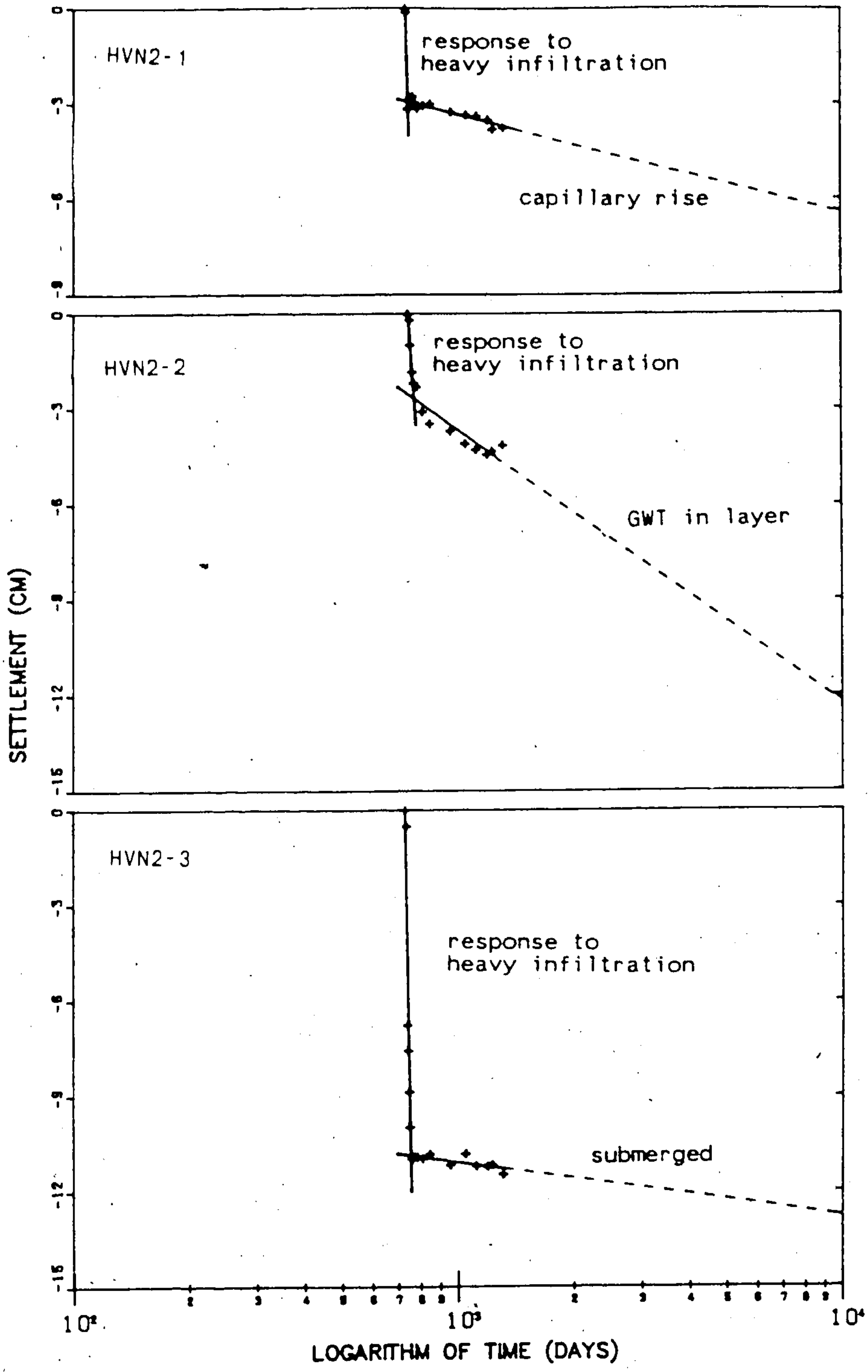


Figure 4.7 Settlement of Layers 1, 2 and 3 at Highvale North Site 2

partially submerged. The Ps value for layer 3 is 5.69, related to the settlement behavior of partings while submerged.

4.5.4 Highvale North Site 3 (HVN3)

Highvale North Site 3 is divided into four layers. Layers 1, 2 and 3 consist of sand and clay and clayey sand. For ease of analysis, all three layers will be considered as sandy clay. Layer 4 is partings.

Layer 1 is well above the groundwater table and the Ps value is 31.4. Because settlement of this layer began after heavy infiltration, capillary rise is a possible factor. Although the layer initially appears to be arching, (Figure 4.8), it has nonetheless exhibited 'straight line' settlement (Figure 4.9, graph HVN3-1).

Layer 2 had an initial Ps value of 231, reflecting response to the heavy rainfall infiltration of July 1982, and a final value of 18.4, related to capillary rise.

Layer 3 was also initially affected by the heavy July 1982 rainfall, but not as much as layer 2. The value of Ps for layer 3 for the first three months of monitoring was 43.3, dropping to 11.8 (Figure 4.9, graph HVN3-3). This value (11.8) is considered to be a function of capillary rise.

Layer 4 had an initial Ps value equal to 300 (related to infiltration) and levelled off to 6.15. The groundwater

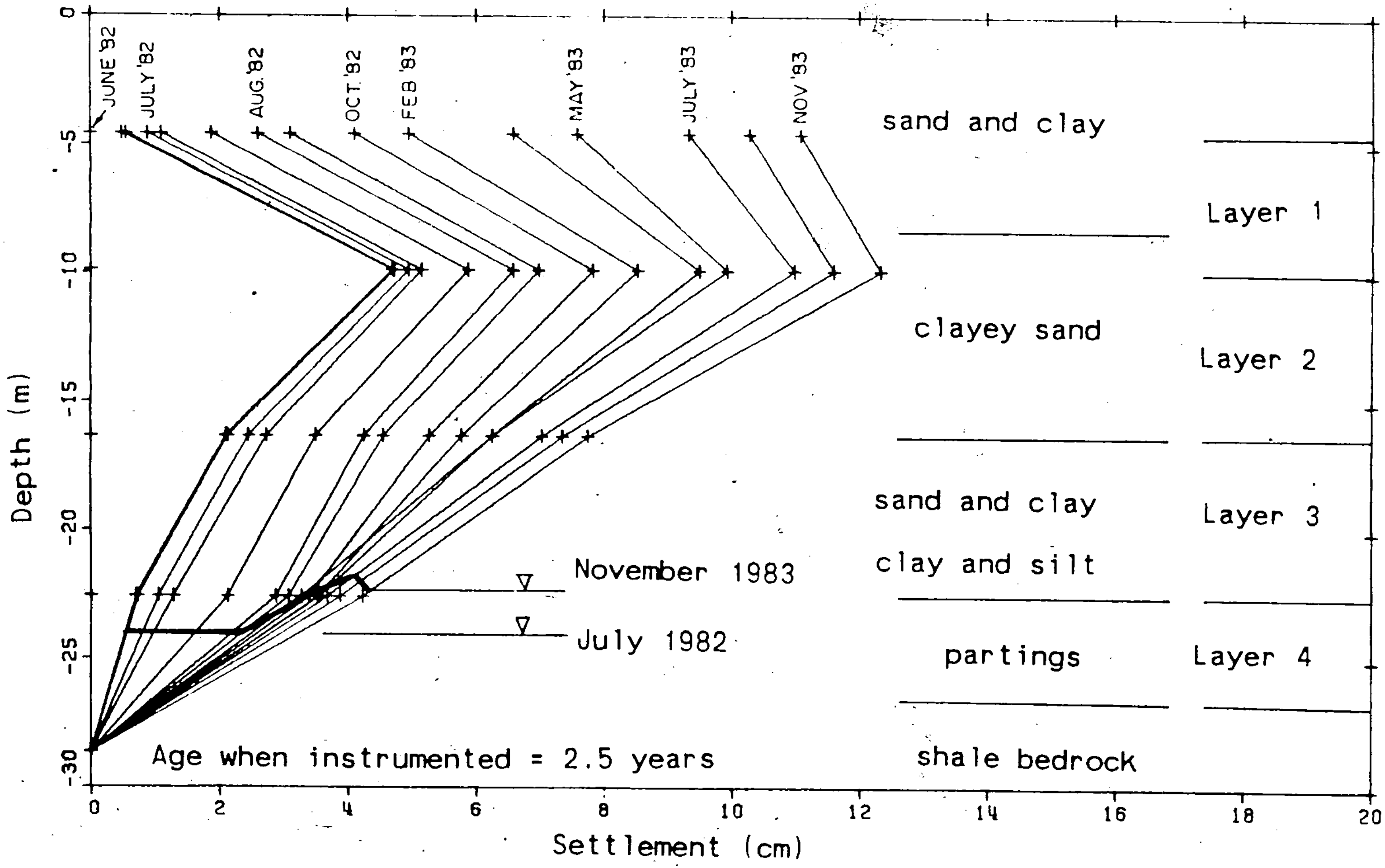


Figure 4.8 Settlement at Highvale North Site 3

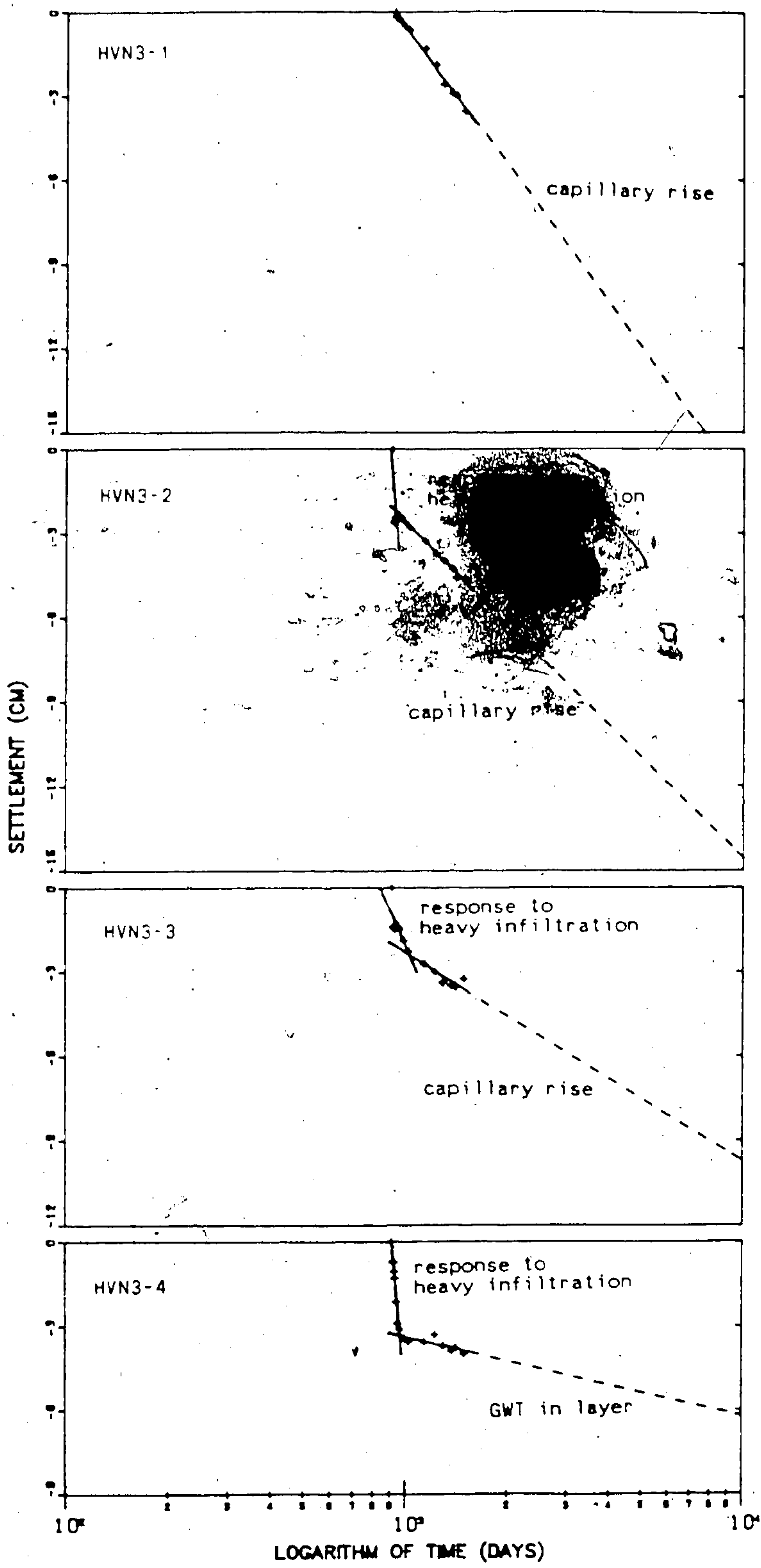


Figure 4.9 Settlement of Layers 1, 2, 3, and 4 at Highvale North Site 3

table initially was about two-thirds of the way through this layer and rose 1.5 m to submerge the layer about half way through the period of monitoring.

4.5.5 Highvale North Site 4 (HVN4)

This site is comprised of 2 layers. Layer 1 is a large layer of clay and has not exhibited any settlement whatsoever, even though subjected to heavy rainfall, reflecting perhaps a very impermeable crust. The Ps value for this layer is 0.0.

Layer 2, partings, is a thin layer (3 m), and all the lement between bedrock and the extensometer at 19.16 m gure 4.10) is assumed to have occurred in this layer. This assumption is based on the lack of settlement in the clay. Although total settlement is small (less than 2 cm), the Ps values calculated are large. This is because the layer is thin. A value of Ps equal to 74.6 was calculated after heavy infiltration, levelling off to 31.1 (Figure 4.11, graph HVN4-2). This is considered a Ps value for submerged partings.

4.5.6 Highvale North Site 5 (HVN5)

The spoil at this site is divided into 3 layers. The first two layers are predominantly clay of high plasticity. Layer 1 is 6.9 m thick and has not settled at all in 584 days of monitoring. Ps equals 0.0. This

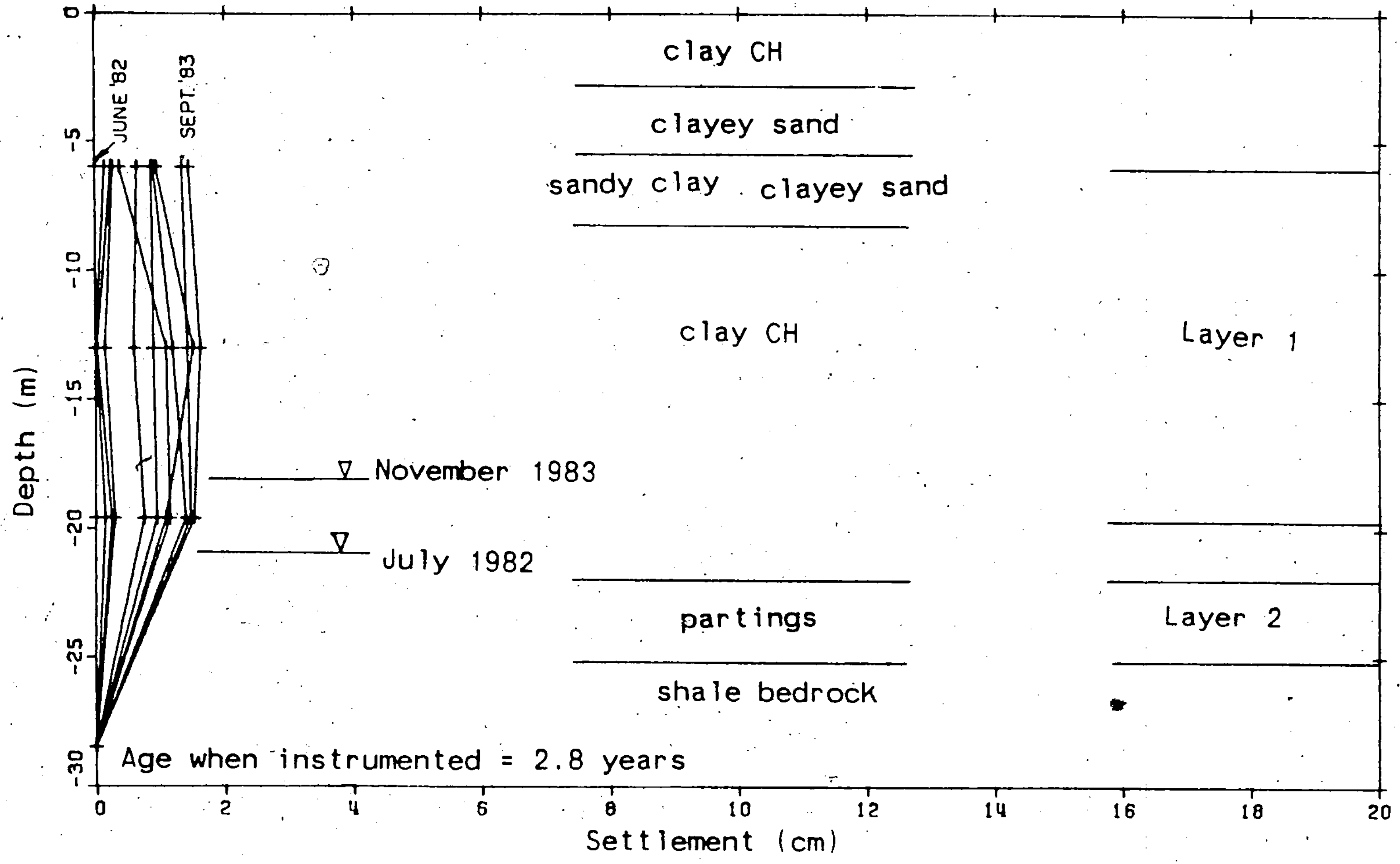


Figure 4.10 Settlement at Highvale North Site 4

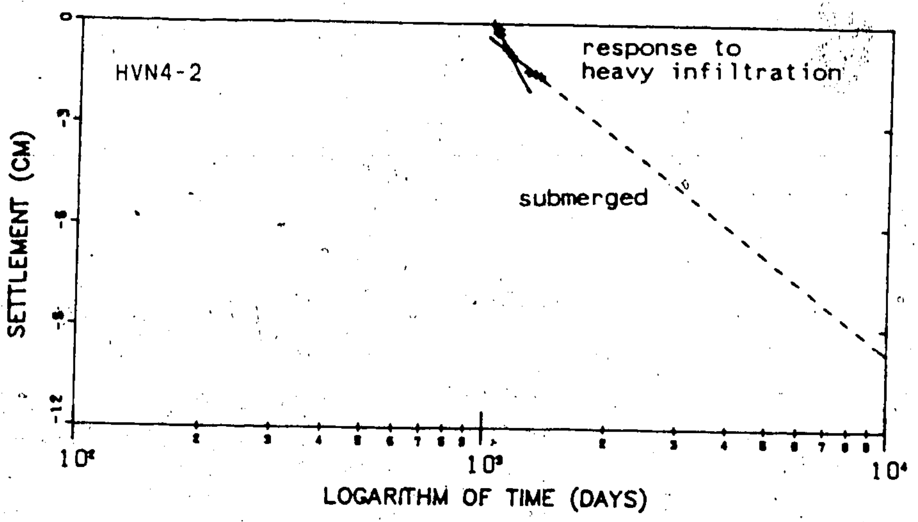


Figure 4.11 Settlement of Layer 2 at Highvale North Site 4

surface layer is well above the groundwater table and is likely a crust.

Layer 2 is measured from the multipoint extensometers at 13.4 to 19.2 m and does include some partings (Figure 4.12) but is considered to be entirely clay for ease of analysis. This layer has settled less then 1 cm and has a Ps value of 4.67, related to self-weight settlement, although the groundwater table is in the bottom of the layer. Capillary rise related settlement does not appear to be a factor here.

Layer 3 is partings and had the groundwater table near the top of the layer at the beginning of testing. The groundwater table is presently above the layer. Initially Ps was 21.7 for layer 3, reflecting a possible slaking reaction of the spoil as the groundwater table rose. Once the groundwater table went above the layer, settlement decreased, resulting in a steady Ps equal to 3.77 (Figure 4.13, graph HVN5-3).

4.5.7 Highvale South Site 1 (HVS1)

This site has 2 layers of spoil, the first comprised mainly of clay and the second is partings. Layer 1, Figure 4.14, does not appear to be settling very much. In the first 180 days of monitoring, no settlement occurred. Ps was 0.0. Then, possibly due to the groundwater table near the bottom of the layer causing capillary rise, 2 cm

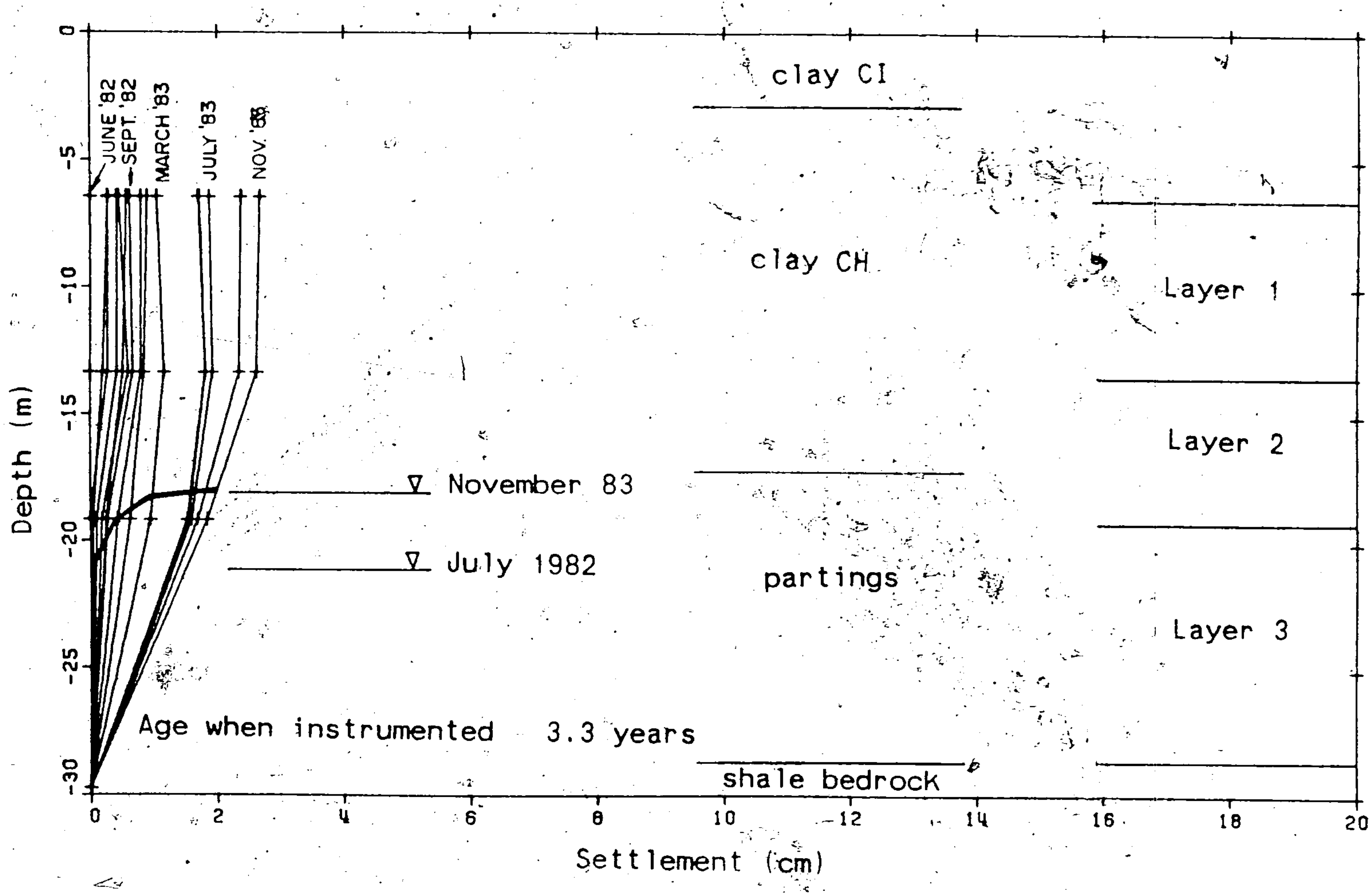


Figure 4.12 Settlement at Highvale North Site 5

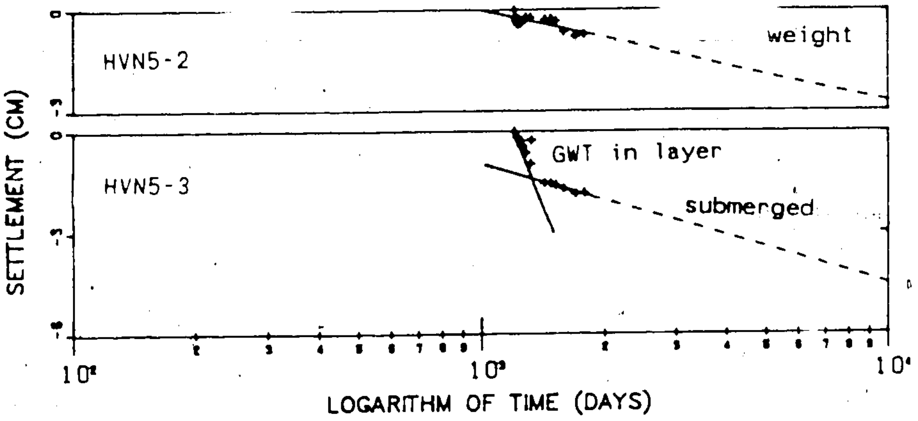


Figure 4.13 Settlement of Layers 2 and 3 at Highvale North Site 5

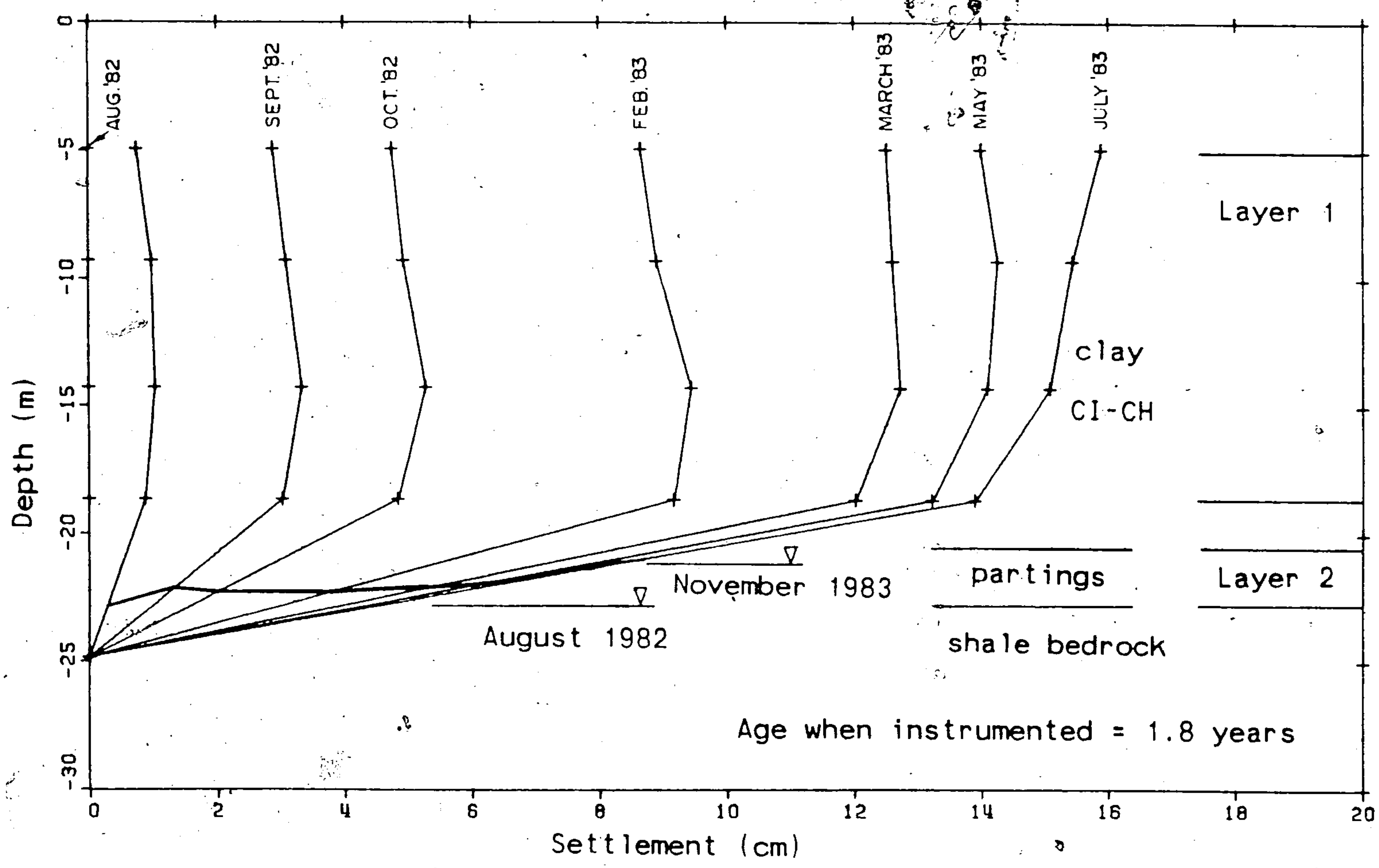


Figure 4.14 Settlement at Highvale South Site 1

of settlement in 160 days resulted in a value of Ps equal to 19.0. Because Shelby tube samples of clay from this layer show high degrees of saturation (100% at 8.5 m, 75% at 13.1 m, 98% at 17.7 m), capillary rise as the cause of settlement is questioned. Self-weight settlement is not a possibility as it does not explain why the layer did not settle for the first 180 days. It is not clear why this layer began to settle after 180 days but capillary rise is assumed. Only a few points define the plot of graph HVS1-1 on Figure 4.15.

Layer 2 is 2.8 m thick and has had the groundwater table rise through it throughout the period of monitoring (Figure 4.14). This layer is assumed to have undergone all the settlement between the extensometer at 18.7 m and shale bedrock. Similar to Highvale North Site 4, this assumption is based on the fact that layer 1 was not settling at all while the material below layer 1 was. Partings is the suspected settling component in the material below layer 1 and for this reason partings is considered to be the material that comprises layer 2 (Figure 4.14). Initially, Ps for layer 2 was 309, possibly reflecting response to the heavy rainfall of July 1982, a month before the site was instrumented. Ps levelled off to 127 after about 240 days (Figure 4.15, graph HVS1-2). This high value is related to slaking of the partings, as the groundwater table has been rising through this layer for

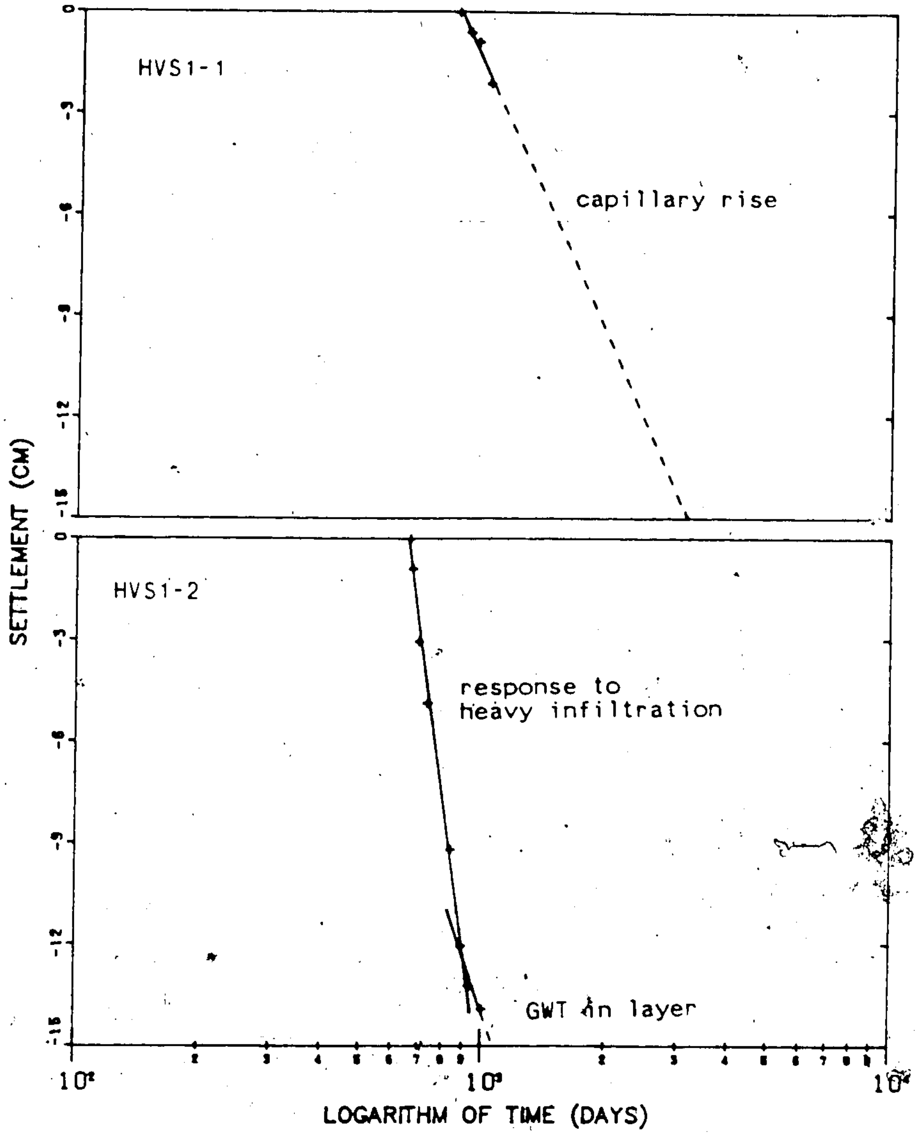


Figure 4.15 Settlement of Layers 1 and 2 at Highvale South Site 1

the duration of the test period. The value of 127 is very high when compared to values from other partings layers, (which is done is Section 4.6.4), and is thus considered an anomaly.

4.5.8 Highvale South Site 2 (HVS2)

The soil profile at this site is divided into 2 layers, similar to Highvale South Site 1. Layer 1 is mostly medium to highly plastic clay. For 350 days, the Ps value for this layer was 17.0 reflecting the effect of surface ponding of runoff around the instruments for a lengthy period of time. When this effect ceased, Ps decreased to a low 0.54, reflecting a crust-like stability. The effect is too sudden for the development of a crust, however, (Figure 4.16), that this is questioned. It is not known why settlement of this layer stopped so drastically. The groundwater table is below this layer. When it rises into the clay layer, its effect will not be as pronounced as if surface ponding related settlement had not occurred.

Layer 2 is partings and has had the groundwater table in the middle of the layer throughout the test period. Initially Ps for this layer was 19.0, possibly due to the heavy rainfall infiltration of July 1982 causing collapse settlement, but 2 months after the beginning of monitoring, Ps levelled off to 2.55 (Figure 4.17, graph

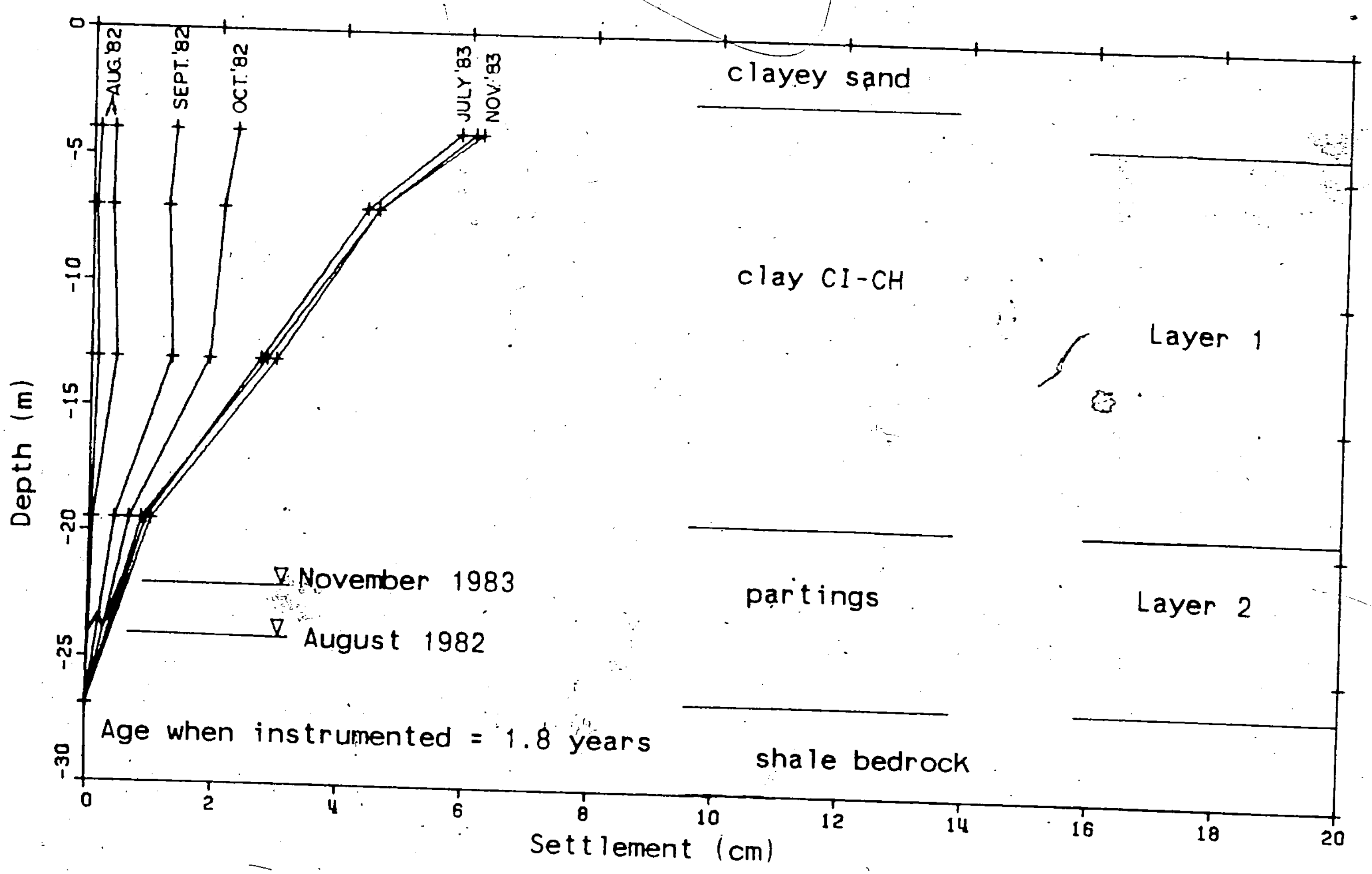


Figure 4.16 Settlement at Highvale South Site 2

HVS2-2).

4.5.9 Highvale South Site 3 (HVS3)

The spoil at this site is divided into four layers (Figure 4.18). Layer 1 is highly plastic clay, layer 2 is medium plastic clay, layer 3 is partings above the groundwater table and layer 4 is partings below the groundwater table.

Layer 1 has not settled at all in the 680 days of monitoring, possibly due to the development of a surface crust. Ps equals 0.0.

Layer 2 initially had a Ps equal to 15.3, related to self-weight settlement, then after 180 days, it jumped to 50.5. This phenomenon is similar to that at Highvale South Site 1 layer 1. It is possible that the groundwater table rise of 2.0 m in layer 4 resulted in capillary rise entering layer 2. This value (50.5) is high for capillary rise in clay and is thus considered an anomaly.

Initially Ps for layer 3 was 155 levelling off to 14.5 after 80 days (Figure 4.19, graph HVS3-3). Even though this site was instrumented after the heavy rainfall of July 1982, it is possible that the effect of the rainfall, (i.e. a short-term increase in the groundwater table), is related to the initial high Ps value of 155. The Ps value of 14.5 is very likely a capillary rise related value.

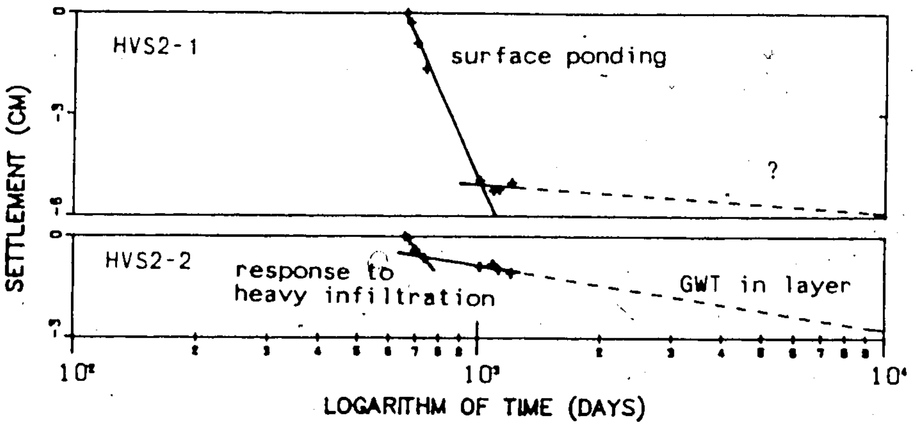


Figure 4.17 Settlement of Layers and 2 at Highvale South Site 2

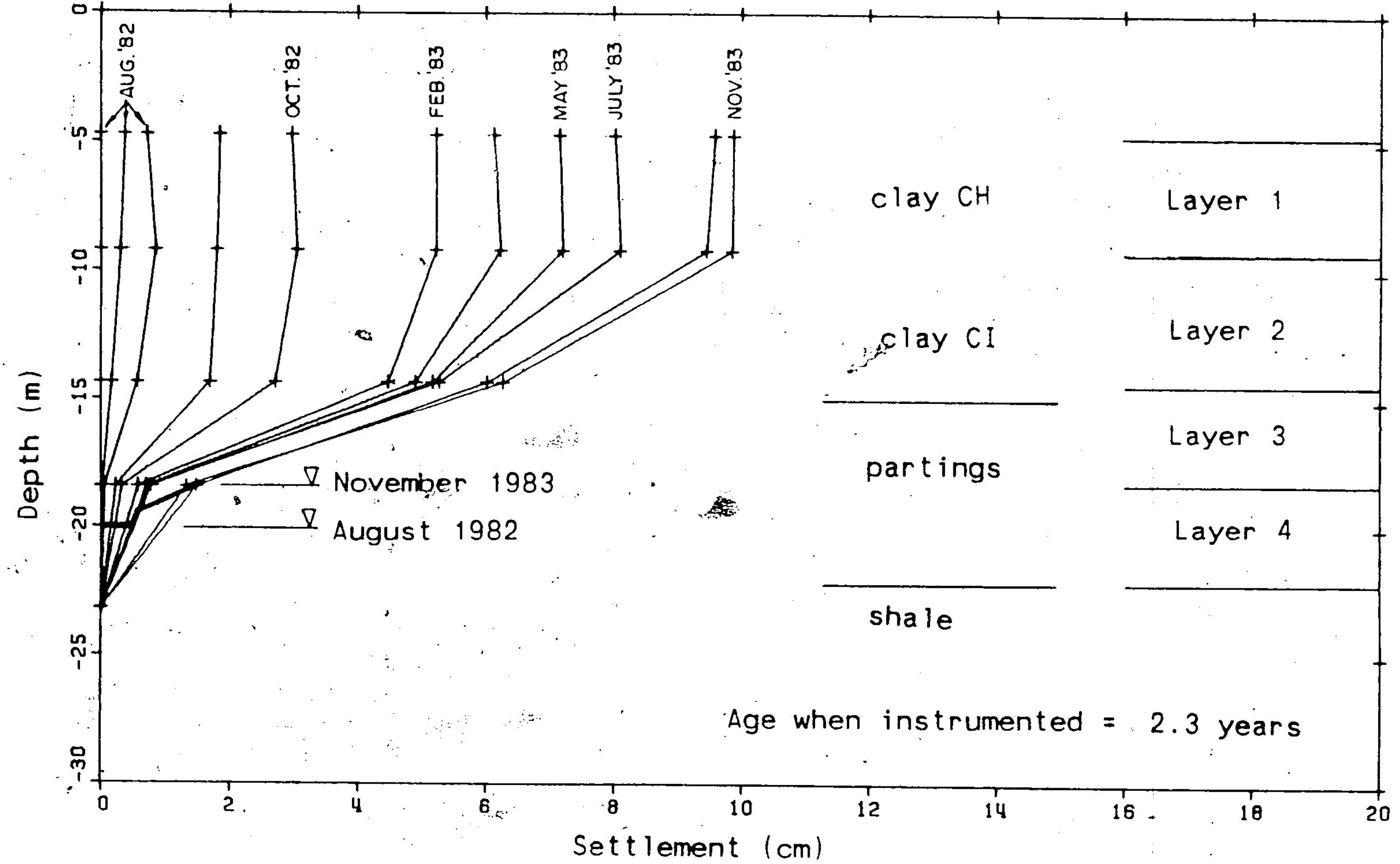


Figure 4.18 Settlement at Highvale South Site 3

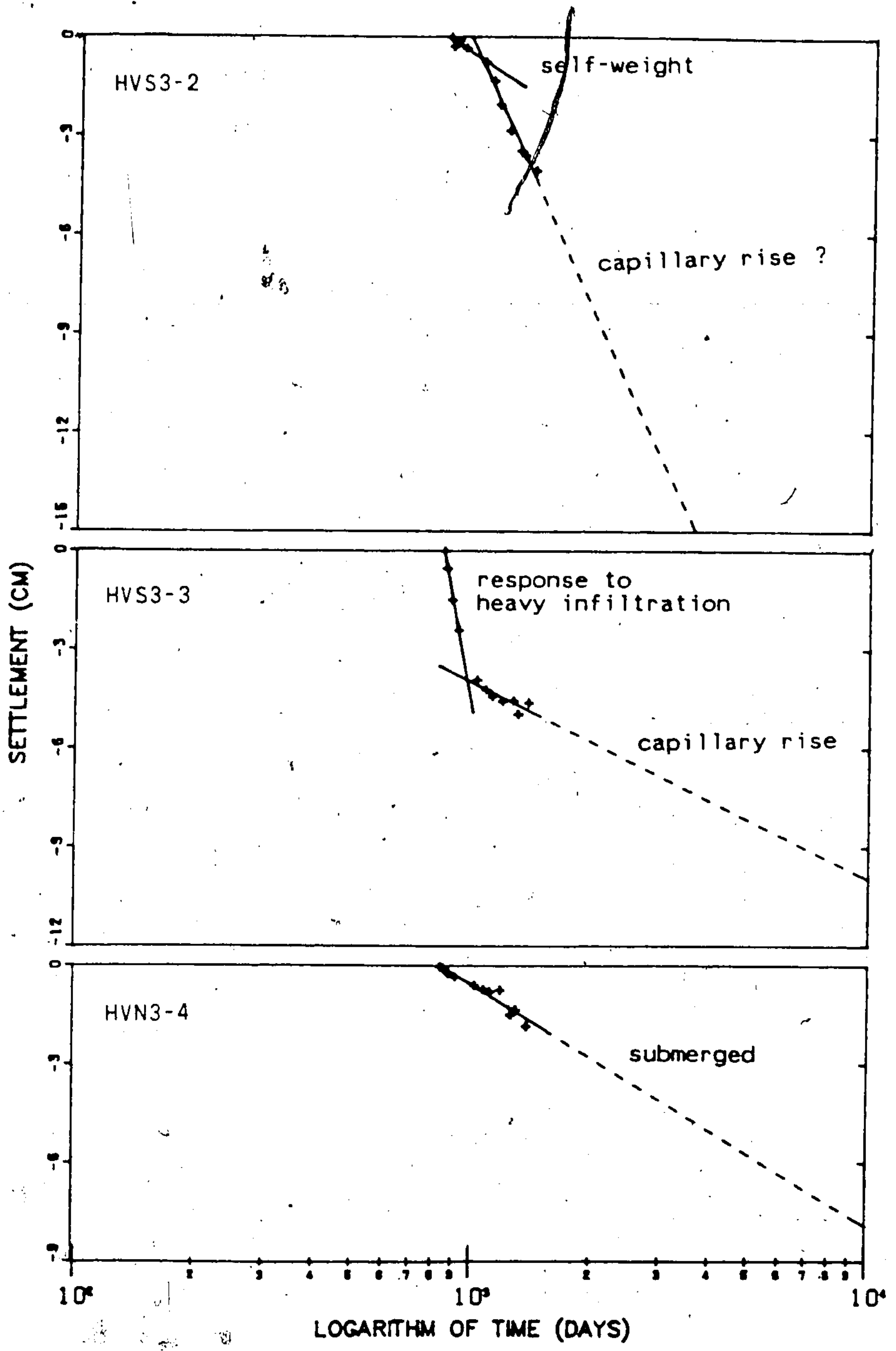


Figure 4.19 Settlement of Layers 2, 3 and 4 at Highvale South Site 3

Layer 4 was partially and then totally submerged throughout the test period. A constant value of Ps equal to 19.4 was calculated (Figure 4.19, graph HVS3-4).

4.5.10 Highvale South Site 4 (HVS4)

The soil profile at this site is not similar to any of the others (Figure 4.20). Partings comprises the first layer, layer 2 is clay with a seam of partings material at the top and bottom of the layer, and layer 3 is partings. For ease of analysis, all three layers will be considered as 'partings'.

Layer 1 did not settle for the first 170 days, and in the next 360 days settled less than 1 cm (Figure 4.21, graph HVS4-1) resulting in a Ps value of 5.60. This layer is well above the groundwater table and likely any settlement is related to self-weight.

Layer 2 also did not settle for the first 170 days of monitoring, but since then has had fairly steady settlement (Figure 4.21, graph HVS4-2) with Ps equal to 15.7. Very likely capillary rise is a factor.

Layer 3 has settled continuously since the beginning of monitoring (Figure 4.21, graph HVS4-3), and Ps equal to 26.5 is related to the layer being submerged with slaking possibility.

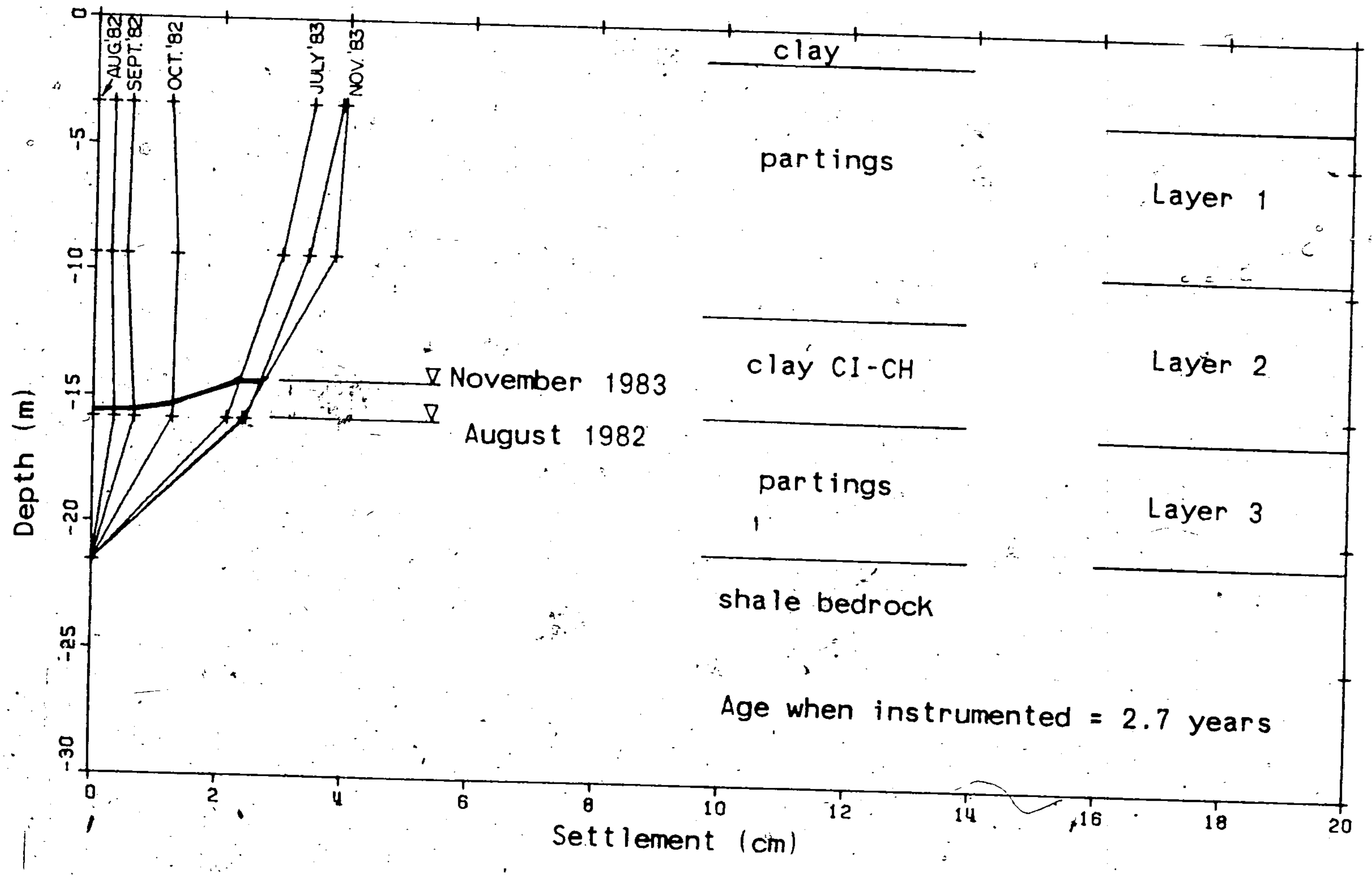


Figure 4.20 Settlement at Highvale South Site 4

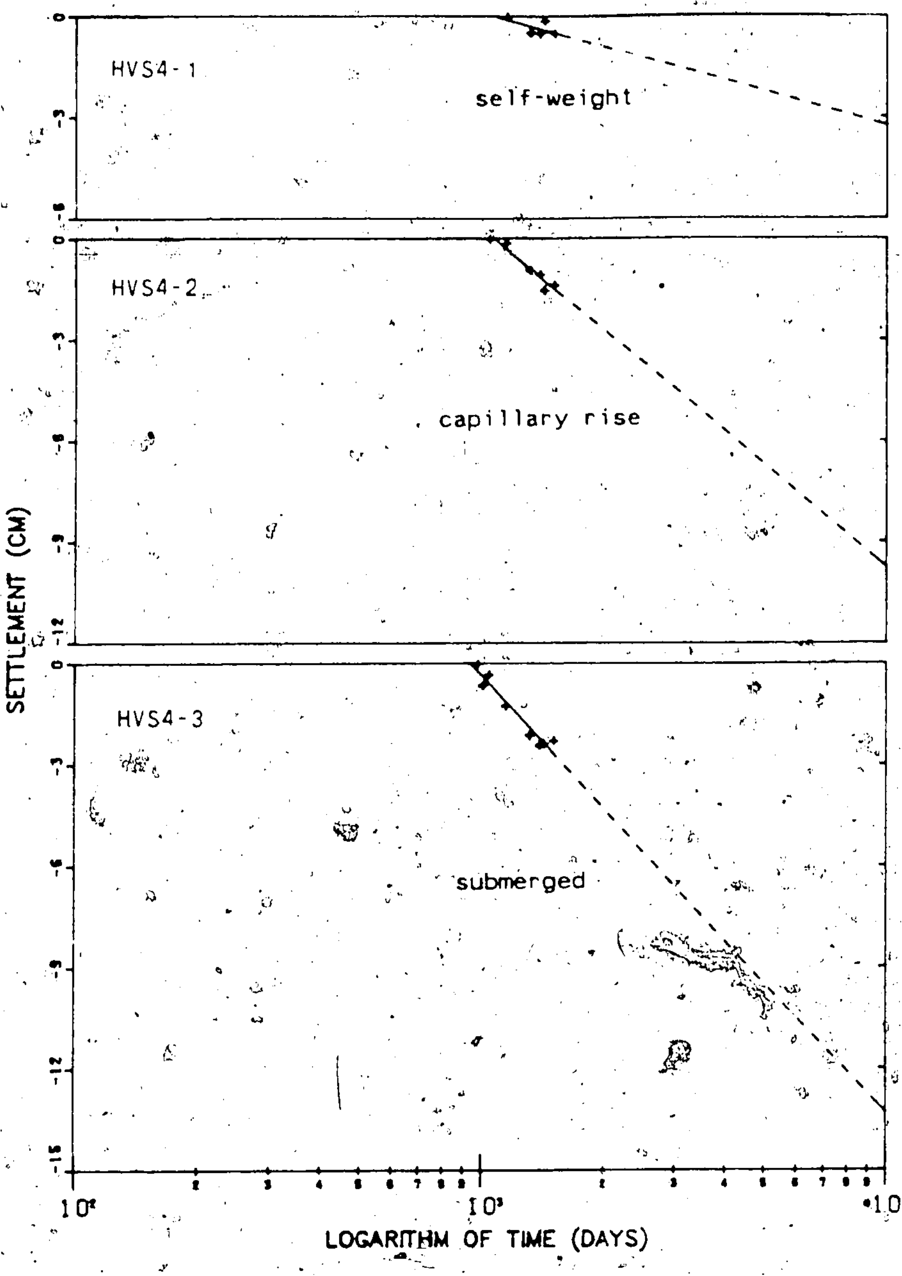


Figure 4.21 Settlement of Layers 1, 2 and 3 at Highvale South Site 4

4.5.11 Highvale South Site 5 (HVS5)

This site is divided into three layers. The top half of layer 1 is clay and the bottom half is partings (Figure 4.22). This layer, well above the groundwater table, has not settled at all which is likely a function of the development of a crust.

Layer 2 is primarily partings and has settled only 0.33 cm with a resulting Ps value equal to 2.07. The development of a crust has likely stabilized this site.

Layer 3 is mostly clay with a thin layer of partings at the top. Ps is equal to 4.09 and is considered a Ps value for submerged clay. The groundwater table is in this third layer. This small value (4.09) suggests that for this layer, much of the settlement caused by the groundwater table occurred before the groundwater table actually reached the layer. In other words, it is likely that capillary rise caused most of the settlement before the groundwater table reached the layer. After this layer became submerged, any further settlement is related to slaking of the material.

No graphs were made for this site due to the small settlements in the order of half a centimeter.

4.5.12 Whitewood Site 2 (WW2)

This site is almost entirely sand with clay mixed throughout, and will be considered as sandy clay (Figure

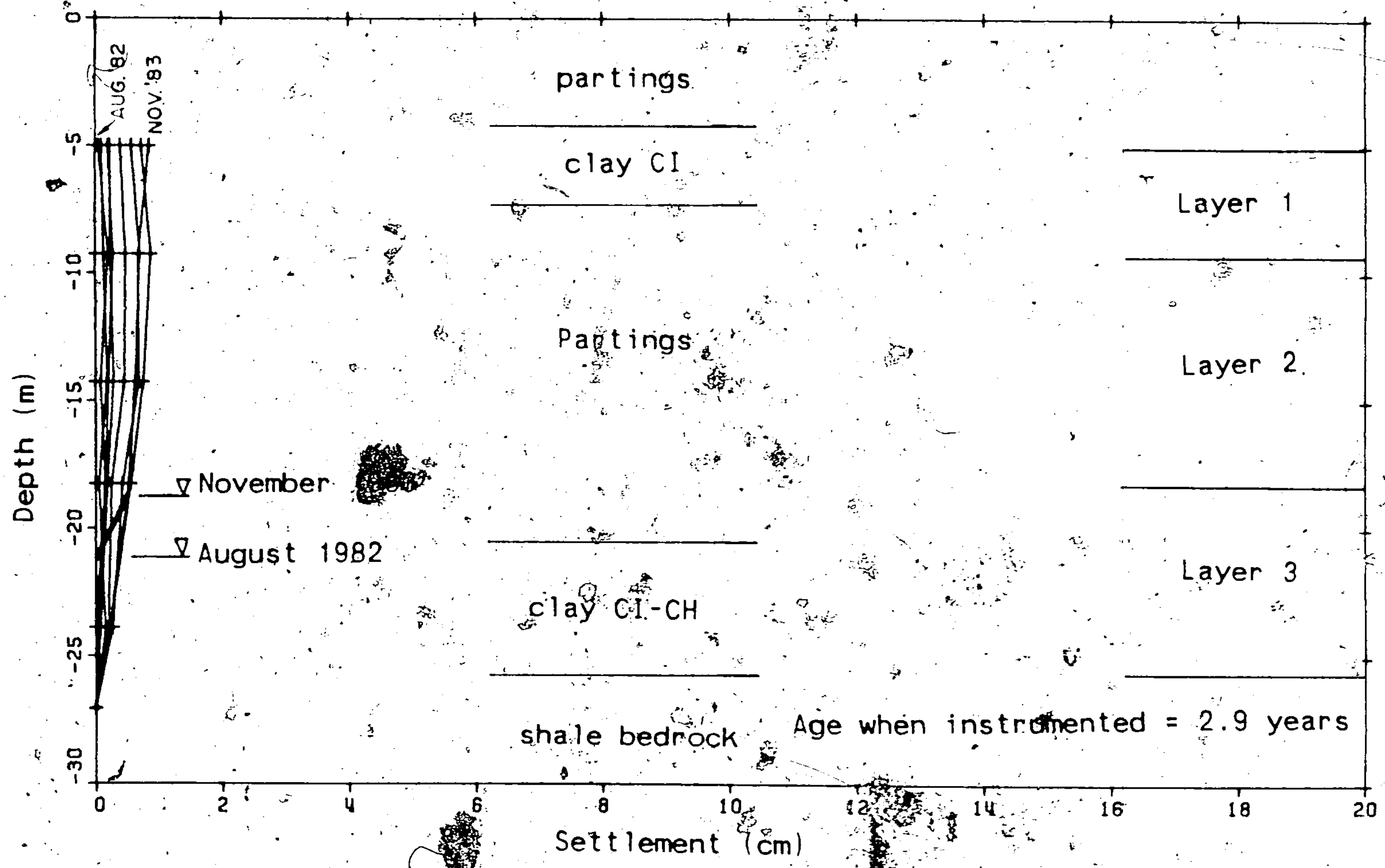


Figure 4.22 Settlement at Highvale South Site 5

4.23). For 230 days Ps was 8.93 and then for 300 days Ps was 3.88 (Figure 4.24, graph WW2-1). It is not known why the Ps value changed. As the present settlement pattern appears stable, the value of 3.88 will be used as a self-weight Ps value in the analyses to follow. The groundwater table is very near the bottom of the strata.

4.5.13 Whitewood Site 4 (WW4)

This site is divided into 2 layers (Figure 4.25). Layer 1 is almost 34 m thick and is comprised of sand, clay and some thin seams of partings. Ps is equal to 1.22 as less than 1 cm of settlement has been recorded for this thick layer. Layer 2 is partings with the groundwater table near the bottom of the layer. Settlement is fairly consistent (Figure 4.26, graph WW4-2) with Ps equal to 12.7.

4.6 Tabulation and Correlation of Ps Values

4.6.1 Introduction

By analyzing the common settlement related phenomenon of the three main types of spoil discussed (clay, sandy clay, and partings), it was possible to correlate Ps values. These values will be used in Chapter 5 in a manner to demonstrate their use in long-term predictive analyses. All Ps values are to be multiplied by 10^{-3}.

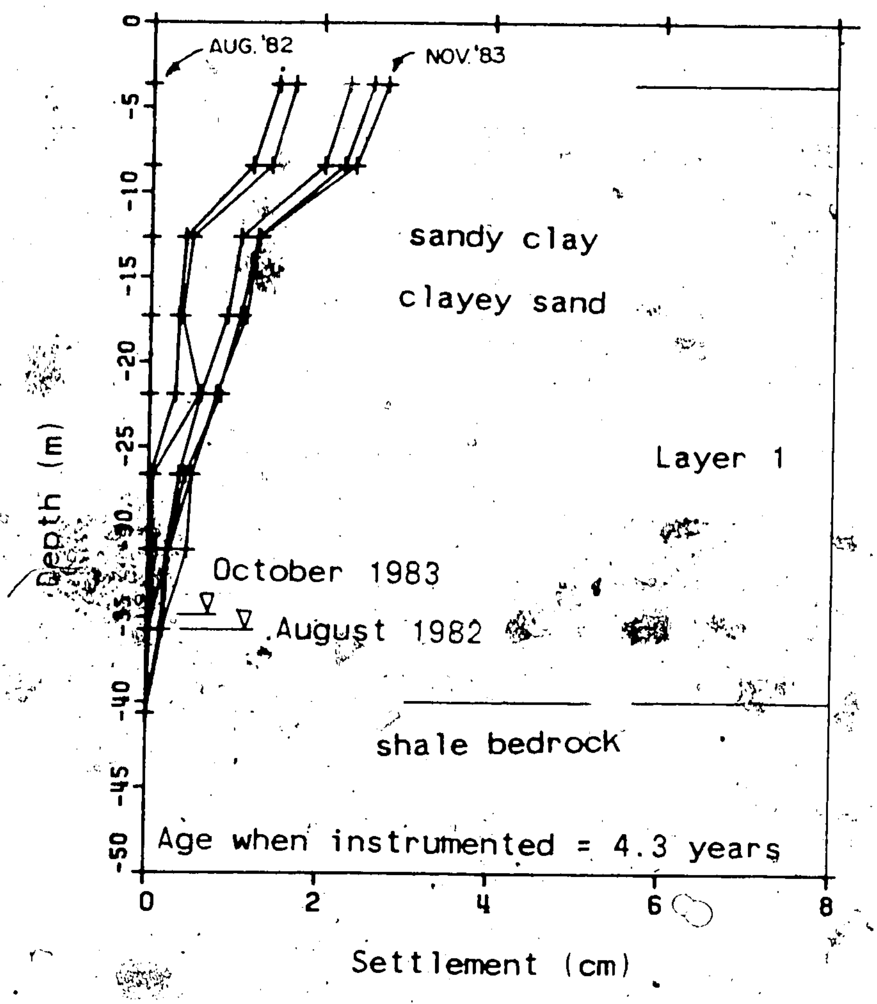


Figure 4.23 Settlement at Whitewood Site 2

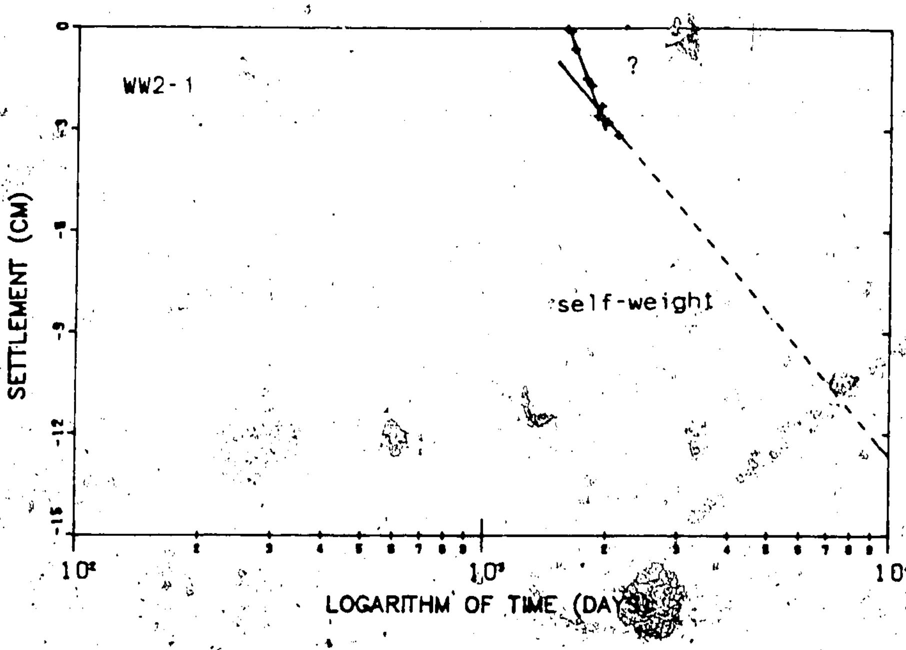
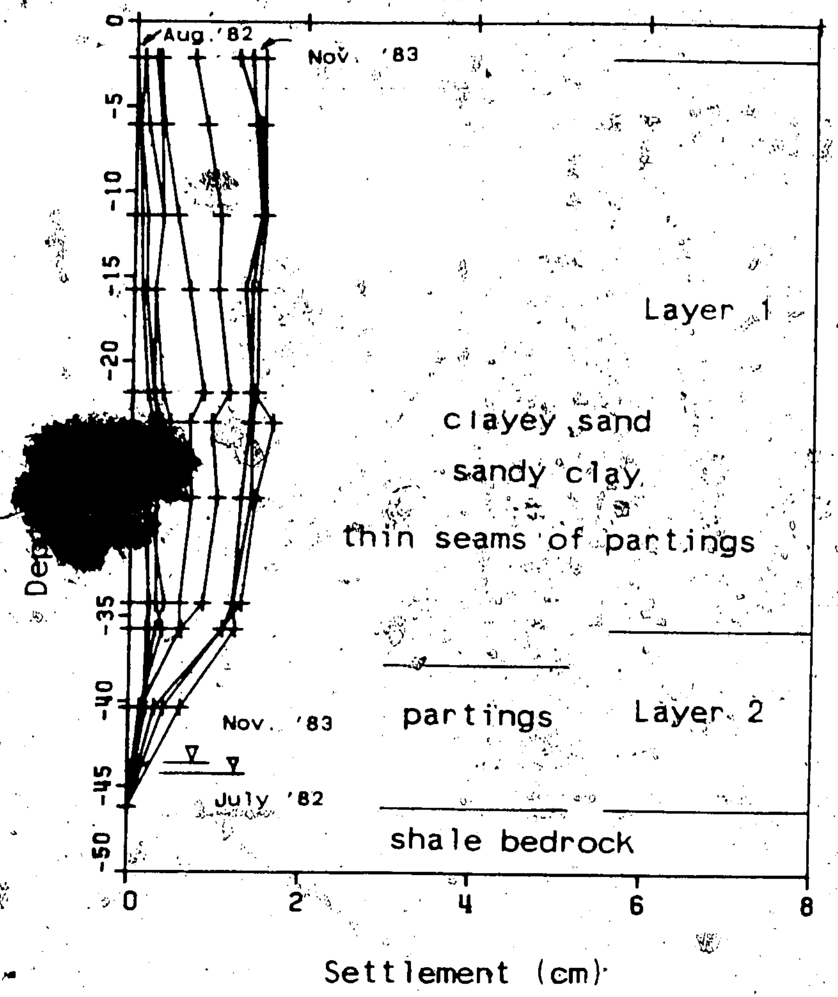


Figure 4.24 Settlement of Layer 1 at Whitewood Site 2.



Age when instrumented = 4.9 years

Figure 4.25 Settlement at Whitewood Site 4

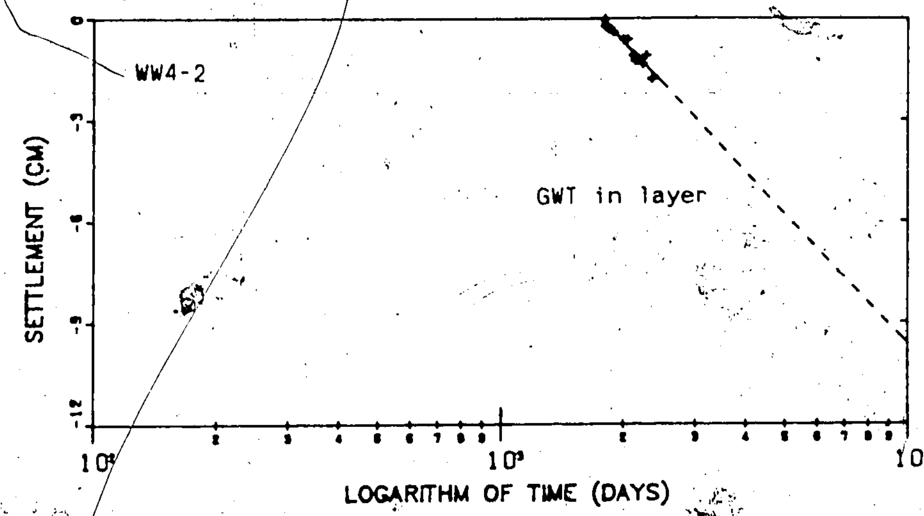


Figure 4.26 Settlement of Layer 2 at Whitewood Site 4

4.6.2 Ps Values for Clay

Table 4.2 shows Ps values for clay, the conditions related to the values and the sites where the conditions occurred. Five years after spoiling (or reclaiming), if the groundwater table is at depth (i.e. capillary rise is not a factor), it believed that the development of a partially indurated crust may have an effect up to 10 m in depth. Ps is equal to 0.0 for this phenomenon. To be liberal, analysis of site settlement will use this Ps value only up to a depth of 5 m below the ground surface.

In the zone below this crust but not influenced by capillary rise or groundwater table effects, Ps values of 4.67 to 15.3 were calculated. This is related to self-weight of the spoil. Only two sites demonstrated this effect (Table 4.2), suggesting the possible complexity of interaction between various settlement related effects. In other words, self-weight settlement is a phenomenon that continues in clay spoil but is affected by such things as the development of a crust and capillary rise, so that self-weight settlement occurring on its own may not be common. However, for zones below the arbitrary 5 m thick crust and above the range of capillary rise (as will be discussed), it is liberal to consider self-weight as a settlement factor.

In clay layers above the groundwater table, capillary rise related settlement has Ps values of 8.04 to 19.0. The

CLAY

Ps VALUES	CONDITION	SITE-LAYER / Ps VALUE
0.0	Partially indurated crust	HVN4-1 / 0.0 HVN5-1 / 0.0 HVS1-1 / 0.0 HVS3-1 / 0.0 HVS2-1 / 0.54*
4.67-15.3	Self-weight	HVN5-2 / 4.67 HVS3-2 / 15.3
8.04-19.0	Capillary rise (a)Capillary rise following heavy infiltration	HVN2-1 / 8.04 (a) HVN1-1 / 8.08 (a) HVS2-1 / 17.0 HVS1-1 / 19.0 HVS3-2 / 50.5*
4.09-19.9	Submerged (a)semi-submerged	HVS5-3 / 4.09 HVN2-2 / 19.9 (a)
38.7-395	Heavy infiltration response	HVN1-1 / 38.7 HVN2-2 / 395 HVN2-1 / 1297*

* = anomaly

SANDY CLAY

Ps VALUES	CONDITION	SITE-LAYER / Ps VALUE
1.22-3.88	Self-weight, and well above the groundwater table	WW4-1 / 1.22 WW2-1 / 3.88
11.8-31.4	Capillary rise following heavy infiltration	HVN3-3 / 11.8 HVN3-2 / 18.4 HVN3-1 / 31.4
43.3-231	Heavy infiltration response	HVN3-3 / 43.3 HVN3-2 / 231

Table 4.2 Ps Values For Clay and Sandy Clay

value of Ps equal to 17.0 from HVS2-1, (Table 4.2), which was affected by surface ponding of runoff, is thought to have had an effect similar to capillary rise. Again, capillary rise in clay is assumed, on the liberal side, to be 5 m.

The settlement effect of capillary rise on a crust is unknown. Self-weight of the upper 5 m of a spoil profile is virtually stopped by the factors that contribute to the development of a crust. It is therefore quite likely that capillary rise would cause more settlement to occur in the crust than in spoil at depth. For the analyses to follow, if the groundwater table does reach a point where the 5 m zone of capillary rise reaches into the upper 5 m of crust, the Ps values for capillary rise assigned to clay at depth (8.04-19.0) will be used. This assumption provides a close approximation and may be reasonable due to the relatively small assumed thickness (5 m) of the crust.

The groundwater table has not risen sufficiently to provide data for the calculation of Ps values for clay below the groundwater table. This condition would indicate the slaking response of clay while submerged. Because of this, a limited understanding is available of the settlement response of clay while submerged. Only two sites, HVN2-2 and HVS5-3, have provided information related to the submerged settlement response of clay. Site

HVS5-3 (Figure 4.22) is almost totally submerged and a Ps value of 4.09 was calculated. Site HVN2-2 (Figure 4.6) is only half submerged and so the Ps value of 19.9 is likely related to submerged conditions, and capillary rise. The former condition is considered, to enable the application of a range of Ps values for submerged clay. Thus, in the analyses to follow, Ps for submerged clay is taken as 4.09 to 19.9 and is effective only for the submerged portion of any clay layer.

Collapse settlement of clay related to the infiltration of heavy rainfall of the intensity of 18 cm in 4 days has resulted in Ps values of 38.7 and 395. This large range will take into account the possibility of varying response to heavy infiltration. It appears that the effect of heavy infiltration has a duration of about 100 days (Figures 4.7 and 4.9). After a heavy infiltration event, it is important to note that settlement of the spoil profile will be at a lower rate than before the heavy infiltration. This means the application of the lower Ps values of the ranges found in Tables 4.2 and 4.3. This is discussed further in Section 5.4.1.

4.6.3 Ps Values For Sandy Clay

There are not extensive field data to correlate predictive settlement Ps values for sandy clay. Some data are available, however, and provide a framework for settlement analysis.

Table 4.2 indicates the range of Ps values determined for sandy clay. Data from the Whitewood Mine provided Ps values for sandy clay well above the groundwater table and not affected by heavy rainfall. It is believed that most self-weight of sandy clay occurs in a relatively short time after it is disturbed by spoiling. Ps values of 1.22 to 3.88 are assigned to self-weight of sandy clay.

There is no definite information regarding the settlement effects of capillary rise on sandy clay. However, at Highvale North Site 3 (Figure 4.8), layers 2 and 3 have exhibited similar Ps values, after heavy infiltration, of 18.4 and 15.2 respectively. These values are believed to be a function of capillary rise related settlement. Layer 1 at HVN3 did not settle dramatically after the heavy rainfall of July 1982 (as did layers 2 and 3), but settled uniformly, with a Ps value of 31.4, believed related to capillary rise. For the analysis to follow, values of 11.8 to 31.4 are used for capillary rise related settlement in sandy clay, up to an arbitrary 5 m above the groundwater table.

There is no data regarding the effect of the groundwater table submerging a sandy clay layer and so, for analysis, the same Ps values for capillary rise will be used for submerged sandy clay.

Sandy clay responded widely to heavy rainfall. Ps values of 43.3 and 231 were calculated and are assigned to sandy clay layers when there is heavy rainfall of the intensity of 18 cm in 4 days. It should be noted here that if a sandy clay layer undergoing self-weight settlement is subjected to heavy rainfall (for a maximum length of effect of 100 days), the Ps values assigned to the layer after the rainfall will be those related to capillary rise (Ps equal to 11.8 to 31.4) and not Ps values related to self-weight. This is because the Ps values for capillary rise in sandy clay were calculated from layers that had exhibited capillary rise related settlement after being subjected to infiltration due to heavy rainfall. In other words, capillary rise related settlement is more likely to occur in sandy clay after a heavy rainfall than self-weight settlement by itself.

4.6.4 Ps Values For Partings

In Table 4.3, Ps values for various settlement conditions of partings, and the sites and layers related to these, can be found.

If a partings layer is above the groundwater table and the influence of capillary action is not a possibility, Ps values of 0.0 to 5.60 are assigned, related to self-weight. Because partings tend to be at depth, settlement due to overburden is more likely to

PARTINGS

Ps VALUES	CONDITION	SITE-LAYER / Ps VALUE
0.0-5.60	Above water table, no capillary rise, self-weight.	HVS4-1 / 0.0 HVS4-2 / 0.0 HVS5-1 / 0.0 HVS5-2 / 2.07 HVS4-1 / 5.60
14.5-15.7	Capillary rise	HVS3-3 / 14.5 HVS4-2 / 15.7
2.55-21.7	Water table in the layer (slaking and capillary rise)	HVS2-2 / 2.55 HVN3-4 / 6.15 WW4-2 / 12.7 HVN1-2 / 13.3 HVS3-4 / 19.4 HVN5-3 / 21.7 HVS1-2 / 127*
3.77-31.3	Layer submerged (slaking)	HVN5-3 / 3.77 HVN2-3 / 1.69 HVN1-3 / 12.2 HVS4-3 / 26.5 HVN4-2 / 31.1
19.0-375	Heavy infiltration response (collapse) (1) Water table in the layer (2) layer submerged	HVS2-2 / 19.0 (1) HVN4-2 / 74.6 (2) HVS3-3 / 155 (1) HVN3-4 / 300 (1) HVS1-2 / 309 (1) HVN1-2 / 375 (1) HVN2-2 / 2250* (2)

* = anomaly

Table 4.3 Ps Values For Partings

override the possible development of a partially indurated crust. However, like clay, self-weight is not a singular settlement phenomenon and is affected by other factors. The Ps value of 0.0 from HVS5-1 (Figure 4.22) may be related to the development of a crust because of its proximity to the surface where there is not significant overburden.

A limited amount of data related to capillary rise in partings is available. Ps values of 14.5 to 15.7 (Table 4.3) are applied to capillary rise conditions in partings, with an arbitrary rise of 5 m to be used in analysis.

There is sufficient data to analyze and compare the phenomenon of the groundwater table in a partings layer (partial submersion) and the layer being completely submerged. Table 4.3 shows Ps values of 2.55 to 21.7 calculated for when the groundwater table travelled through a layer of partings during the monitoring period, or remained at some location in a layer (i.e. the layer is not completely submerged). Layers that were already submerged when monitoring began or became submerged during the monitoring period have Ps values that range from 3.77 to 31.1. It is difficult to ascertain to what extent the settlement factors (i.e. capillary rise or submerged related settlement) in a semi-submerged layer contribute to settlement. For this reason, submerged Ps values will be used for partings below the groundwater table and capillary rise values will be used for a 5 m zone above the groundwater table. Semi-submerged Ps values (2.55 to 21.7) therefore will not be used.

The partings layers have undergone marked response to heavy infiltration whether the groundwater table was at some elevation in a layer or whether the layer was submerged (Table 4.3). Values of Ps ranging from 19.0 to 375 are used in the examples to follow where heavy infiltration is due to rainfall of the intensity of 18 cm in 4 days. The duration of the effect of the infiltration will be 100 days.

4.7 Large Diameter Consolidation Test Results - Highvale Mine

The purpose of the large diameter consolidation tests was to measure the settlement of the spoil material under load, and to observe the spoil settlement response to saturation under load.

The test procedure is outlined in Appendix B. To summarize briefly, the procedure was to place a sample in a large diameter cell, apply a load, and measure settlement. When the settlement under the load had essentially ceased, infiltration of water through the base of the sample was allowed. Four samples (tests 1-4) were dynamically compacted into the cell, simulating the behavior of the dragline in creating the windrows, and four samples (tests 5-8) were prepared by adding a static load to represent a predetermined depth of overburden.

All the samples were from the Highvale Mine. Samples 1,2 and 4-8 were clay materials, samples 1 and 2 being from the extensometer borehole at Highvale South Site 3, and samples 4-8 from a freshly deposited surface sample from Highvale North near Site 1. Sample 3, a partings material, was taken from the surface at Highvale South Site 5.

4.7.1 Samples 1,2 and 4

Figures 4.27 and 4.28 show the initial loading stages of the consolidation tests for Samples 1 and 4 respectively. Sample 1 was loaded to 300 kPa in one step and Sample 4 was loaded incrementally. Both are shown on a logarithmic time scale and it is seen that the initial rate of strain is extremely rapid. This is due to the unsaturated state of the materials, and therefore the initial compression is that of the air voids. Both figures show that under the maximum pressure of 300 kPa the samples showed a decreasing rate of settlement with time.

In the figures referred to above, it is shown on the diagram the point at which infiltration of water into the spoil material began. Sample 4 showed a large increase in strain when infiltration began, (Figure 4.28), while Sample 1 did not (Figure 4.27). This can be attributed to

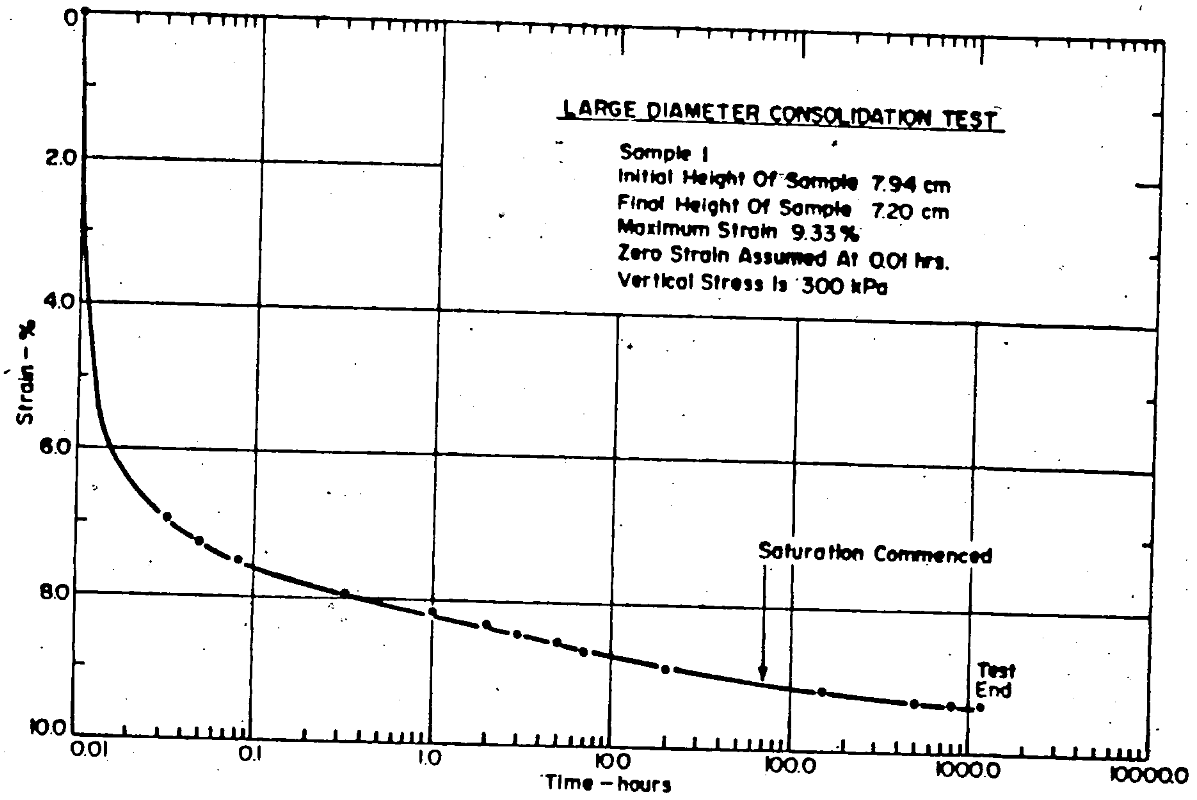


Figure 4.27 Consolidation From Loading and Saturation of Sample 1

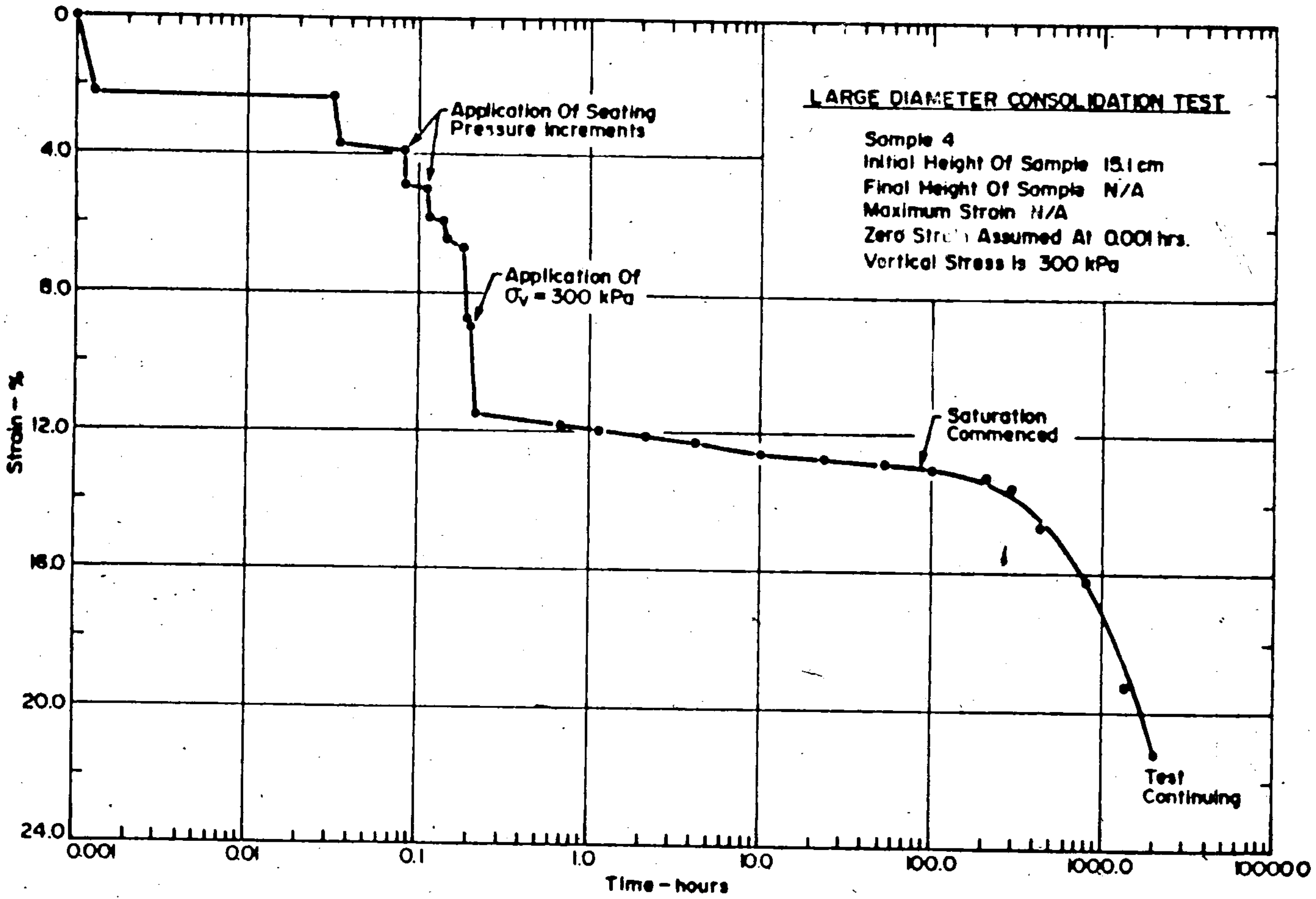


Figure 4.28 Consolidation From Loading and Saturation of Sample 4

the difference in materials. Sample 1 is a highly plastic clay with its activity very close to 2, whereas Sample 4, highly plastic as well, only has an activity of 0.52. An activity value less than 0.75 means that the clay particles are inactive or low swelling, whereas an activity value greater than 1.25 means that the clay particles are highly swelling (Skempton, 1953). This observable difference in settlement response when saturated demonstrates the variability in spoil material at the Highvale Mine.

4.7.2 Sample 3

Figure 4.29 shows percent strain as a function of the logarithm of time for Sample 3, the partings material. It strained by approximately 15 per cent within the first 1.2 hours of loading, more than any of the clay samples. The initial void ratio of this material was higher, however, than those of the clay samples. Before saturation, it had strained approximately 15.7 per cent. The reaction to saturation is seen to be fairly rapid, with the sample undergoing another 9 per cent strain during the next 200 hours. There was no evidence of slaking of the material when the cell was dismantled, even though the sample was saturated for over two months.

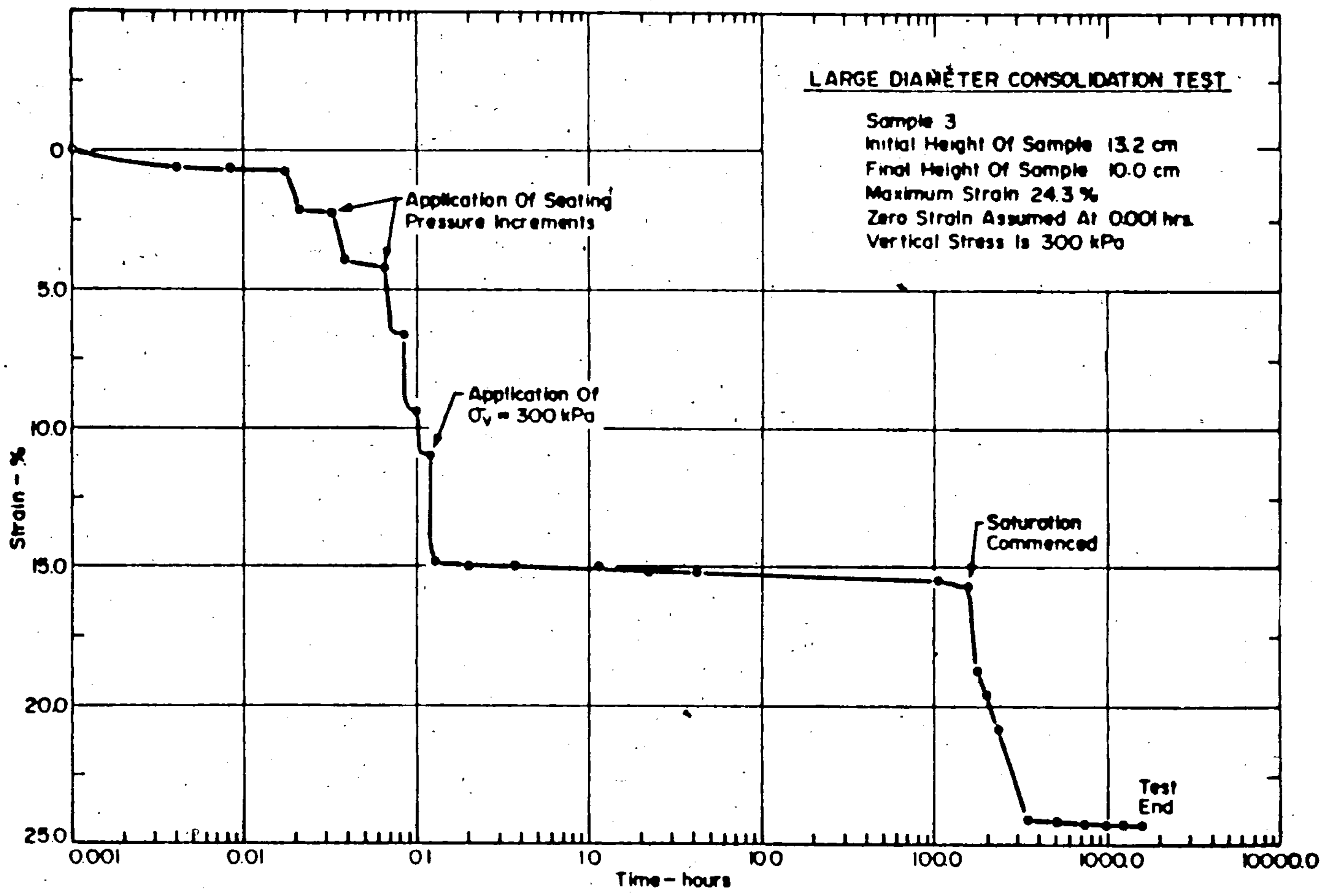


Figure 4.29 Consolidation From Loading and Saturation of Sample 3

4.7.3 Samples 5-8

Samples 5-8 were were tested under varying loads. Test loads used in the oedometer tests were 60.5 kPa, 92.0 kPa, and 320 kPa, representing 3.4 m, 5.1 m and 17.8 m of overburden respectively. Two samples were tested at a pressure of 320 kPa. It was found that at a saturation of roughly 85%, consolidation of the samples ceased. All samples had shown pronounced signs of slaking behavior when the test cells were dismantled.

4.8 Slaking Tests - Highvale Mine

Slaking tests were performed on the Paleocene Paskapoo and Upper Cretaceous Wapiti Formation Bedrock at the Highvale Mine. The spoil at the mine is comprised of this material. The testing method used was the Morgenstern and Eigenbrod Rate of Slaking Test (1974) and is described in Appendix C.

Nearly all of the samples tested underwent total disintegration after two hours of water immersion, and were classified as very fast slaking material (Watson, 1983).

5. DISCUSSION OF DATA AND EXAMPLES OF THE PREDICTIVE SETTLEMENT METHOD

5.1 Introduction

Before examples of the Predictive Settlement Method are discussed, a brief summary of the factors that influence the settlement of mine spoil is presented, followed by an explanation of groundwater conditions and how the long-term groundwater table can be estimated at the Highvale Mine. Generally, the settlement at the Highvale and Whitewood Mines tends to be a function of any of the following, or a combination of the following factors: saturation of the spoil and groundwater table effects, the stress level applied, soil composition, stratigraphy and the initial degree of soil compaction. Based on the data gathered, these categories will now be summarized.

5.2 Summary of Settlement Factors

5.2.1 Saturation of the Spoil and Groundwater Table Effects

Many aspects of the research for this thesis point to the significance of saturation of spoil material with regard to settlement.

The laboratory consolidation experiments of material from the Highvale Mine indicated the potential for marked settlement response of spoil when saturated under load. Tests showed that consolidation samples settled rapidly under an applied load, with further settlement caused by water infiltration (Figure 4.28 and Figure 4.29). At a saturation of about 85%, it appears from the laboratory consolidation tests that settlement ceases. Determining a correlation factor between laboratory results and observed field behavior is difficult because of the variability of the in-situ degree of saturation of spoil, and the lack of control on the movement of the groundwater table in field tests. Strains obtained in laboratory tests are much higher than those observed in the field, due in part to the control exerted on water infiltration in the laboratory. Saturation of the entire sample in a consolidation cell can be achieved within months, whereas in the field the soil may remain partially saturated for many years.

Several footing load tests were performed at the Highvale and Whitewood Mines. Data from these tests showed that saturation of cohesive spoil material such as at Highvale North, caused settlement (Figure 5.1).

The presence of the groundwater table has an important effect on settlement, depending on the type of spoil material. At the Whitewood Mine, where the spoil is

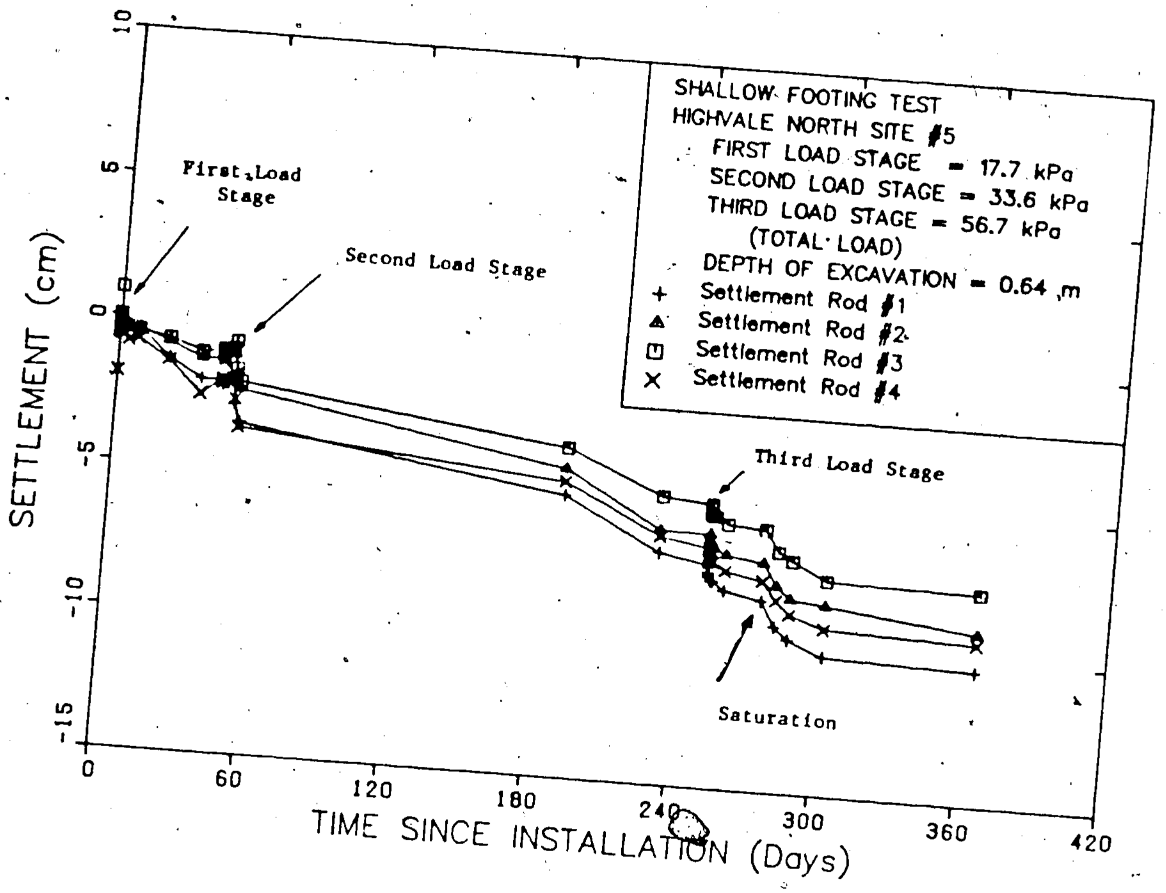


Figure 5.1 Settlement of the Shallow Footing Load Test at Highvale North Site 5

predominantly cohesionless, the location of the groundwater table at Site 2 had no appreciable effect on settlement. At the Highvale Mine, where the spoil is cohesive, there appears to be a relationship between the presence of the groundwater table and settlement of the spoil. In fact, much of the settlement at Highvale North and South is localized near the base of the spoil piles and appears directly related to the presence of the groundwater table. Figure 4.14 shows how the groundwater table has affected settlement at Highvale South Site 1. Slaking is believed to be the major form of settlement in material in the immediate vicinity of the groundwater table, and after the material is submerged.

Capillary rise is another phenomenon which can enhance settlement. Capillary rise is a function of the amount of fines present and the in-situ porosity of the soil. At several sites at the Highvale Mine, capillary rise appears to be the factor causing settlement.

Collapse and compression of soil structure has also been observed when spoil has undergone severe wetting. In July, 1982, a heavy rainfall of 18 cm in 4 days caused significant settlement of spoil piles. This is indicated by the initial slopes on Figure 4.7 from Highvale North Site 2. Generally, settlement rates at the Highvale Mine increased significantly during this time (Figure 4.3). At the older sites, Highvale North Sites 4 and 5, excessive wetting by the rainfall did not cause large settlements. However, the settlement rate shortly after the heavy infiltration did increase for a period of about 100 days.

5.2.2 Stress Level Applied

Depending upon the age and type of spoil material, an increase in load applied to the spoil increases settlement. This was observed at the valley site (Site 6) at the Whitewood Mine. Figure 4.2 indicates that most of the settlement occurring at this valley site is in the material below the valley and not in the valley fill itself.

Footing tests at the Whitewood Mine (on cohesionless subsoil) were not significantly affected by loading as were the footings at Highvale North (cohesive subsoil), and to a lesser extent at Highvale South (on partings subsoil). The loads applied were relatively small (approximately 50 kPa) compared with the load of about 180 kPa applied by infilling Whitewood Site 6 with about 10 m of fill.

Consolidation testing showed that an increase in stress increased settlement and that the combination of loading and saturation increased settlement (Figure 4.28).

5.2.3 Soil Composition

If the spoil material is predominantly granular, as at the Whitewood Mine, settlement due to self-weight occurs relatively quickly after placing and levelling spoil piles. Settlements of only 3 cm in 544 days for a 36 m depth of spoil of 4 years age have been recorded. At this same site, it is evident that the material has been unaffected in any way by the groundwater table (Figure 4.23).

Cohesive material, as at the Highvale Mine, tends to settle by self-weight over longer periods of time. It is possible that cohesive spoil material can still undergo significant settlement after a long time if subjected to a rise in the groundwater table or to infiltration by heavy rainfall.

5.2.4 Stratigraphy

The settlement of a reclaimed mine spoil site is a function of the existing soil profile. In other words, the settlement of a site composed of 3 or 4 different layers of material is a function of the settlement of each layer. This is because various spoil materials settle at various rates, as outlined in Chapter 4. These rates are influenced by such things as groundwater table rise and heavy infiltration.

5.2.5 Degree of Soil Compaction

It is of interest to note that the spoil material at the Highvale and Whitewood Mines tends to have similar densities in both peaks and valleys. That is, the densities of the spoil pile materials which are dynamically compacted by the draglines do not differ significantly from the densities of the spoil bulldozed from the spoil piles into the valleys. This observation, however, is based on limited data. More analysis and testing is needed to better understand this phenomenon.

In areas where the groundwater table is not an influencing factor, it appears that the age of spoil and not its density is a significant factor in settlement analysis. The older the spoil material, the more stable the soil structure. This is related to the development of a partially indurated crust. This crust becomes somewhat impermeable to infiltration and thus inhibits settlement. It is possible that a crust may act as a mat and thus aid in preventing differential settlement of a building. Further analysis of the properties of a partially indurated crust is necessary to lead to an understanding of its structural behavior.

Although voids of any significance were not discovered while drilling at the Highvale and Whitewood Mines, voids are known to exist. This was evidenced by field technicians who observed that runoff from heavy rainfalls in July, 1982 was not ponding at low points between spoil peaks, but was disappearing into the spoil material.

5.3 Discussion of the Groundwater Table and Long-Term Groundwater Table Estimation at the Highvale Mine

Based upon groundwater table data in the Highvale Mine area recorded since mining began in 1976-1977, and on the assumption that the groundwater table will return to original levels, it is possible to estimate long-term groundwater table elevations at the mine.

Drawdown is very small adjacent to the highwall (Pelz, 1984), and in the mined out area the groundwater level has remained low. This is due to the existence of two phreatic surfaces, one above the coal seams, and one below. Generally, the coal seams in the mine area are an important acquifer. However, in the region of the instrumentation monitored for this thesis, decreased fracture permeability of the coal caused by increased overburden thickness, has resulted in the coal not being an important acquifer (Monenco, 1981). Pumping keeps the upper phreatic surface from entering the spoil, with the result that the groundwater level in the spoil rises only as high as the lower phreatic surface, once the coal is removed. When mining ceases and pumping stops, it is assumed that the upper phreatic surface will be permitted to return to its original level.

Using data from Piezometer Data, Highvale Mine Area, 1983, (1983), the water levels from four piezometers in the area of instrumentation monitored for this thesis, were analyzed (Figure 5.2). The average of the highest recorded water levels attained at each of two piezometer nests was considered as the "worst" case or the highest likely groundwater table level that will occur once pumping ceases. Data from piezometer nest HG77-13 gave the highest possible groundwater table of the two nests.

uming a linear phreatic surface as an estimate (Figure), for a given ground surface elevation, it is a simple calculation to predict, as a rough approximation, a final groundwater table elevation. Thus for each site at the Highvale Mine, a final groundwater table elevation was estimated, values of which are shown in Figure 5.2. This information will be useful in ascertaining long-term settlement.

5.4 Examples Using the Predictive Settlement Method

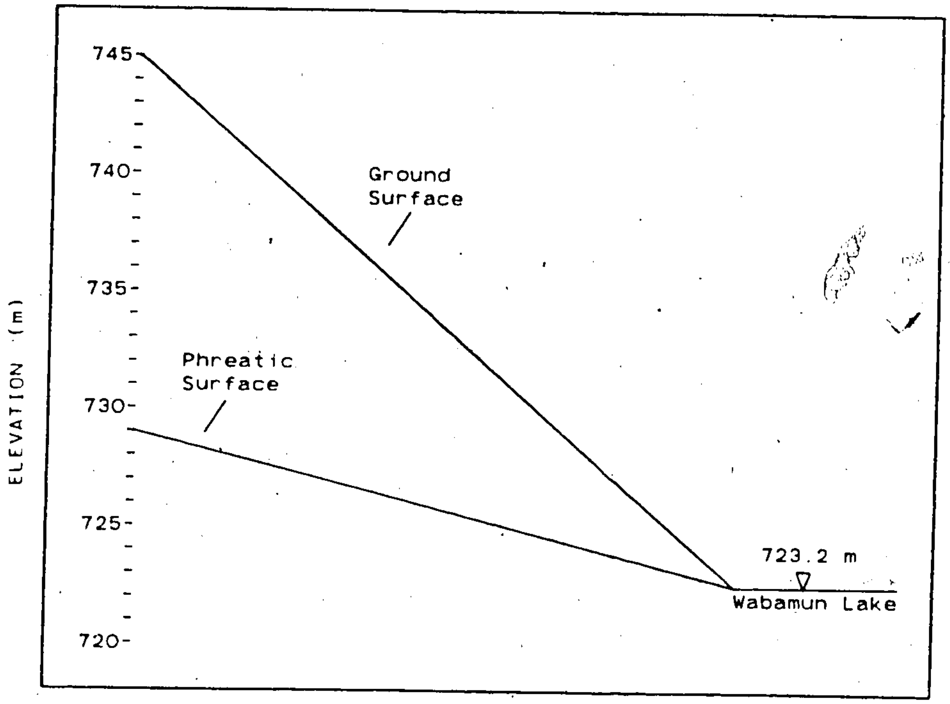
5.4.1 Introduction

It is possible to demonstrate that by knowing the location of the groundwater table and predicting its movement, and by knowing the stratigraphy of any spoil site, long-term settlement can be predicted. Ps values are

PIEZOMETER NUMBER	GROUND ELEV. (m)	DEPTH OF PIEZ BELOW GROUND SURFACE(m)	ELEVATION OF MEASURING POINT (m)	DEPTH TO HIGHEST RECORDED GWT (m)	DATE	ELEV. OF GWT (m)	AVERAGE ELEV. (m)
HG77-13-01	744.7	30.2	745.3	18.3	Nov. 20/77	727.0	729
HG77-13-02	744.7	28.6	745.3	14.8	Nov. 20/80	730.5	
HG77-17-01	736.7	30.2	737.3	14.6	Apr. 23/78	722.7	726
HG77-17-02	736.7	15.5	737.3	7.3	May 3/78	730.0	

1. At 745 m (ground surface), the groundwater table is at 729 m.
2. At 737 m (ground surface), the groundwater table is at 726 m.

Case 1 gives the highest resultant phreatic surface.



SITE	GROUND ELEV. (m)	PRESENT GWT ELEV. (m)	DEPTH (m)	EST. FINAL GWT ELEV. (m)	DEPTH (m)	RISE IN GWT (m)
HVN1	726.4	712.2	14.2	724.1	2.3	11.9
HVN2	726.7	713.8	12.9	724.1	2.6	10.3
HVN3	737.3	715.4	21.9	727.0	10.3	11.6
HVN4	736.4	717.6	18.8	726.7	9.7	9.1
HVN5	737.4	719.9	17.5	727.0	10.4	7.1
HVS1	737.7	717.3	20.4	727.1	10.6	9.8
HVS2	738.8	717.2	21.6	727.4	11.4	10.2
HVS3	735.5	717.8	17.7	726.5	9.0	8.7
HVS4	733.7	719.7	14.0	726.0	7.7	6.3
HVS5	738.7	720.4	18.3	727.3	11.4	6.9

Figure 5.2 Groundwater Table Data and Long-Term Groundwater Table Estimation at the Highvale Mine

assigned to spoil depending upon whether it is submerged, affected by capillary rise, undergoing self-weight, inhibited by a partially indurated crust, or subjected to heavy infiltration.

The void ratio of spoil material will ultimately reach a minimum, and settlement will virtually cease. Thus, the quantity of settlement possible at a site may occur in 25 years if the material is settling only by self-weight and not influenced by capillary rise or heavy infiltration, or may occur in as little as 100 days if subjected to a very heavy rainfall infiltration. In other words, total settlement will likely be the same regardless of the settlement path or series of settlement events. This means that after a heavy infiltration event, applied Ps values will be smaller than before the event. The amount of decrease in Ps values applied is a function of the settlement effect of the heavy infiltration event.

The most settlement that is possible for the three types of spoil (clay, sandy clay, and partings) is related to submerged conditions. This is because the largest Ps values (other than for heavy infiltration) are assigned for this condition (Ps = 19.9 for clay, Ps = 31.4 for sandy clay, Ps = 31.1 for partings [illegible]bles 4.2 and 4.3). Therefore total possible settlement [illegible] site can be predicted using these Ps values. It [illegible]so possible to predict settlement over a fixed period [illegible] years for example, using the range of Ps values applicable to whether the spoil is settling by self-weight, affected by capillary rise, or submerged.

Due to the random occurrence and unpredictable intensity of rainfall events, it is not possible to predict their effect. Subsequent rainfalls will likely have a decreasing settlement effect and settlement of spoil after heavy rainfall will likely be less than before the rainfall. Thus, Ps values assigned to spoil after a heavy infiltration are less than before.

The following examples will analyze the settlement of a fictitious spoil profile to show how the method is used, and then will be applied to the spoil at Highvale North Site 1 (HVN1). Possible ranges of settlement will be predicted for up to 20 years after the material is spoiled. Various settlement phenomenon will be analyzed. In each fictitious example, the spoil profile will be comprised of 10 m of partings, 5 m of sandy clay and 15 m of clay, the top 5 m of which is assumed to be a crust. In the following examples, the term "layer" refers to a thickness of spoil material, and "bedrock" defines the bottom of the spoil pile.

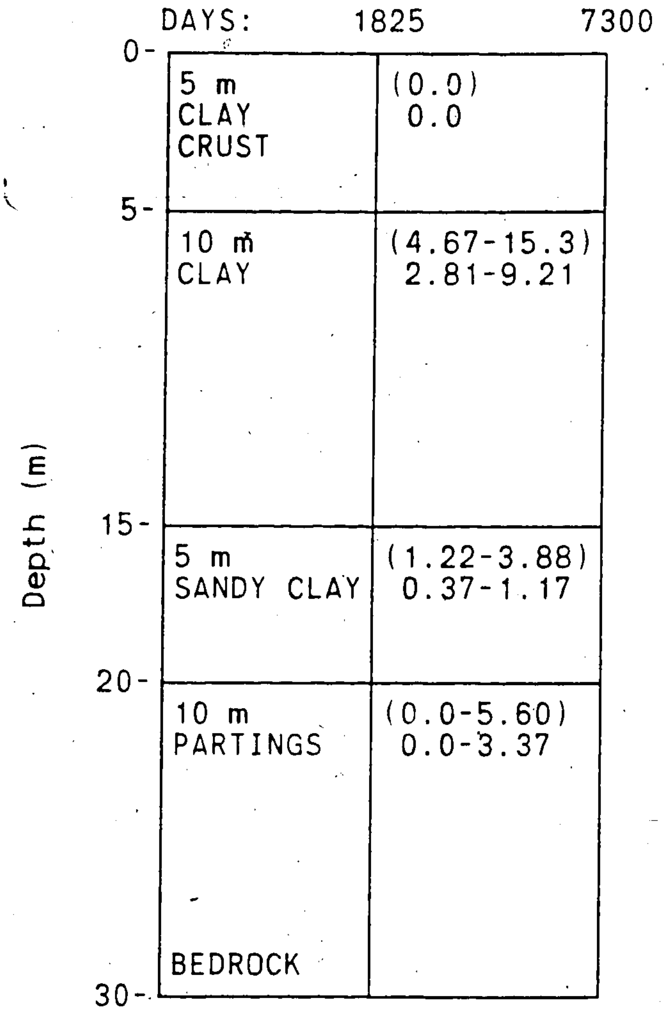
In each example, except example 7, settlement is calculated from five years after the material has been spoiled and reclaimed. This is to allow for uniform settlement patterns to develop. After five years, it is assumed that a partially indurated crust will have developed in the upper 5 m of clay. If conditions do not change, settlement can be calculated over any time interval (i.e. from 5 to 20 years) in one calculation (Example 1). However, with changing conditions, such as a rising groundwater table (Example 4), the smaller the time interval per calculation, the more precise will be the prediction. For changing conditions, then, calculations on a yearly interval are used. Although the groundwater table rises constantly through the spoil in some of the following examples, calculations involving the groundwater table are based on the location of the groundwater table at the beginning of each year.

The figures relating to each example show Ps values in brackets, with the affiliated settlement immediately below. Although three significant figures are used to calculate settlement, it is suggested that values of total settlement be rounded off to the nearest centimeter. Because the Ps values in Tables 4.2 and 4.3 were calculated from spoil at the Highvale and Whitewood Mines, it is recommended that predictions be made only at these mines using these values.

5.4.2 Example 1 - Spoil Profile With No Groundwater Table

Figure 5.3 shows how the Predictive Settlement Method and Ps values are applied to a spoil profile with

Predicted Settlement Between Days Shown



Total settlement between
day 1825 and day 7300 = 3 - 14 cm

Numbers in brackets are Ps values, numbers underneath are predicted values of settlement.

Not to scale.

Figure 5.3 Settlement Prediction of Example 1
(Spoil profile with no
groundwater table)

unchanging settlement conditions. This example depicts a spoil strata comprised of 10 m of partings, 5 m of sandy clay, and 15 m of clay, the top 5 m of which is a crust. The groundwater table is assumed to be non-existent throughout the period of analysis (5 to 20 years, 1825 to 7300 days). It is also assumed that in this time period there will not be a rainfall heavy enough to infiltrate the spoil profile and cause settlement. Ps values assigned to each layer (as found in Tables 4.2 and 4.3) are 0.0 for the 5 m clay crust, and the following self-weight values: 4.67 to 15.3 for the 10 m of clay, 1.22 to 3.88 for the 5 m of sandy clay and 0.0 to 5.60 for the 10 m of partings. The possible settlement in each layer is then calculated.

For example, to calculate the possible range of settlement in the 10 m clay layer from 1825 to 7300 days, the formula

$$Ps = \frac{\delta H/H}{\log(T2/T1)}$$

is rearranged as follows:

$\delta H = Ps * H * \log(T2/T1)$

Therefore,

$\delta H = 4.67 * 10^{-3} * 1000 \text{ cm} * \log(7300/1825) = 2.81 \text{ cm}$

and

$\delta H = 15.3 * 10^{-3} * 1000 \text{ cm} * \log(7300/1825) = 9.21 \text{ cm}$

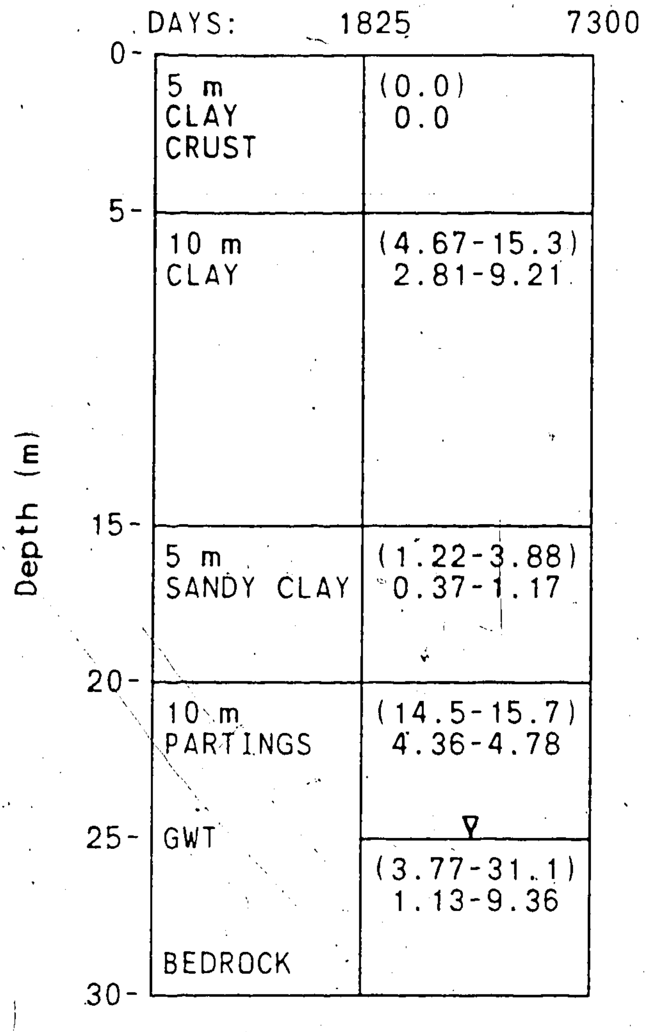
Thus, the range of possible settlement between 5 and 20 years after the material was spoiled is about 3 to 9 cm for this layer. As seen in Figure 5.3, this layer is the likely location of the major settlement that would occur in the spoil profile over the prediction period.

Similar calculations result in total settlement for the whole strata to be from 3 to 14 cm during this 15 year period. It is noted that the 5 m clay crust will not settle at all in the 5 to 20 year time span.

5.4.3 Example 2 - Spoil Profile With a Static Groundwater Table

Figure 5.4 shows the same spoil profile as in Figure 5.3 but with the groundwater table 5 m above bedrock and midway through the partings layer. The groundwater table is assumed to remain static throughout the prediction period and the soil strata not subjected to any heavy rainfall infiltration. Ps values for the clay and sandy clay are the same as for Figure 5.3. The partings layer, now having the groundwater table in the layer, has two ranges of Ps values applied. The 5 m above the groundwater table is considered to be undergoing capillary rise related settlement and Ps values of 14.5 to 15.7 are applied. The 5 m of partings that are submerged have Ps values of 3.77 to 31.1. Settlement is calculated similar to Example 1 and total settlements for the 15 year period

Predicted Settlement Between Days Shown



Total settlement between
day 1825 and day 7300 = 9 - 25 cm

Numbers in brackets are Ps values, numbers underneath are predicted values of settlement.

Not to scale.

Figure 5.4 Settlement Prediction of Example 2 (Spoil profile with a static groundwater table) range from 9 to 25 cm, almost double that from example 1. Figure 5.4 also shows the possible locations of the major settlements in the spoil profile for this example.

5.4.4 Example 3 - Spoil Profile Subjected to Heavy Infiltration

Figure 5.5 considers the same spoil profile as in the previous two examples. No groundwater table is assumed. As a demonstration of the possible effects of heavy infiltration, a heavy rainfall with an intensity in the range of 18 cm in 4 days is shown to occur, the effects of which last for 100 days. Following this, Ps values for capillary rise are assigned as it is assumed that the heavy infiltration will have increased the moisture content of the spoil material.

It is important to note that the settlement behavior of the spoil after the heavy infiltration is a function of the effect of the heavy infiltration. This is discussed in Section 5.4.1. Thus, if the heavy infiltration causes only a small amount of settlement (e.g. 1 cm), then the post heavy infiltration Ps values that are applied are from the upper range in Figure 5.5, resulting in settlement of approximately 17 cm. Similarly, if the heavy infiltration caused much settlement (e.g. 13 cm) then settlement afterward is calculated using the lower Ps values on Figure 5.5, resulting in the relatively small

Predicted Settlement Between Days Shown

Depth (m)	DAYS:	1825	3650	3750	7300
0	5 m CLAY CRUST	(0.0) 0.0	(38.7-395) 0.68-6.96	(8.04-19.0) 3.49-8.24	
5	10 m CLAY	(4.67-15.3) 1.41-4.61			
15	5 m SANDY CLAY	(1.22-3.88) 0.18-0.58	(43.3-231) 0.25-1.36	(11.8-31.4) 1.71-4.54	
20	10 m PARTINGS BEDROCK	(0.0- 5.60) 0.0-1.69	(19.0-375) 0.22-4.40	(14.5-15.7 4.19-4.54	
30	Sub-totals(cm):	1.59-6.88	1.15-12.7	9.39-17.3	

Numbers in brackets are Ps values, numbers underneath are predicted values of settlement.

Not to scale.

	Settlement if Low Intensity Rainfall, cm	Settlement if High Intensity Rainfall, cm
Before Infiltration During Infiltration After Infiltration	1.59-6.88 1.15 17.3	1.59-6.88 12.7 9.39
Totals:	20 - 25 cm	24 - 29 cm

Figure 5.5 Settlement Prediction of Example 3 (Spoil profile with no groundwater table subjected to heavy infiltration ten years after spoiling)

settlement of 9 cm. If the heavy infiltration caused large settlements, future heavy infiltration events will likely have decreasing settlement effects.

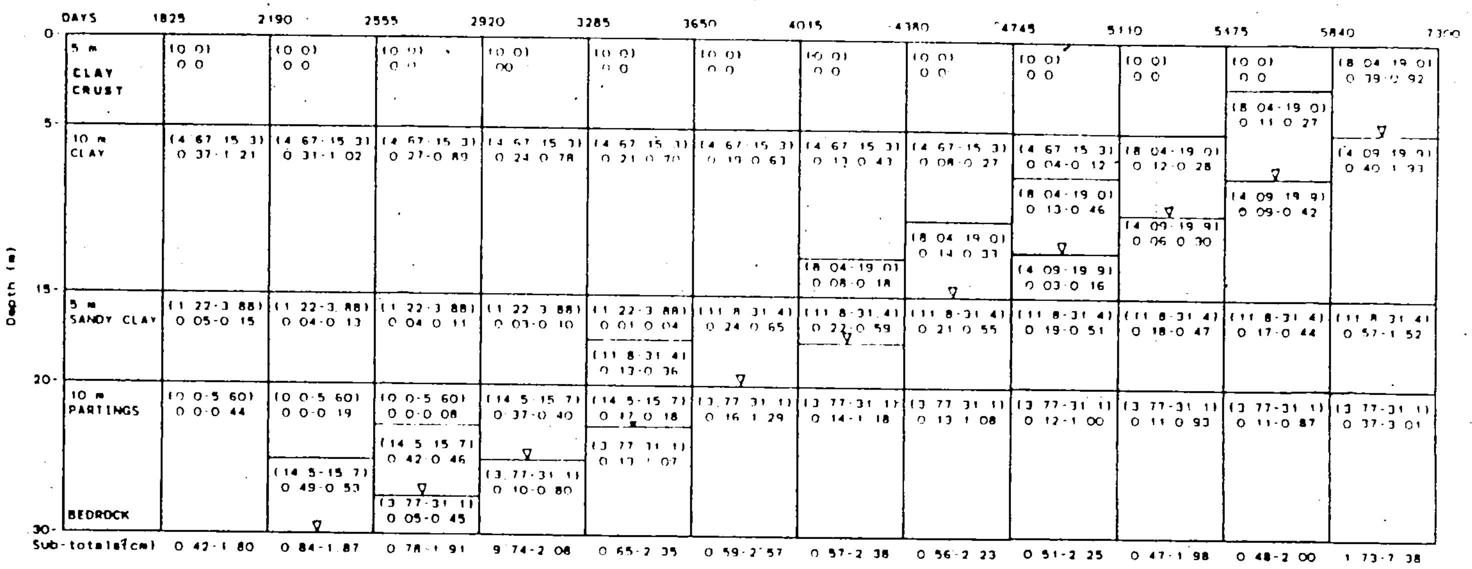
Due to the random timing of heavy infiltration events, it is emphasized that although total settlement at a site can be predicted, the series of heavy infiltration events that contribute to total settlement values cannot be predicted.

5.4.5 Example 4 - Soil Profile With a Rising Groundwater Table

This example will show the process involved in predicting long-term settlement at a site where settlement conditions change.

Figure 5.6 shows the same spoil profile as for the previous examples. Using hydrological and groundwater recovery information, it is predicted that the groundwater table, initially non-existent, will rise at a rate of 2.5 meters per year and, more importantly, that it will reach an elevation 5 m below the ground surface. From year 5 to year 6 (1825 to 2190 days), Ps values similar to example 1 are assigned. At the beginning of year 6 the groundwater table appears at the base of the spoil and the bottom 5 m of partings are affected by capillary rise. One year later (at 2555 days) when the groundwater table is 2.5 m above bedrock, the top 2.5 m of partings has Ps values assigned

Predicted Settlement Between Days Shown



Total settlement between day 1825 and day 7300 = 8 - 31 cm

Numbers in brackets are Ps values, numbers underneath are predicted values of settlement.

Not to scale.

Figure 5.6 Settlement Prediction of Example 4 (Spoil profile with the groundwater table rising 2.5 meters per year) for self-weight settlement (0.0 to 5.60), the 5 m below has Ps values assigned related to capillary rise (14.5 to 15.7), and the bottom 2.5 m has Ps values for submerged partings (3.77 to 31.1). Thus, as the groundwater table rises, Ps values are assigned depending upon whether the spoil is settling by self-weight, affected by capillary rise, or submerged.

In all three spoil types it is observed that an arbitrary value of 5 m of spoil above the groundwater table at any time is affected by capillary rise. It is not until the groundwater table rises enough to allow capillary rise to reach the clay crust (at about year 15, or 5475 days), does this layer undergo settlement. Although it would likely be the case that a partially indurated crust would settle more than a non-indurated clay layer of the same material, age, and thickness when subjected to a rise in the groundwater table, this variable is unknown at present. Because the crust is assumed to be not more than 5 m thick, it is deemed a reasonable assumption to assign Ps values to it that are assigned to clay at depth. Total possible settlement after 20 years for this example is 8 to 31 cm.

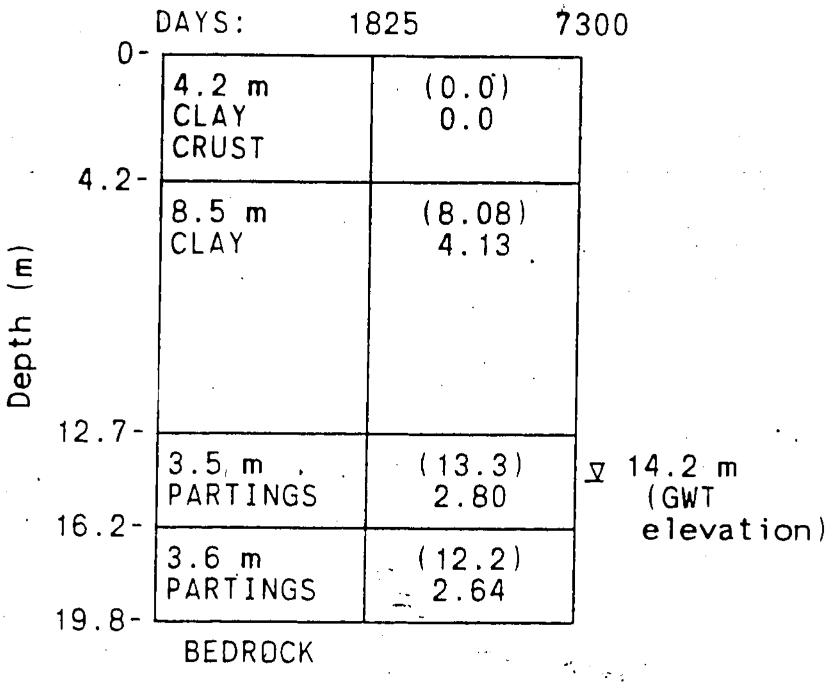
5.4.6 Example 5 - Settlement Prediction at Highvale North Site 1 Assuming a Static Groundwater Table and Using Known Ps Values

This example will predict settlement at Highvale North Site 1 using the Ps values that were calculated for this site (discussed in Section 4.5.2), and assuming that the groundwater table stays at its present elevation and that no heavy infiltration events occur.

Figure 5.7 shows the spoil profile at Highvale North Site 1 (HVN1) consisting of 12.7 m of clay and 7.1 m of partings. Both of these layers are divided in two on the basis of extensometer settlement data obtained from the site. The upper 4.2 m was not monitored with a multipoint extensometer and is considered at 1875 days not to be settling (i.e. this layer is believed to be a partially indurated crust), with a Ps value equal to 0.0. The layer from 4.2 to 12.7 m is known to have a Ps value equal to 8.08. The partings was monitored with two extensometers, the resulting layers having similar Ps values for submerged partings (13.3 and 12.2), the upper partings layer being semi-submerged. If the groundwater table were to remain steady at 14.2 m below the ground surface where it is presently, and the site were not to be subjected to heavy infiltration, the total settlement at this site from 1825 to 7300 days will be about 10 cm.

5.4.7 Example 6 - Settlement Prediction at Highvale North Site 1 Using Known Ps Values Changing With a Rising Groundwater Table

Predicted Settlement Between Days Shown



Total settlement between day 1825 and day 7300 = 10 cm

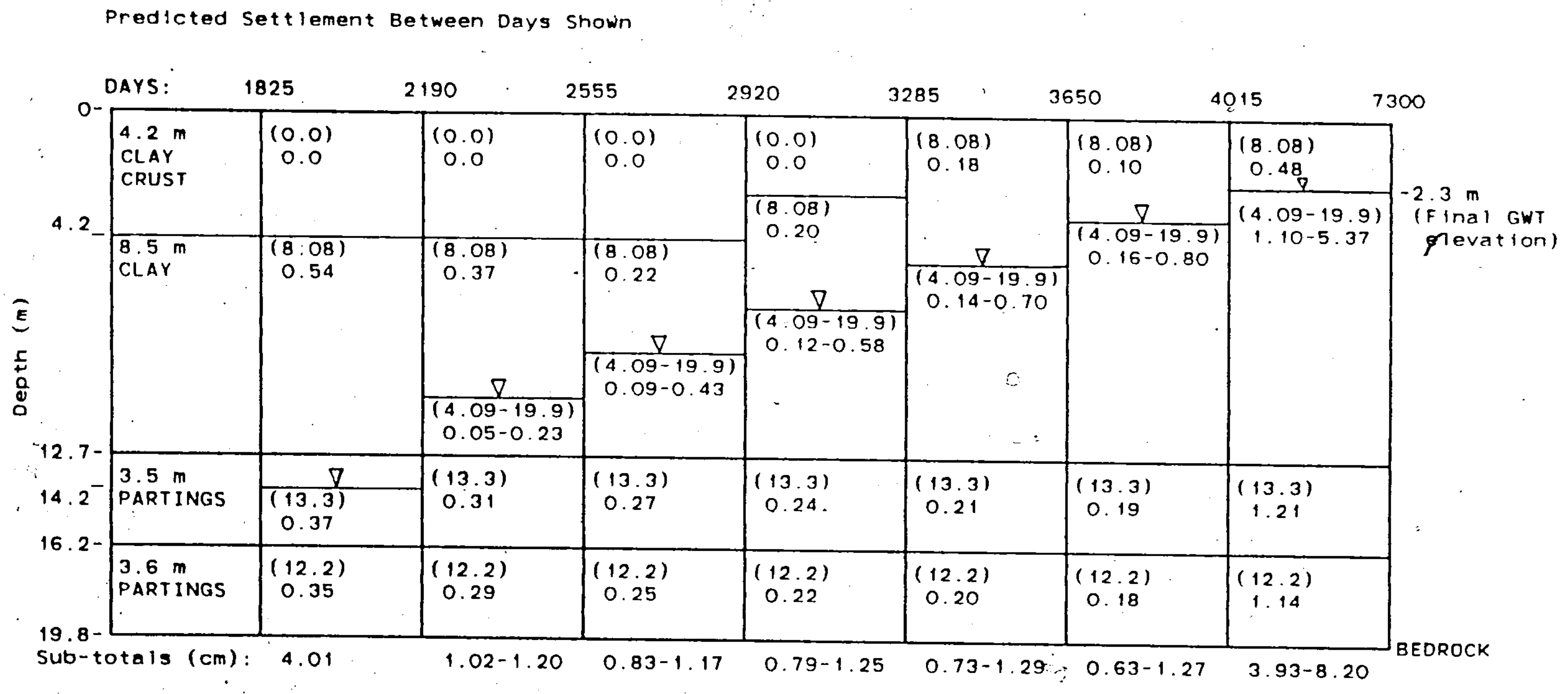
Numbers in brackets are Ps values, numbers underneath are predicted values of settlement.

Not to scale.

Figure 5.7 Settlement Prediction of Example 5 (Highvale North Site 1 assuming a static groundwater table and using known Ps values)

This example (Figure 5.8) will predict settlement at Highvale North Site 1 assuming that pumping at the mine will stop five years (1825 days) after the material at this site has been spoiled, and that the groundwater table will recover to an estimated final elevation of 2.3 m below the ground surface. The derivation of the final groundwater table elevation is shown in Figure 5.2. The spoil profile for this example is the same as in Figure 5.7. The groundwater table is shown to rise 11.9 m over six years and for ease of analysis, rises 3.2 m from 1825 to 2240 days, then 2 m per year for 4 years, then 0.7 m from 3700 to 4065 days, to the predicted final elevation of 2.3 m below the ground surface.

Ps values for the partings layers remain unchanged as they remain submerged. It is assumed that the top 4.2 m of crust will have the same Ps values for capillary rise as the clay below. As mentioned in Section 4.6.2 (Ps Values for Clay), this assumption is deemed reasonable due to the small thickness of the crust. Submerged Ps values for clay at this site are unknown and thus values of 4.09 to 19.9 from Table 4.2 are used. Throughout this thesis, capillary rise is assumed to occur no more than 5 m above the groundwater table. This site, however, has exhibited settlement up to 9.4 m above the groundwater table, thought to be caused by capillary rise. Therefore the calculated Ps value of 8.08, related to capillary rise, is



Total settlement between day 1825 and day 7300 = 12 - 18 cm

Numbers in brackets are Ps values, numbers underneath are predicted values of settlement.

Not to scale.

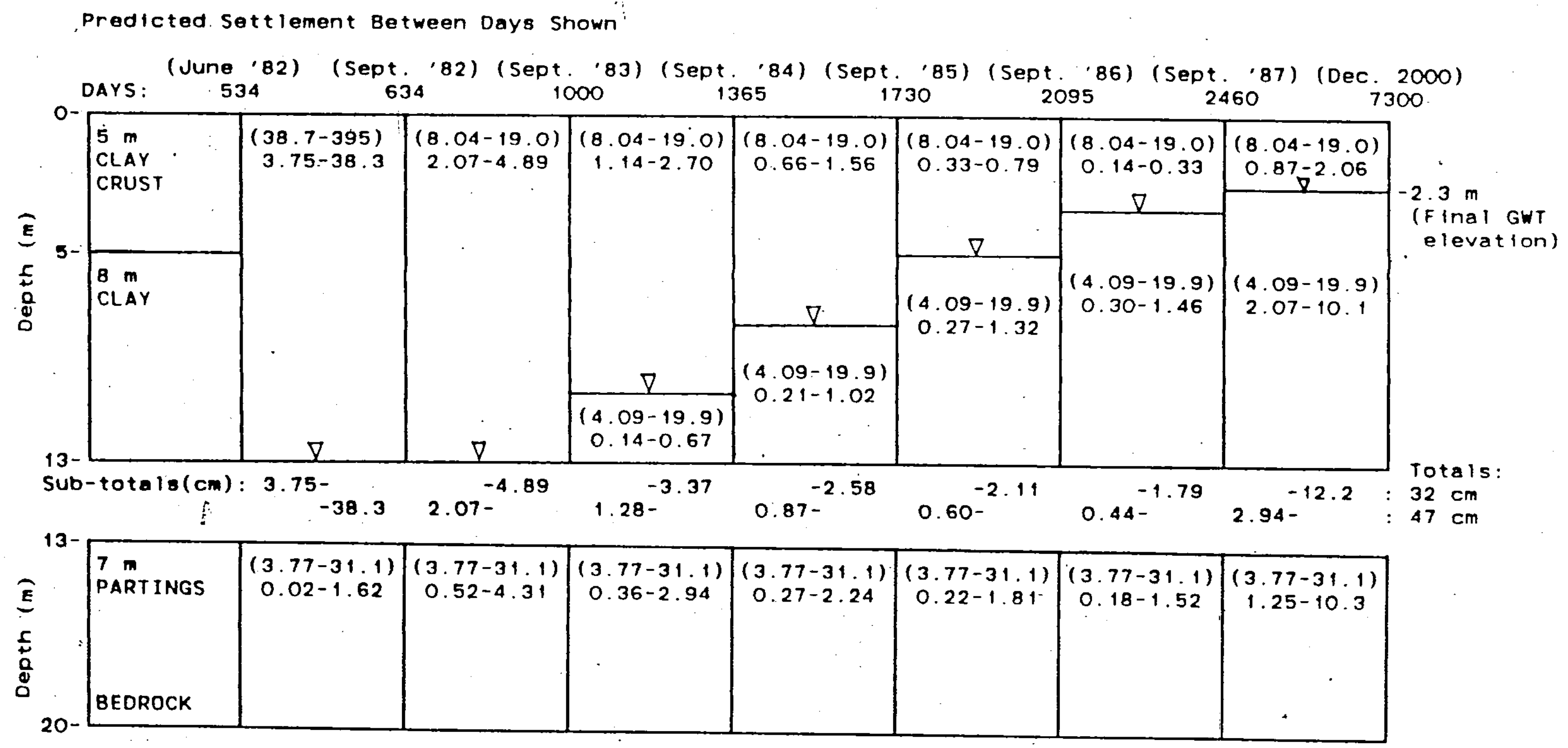
Figure 5.8 Settlement Prediction of Example 6 (Highvale North Site 1 using known Ps values changing with a rising groundwater table) used for the 8.5 m clay layer throughout this analysis. It is assumed that not until about 2920 days have passed will the 5 m zone of capillary rise above the groundwater table have an effect on the crust. Total settlement is calculated to be from 12 to 18 cm from day 1825 to day 7300.

If a prediction is made but assumed conditions change during the course of the prediction (a change in the recovery rate of the groundwater table for example), then it is possible to re-evaluate the settlement conditions at a site to develop a new prediction. If in this example the groundwater table rose to an elevation of 10 m below the ground surface instead of the elevation indicated, a new prediction would need to be formulated.

5.4.8 Example 7 - Settlement Prediction at Highvale North Site 1 Using General Ps Values

This example will predict the settlement at Highvale North Site 1 as if the site were just recently instrumented, no settlement data were available, and a long-term prediction of settlement was needed from day 534 to day 7300. General Ps values from Tables 4.2 and 4.3 will be used. It is assumed that only the stratigraphy at this site is known and that instrumentation includes only a surface settlement gauge and a standpipe piezometer.

As seen in Figure 5.9, this site is divided into 3 layers: a clay crust 5 m thick, 8 m of clay, and 7 m of



Total settlement between day 534 and day 7300:

Partings: 3 - 25 cm
Clay, if small infiltration settlement occurs: 32 cm
Clay, if large infiltration settlement occurs: 47 cm
(See text, page 119, for explanation)

Numbers in brackets are Ps values, numbers underneath are predicted values of settlement.
Not to scale.

Figure 5.9 Settlement Prediction of Example 7 (Highvale North Site 1, using general Ps values for conditions of heavy infiltration and a rising groundwater table) partings. The groundwater table is shown at the top of the partings layer, near where it is presently, for ease of analysis.

The prediction includes a heavy rainfall infiltration event (which actually did happen at this site) at the beginning of the prediction. Because the partings is submerged in this example, (at the actual site the groundwater table does not submerge the partings), it is assumed that this material will not be affected by the heavy rainfall event. For this reason, settlement analysis of the partings is shown separately from the clay, and Ps values for submerged partings (3.77-31.1) from Table 4.3 are used. Assuming the groundwater table will rise at a uniform rate to an estimated long-term elevation of 2.3 meters below the ground surface, the process of predicting long-term settlement is begun, and ranges of possible settlement are calculated.

After the heavy infiltration event, all of the clay is shown to be undergoing settlement. This is a function of the degree to which the heavy infiltration saturated the spoil. Monitoring the surface settlement gauge would give an indication of how the spoil was settling during and after the period of heavy infiltration. For example, if total settlement from 1000 to 1365 days was 2 cm (equal to the lowest value of the predicted range for this time period), then it would be reasonable to conclude that the

Ps values for the clay and partings were the lowest values indicated.

Because the Ps values for submerged clay and clay undergoing capillary rise settlement are similar, the estimated rate of recovery of the groundwater table is not crucial. If, however, the groundwater table does not rise to its estimated elevation of 2.3 m below the ground surface but stops at some lower elevation, then it is possible that evaporation of the moisture in the spoil above could result in smaller values of settlement than predicted. Therefore, the rate of recovery of the groundwater table is not as important as is its estimated final elevation.

Liberal analysis would consider the entirety of the clay to be affected by the heavy rainfall, especially because of the young age of the spoil. If the spoil were older (i.e. five years or more), then the spoil profile may not be affected, unless the rainfall were to pond on the surface. Depending upon the impermeability of the partially indurated crust, it is possible that no rainfall will reach the lower layers.

In the first 100 days, 4 to 39 cm of settlement were calculated as possible quantities of settlement in the clay. Actual settlement in this 100 day period was about 4 cm. This is because the Ps value for this layer at Highvale North Site 1 was 38.7, the lower Ps value in the range indicated on Figure 5.9. If detailed index testing was performed on the clay from the standpipe piezometer hole drilled at the site, it may have been possible to estimate the response of the clay to the heavy infiltration event. For example, if the clay was found to be dry and loose, high Ps values for heavy infiltration would be assigned.

Because total possible settlement of the spoil will likely be constant, Ps values applied to the clay after the heavy infiltration will be a function of the settlement effect of the heavy infiltration. If 4 cm of settlement in the clay occurs because of the heavy infiltration, then the settlement following will be higher than if 39 cm of settlement resulted from the heavy infiltration. Thus, small Ps values comprise settlement predictions following large settlements caused by heavy infiltrations, or large Ps values are used if small settlements are caused. For this example, total settlements will be from 32 to 47 cm from 534 to 7300 days for the clay, and 3 to 25 cm for the partings. This is illustrated in Figure 5.9 on page 116.

5.4.9 Summary

The preceding seven examples have demonstrated the use and applicability of the Predictive Settlement Method to predict the settlement of spoil at the Highvale Mine.

Ps values calculated from mine spoil at the Highvale and Whitewood Mines were applied to a fictitious spoil profile to predict long-term settlement. Settlement of the spoil was influenced by varying conditions such as self-weight (Example 1), a static groundwater table (Example 2), heavy infiltration (Example 3), and a rising groundwater table (Example 4). Long-term settlement of spoil at Highvale North Site 1 (HVN1) was predicted using the Ps values calculated for this site (Example 5), using Ps values associated with a rising groundwater table (Example 6), and using general Ps values as if no settlement data existed for this site (Example 7).

The method has shown how much settlement can be predicted at a site, and where in a spoil profile the settlement occurs. The previous examples have shown how a variety of settlement conditions are accommodated in calculating settlement. A similar process could be carried out at other mines where sufficient settlement data existed, the stratigraphy was known, and the groundwater table was monitored. This would allow for the determination of appropriate ranges of Ps values which, in conjunction with an estimated final groundwater table elevation, could be used to predict settlement.

6. APPLICATION OF RESULTS

6.1 Introduction

The Predictive Settlement Method will now be applied to two other minesites. Settlement is analyzed at the Diplomat Mine near Forestburg, Alberta, and at the Horsley Mine in Northumberland, United Kingdom. Some interesting observations were made about settlement patterns at both mines and the viability and limitations of the Predictive Settlement Method are discussed.

6.2 Diplomat Mine

At the Diplomat Mine, the Predictive Settlement Method will be used to derive Ps values possible for this minesite. No predictions of settlement are made as limited data is available and the location of the long-term groundwater table elevation is unknown.

Monitoring of settlement by means of a multipoint extensometer at the mine has been carried out since 1980. The mine spoil is comprised of reclaimed glacial overburden materials (clay and sandy clay), and has been found to be very uniform with depth. The spoil is an average of 11 m deep.

Figure 6.1 shows how the spoil has settled with depth. Settlement data for each layer, (equal to the distance between extensometer magnets, or approximately

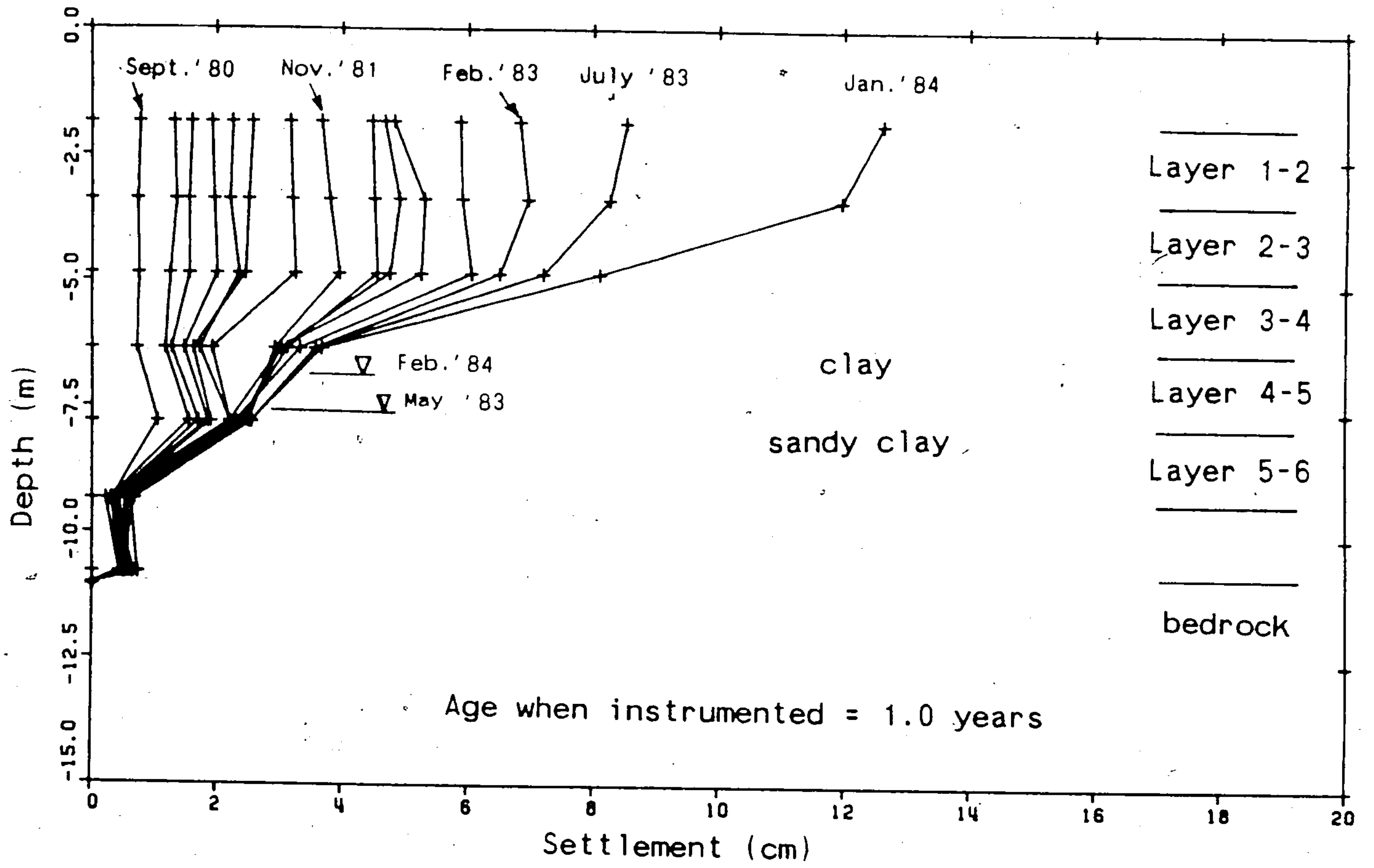


Figure 6.1 Settlement at the Diplomat Mine

1.5 m), was analyzed and plotted with the logarithm of time, and showed some interesting trends. Five layers will be analyzed. Layers are defined by the extensometer at the top and at the bottom of the layer.

Layer 1-2 (1.84 to 3.37 m) did not settle, possibly related, as at the Highvale Mine, to the development of a partially indurated crust. Ps is equal to 0.0 for this layer.

Layer 2-3 (3.37 to 4.86 m) did not settle for almost the entirety of the monitoring period but began to settle very significantly after a heavy rainfall, giving a resulting Ps value of 355, similar to values calculated at the Highvale Mine for similar circumstances. It is possible that tension cracks allowed the infiltration of the rain to reach this layer.

Layer 3-4 (4.86 to 6.33 m) underwent three settlement regimes during the period of monitoring. For 100 days, no settlement was recorded. Then, in the next 600 days, settlement resulting in a Ps value of 23.9 was observed, possibly related to capillary rise. Once again the settlement pattern changed, with Ps working out to 143 for the following 500 days. The settlement versus logarithm of time graph of Figure 6.2 shows a sharp change in slope, indicating how the settlement pattern changed for this layer. What caused this sudden change is unknown. It is believed that the steeper slope of graph 3-4 on

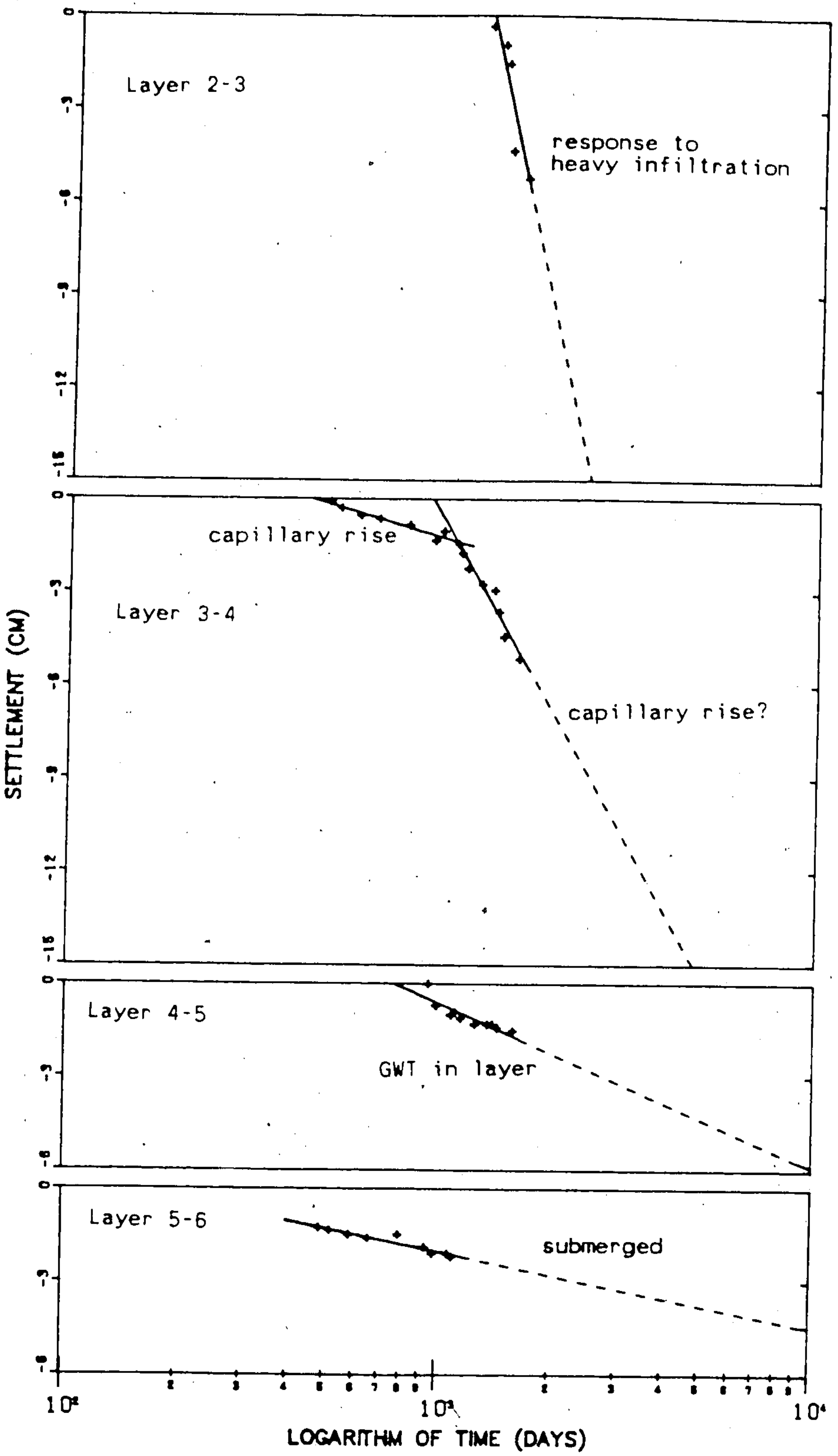


Figure 6.2 Settlement of Layers 2-3, 3-4, 4-5, and 5-6 at the Diplomat Mine

Figure 6.2 will continue until the groundwater table rises into layer 3-4, causing a change in settlement pattern.

Layer 4-5 (6.33 to 7.78 m) had two settlement patterns. For 600 days Ps was 0.0 indicating that no settlement had occurred. Then, prior to the groundwater table entering the layer, (which occurred in May 1983), settlement began, likely related to capillary rise. Ps became 36.2. It is not clear why the layer above this layer began to respond to capillary rise sooner (layer 3-4 began what appeared to be capillary rise related settlement before layer 4-5). Presently, the groundwater table is in layer 4-5 at 7.0 m below the ground surface, and the settlement pattern is seen in graph 4-5 of Figure 6.2.

Layer 5-6 (7.78 to 9.33 m) is the only layer that has not had its settlement pattern altered by capillary rise, or heavy infiltration. For the duration of monitoring, this layer has been submerged. It is observed that the settlement data points for this layer (Figure 6.2, graph 5-6) are proportional to the logarithm of time. Because this layer is subject to the constant condition of being submerged, settlement should continue along the line of graph 5-6. Other layers also show straight line settlement patterns with slopes that change with changing settlement conditions.

Table 6.1 summarizes the Ps values derived from the settlement data of the spoil at the Diplomat Mine. Similar to spoil at the Highvale Mine, the formation of a partially indurated crust appears to inhibit settlement of the surface layers. Self-weight settlement at this site likely occurs relatively soon after the material is spoiled, similar to spoil at the Whitewood Mine. This conclusion is based on the observation that for at least a short period of time, four of the five layers analyzed were not settling at all.

A range of Ps values of 23.9 to 36.2 could be applied to spoil at this site subjected to capillary rise. These values are in the range of Ps values for sandy clay from the Highvale and Whitewood Mines, subjected to capillary rise conditions. It would appear that capillary rise causes the most settlement at this mine, and not submerged conditions, which is the case at the Highvale and Whitewood Mines. If a layer is submerged, a Ps value of 16.8 can be used. This value is similar to those at the Highvale Mine for clay for submerged conditions. A Ps value of 355 can be applied to a layer subjected to heavy infiltration. Further settlement analysis at the Diplomat Mine would determine the duration of the effect of this condition.

This analysis has derived some of the possible Ps values applicable to spoil at the Diplomat Mine, and some

DIPLOMAT MINE

LAYER	Ps VALUE	CONDITION
1-2	0.0	Partially Indurated Crust
2-3	0.0	Self-weight
	355	Response to heavy infiltration
3-4	0.0	Self-weight
	23.9	Capillary rise
	142	Capillary rise
4-5	0.0	Self-weight
	36.2	Capillary rise
5-6	16.8	Submerged

Table 6.1 Summary of Ps Values From the Diplomat Mine

correlation has been made of the effects of various settlement conditions on spoil between the Highvale Mine and Whitewood Mine, and the Diplomat Mine. Significantly more data would be needed, such as borehole logging information and more settlement data, to be able to derive ranges of Ps values applicable to the Diplomat Mine. These values, along with an estimation of the long-term groundwater table elevation, can be used to predict long-term settlement at the Diplomat Mine.

6.3 Horsley Mine, United Kingdom

Settlement has been monitored at the Horsley Mine since 1973 when instrumentation was installed at this reclaimed minesite. The mine spoil is up to 70 m deep and is predominantly a cohesionless fill of mudstone and sandstone fragments. Four sites at the mine will be analyzed using the Predictive Settlement Method.

Enlarged graphs of settlement versus time were provided by J.A. Charles of the Building Research Establishment in the United Kingdom. Charles is presently studying the settlement at the Horsley Mine. Approximate values of settlement and time were obtained from the graphs and settlement versus the logarithm of time graphs were drafted and analyzed. It is assumed that the data obtained from the graphs is reasonably accurate and that the distance between successive extensometers at each site is 6 m. For consistency of calculation, it is assumed that the spoil material was backfilled in January of the year indicated.

Restoration of the minesite to desired contours including replacement of subsoil and topsoil was completed in 1973. Preferably, the Predictive Settlement Method is not to be applied to spoil material until at least five years after it is spoiled and reclaimed. This is to allow for stable settlement patterns to develop. Nevertheless, reasonable settlement patterns were observed at the Horsley test sites analyzed, and so settlement data before the suggested five year time period was used in analysis. Ps values for each site were calculated.

Settlement patterns at this mine are different from those at the Highvale Mine. For example, at the Horsley Mine, when the groundwater table has risen through a layer, settlement of the layer virtually stops. This is in contrast to the Highvale Mine where once a layer of spoil becomes submerged, settlement continues, but at a different rate. This is very likely related to the differences in spoil material. The spoil at the Highvale Mine dates from the Cretaceous (65-70 million years old) and when it is excavated, breaks up and behaves essentially as a soil. The spoil at the Horsley Mine, belonging to the Middle and Lower Coal Measures of the Carboniferous system, some 270-300 million years old, is basically rock. It is highly probable, therefore, that spoil at the Horsley Mine could have a low slaking potential when submerged, for example.

The exact spoil profile at the Horsley Mine was unknown for this analysis. Ps values from site to site, therefore, cannot be compared because of this and also because of the varying history of two of the four sites, one being preloaded and one previously inundated.

A few explanatory comments will aid the reader to more easily understand the figures related to this section. Numbering of the extensometers in each borehole at the Horsley Mine is done starting at the bottom of the spoil pile. Layers are defined by the extensometers, similar to the analyses at the Highvale and Whitewood Mines. Each site discussed has a graph showing the settlement of various extensometers (recorded in millimeters), and the recovery of the groundwater table (in meters), with time. The elevations of the extensometers are shown on the plot depicting the recovery of the groundwater table.

Each site also has a graph of settlement versus the logarithm of time, similar to those from the Highvale and Whitewood Mines. The slopes of the plots on these figures are labelled with the following terms: self-weight, GWT (groundwater table) rise, and submerged, indicating the settlement condition related to each slope.

6.3.1 Site D1

Site D1 (Figure 6.3) was backfilled in 1966 and is 55.5 m deep. The backfill had been previously loaded by a large overburden heap of about 30 m that had been removed two years before monitoring began in 1973. Figure 6.4 shows a graph of settlement versus time, and depth to the groundwater table versus time. The analysis to follow will consider the effect of the groundwater rise between extensometers 4 and 7 (termed layer 4-7).

It is seen from Figure 6.4 that at the time the groundwater table rises above an extensometer, settlement of that extensometer stops (extensometers 4 and 5 for example). It is also seen that extensometer 7 stopped settling about the time the groundwater table stopped rising (April 1977) which would suggest that at this site capillary rise does not occur or that capillary rise related settlement does not occur.

It is assumed that the settlement that occurred was caused solely by the rise of the groundwater table. It is also assumed that the spoil material between extensometers 4 and 7 is the same, and that settlement recorded at any time between extensometers 4 and 7 occurred in the immediate vicinity of the groundwater table. This is based on the observation at this site of no capillary rise related settlement, or settlement of spoil when submerged.

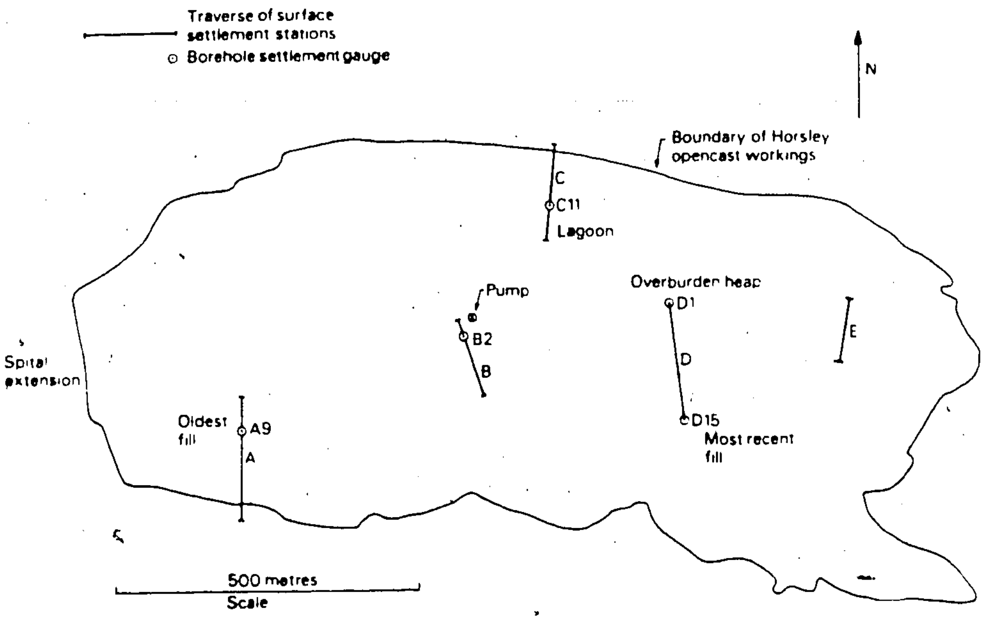


Figure 6.3 Location of the Horsley Mine Boreholes (After Charles et al., in press)

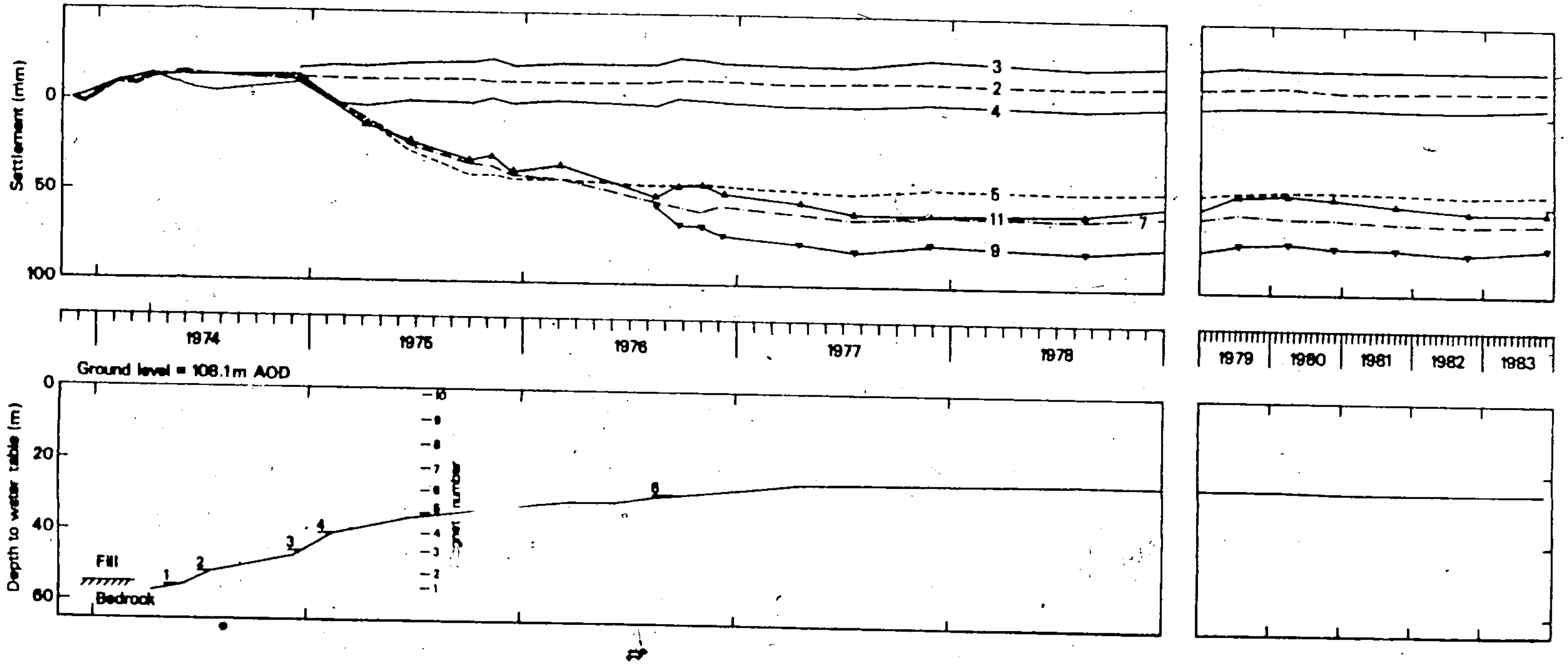


Figure 6.4 Settlement and Groundwater Table Recovery at Site D1, Horsley Mine (After Charles et al., in press)

About 3.2 cm of settlement were recorded from when the groundwater table entered layer 4-5 in February 1975, to when it left layer 4-5 in September 1975. In this layer (4-5), the groundwater table had risen 6 m in 6 months and the Ps value for layer 4-5 was 206. As the groundwater table rose from extensometer 5 to 6, settlement of 2.6 cm was recorded (September 1975 to October 1976). Here the groundwater table had risen at a rate of 6 m in 14 months, less than half the rate that was recorded as it rose through layer 4-5. The Ps value for layer 5-6 was 85.8. From October 1976 until April 1977, settlement in layer 6-7 was 0.7 cm and stopped when the groundwater table stopped rising. The rate of groundwater table rise in this layer (6-7) was about 3 m in 7 months, similar to the rise in layer 5-6, and the Ps value was 82.2. For layers 5-6 and 6-7 the rate of groundwater table recovery was the same and Ps values were similar. The settlement versus logarithm of time graph of Figure 6.5 shows the settlement pattern at this site.

It is possible to conclude, then, that Ps values at this site are a function of the rate of groundwater table recovery. In other words, the amount of settlement recorded at any time is not proportional to the rate of recovery of the groundwater table. Again, this statement is made assuming that the material between extensometers 4 and 7 is the same.

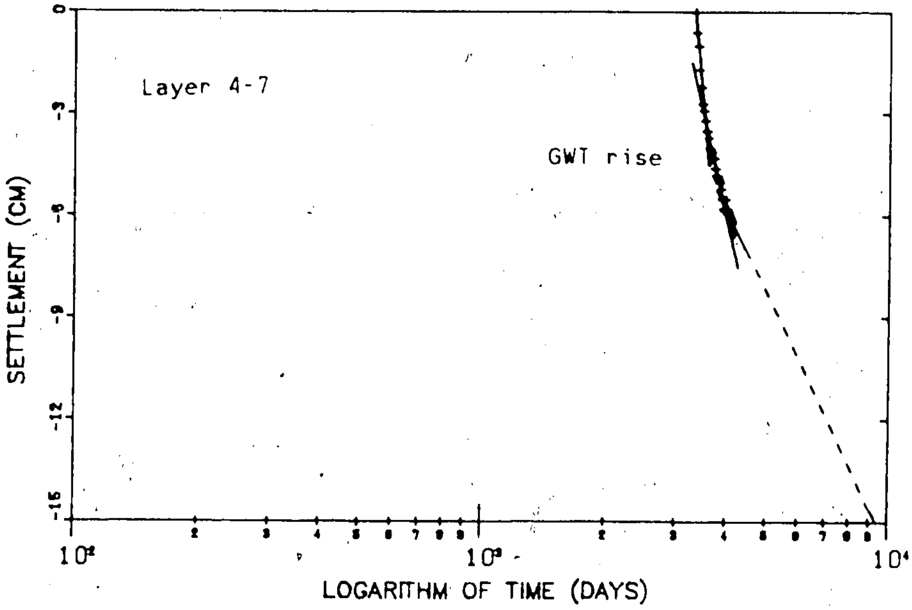


Figure 6.5 Settlement of Layer 4-7 at Site D1, Horsley Mine

6.3.2 Site D15

Site D15 (Figure 6.3) was backfilled in 1970 and is the youngest of the sites analyzed. The fill is 46.5 m deep. Because the instrumentation at this site is situated on high ground, only the bottom 10 m of the backfill have been inundated by the rising groundwater table. This has allowed for the derivation of Ps values related to self-weight settlement, values for the groundwater table rising through the spoil, and for submerged conditions.

As at site D1, it appears that capillary rise at Site D15 is not a settlement factor. This is based on the observation that when the groundwater table stopped rising between extensometers 4 and 6 (Figure 6.6), settlement of this layer slowed down considerably. As can be seen on Figure 6.6, when the groundwater table has passed through a layer, settlement of that layer virtually stops.

Layer 2-4 was analyzed for the time period when the groundwater table rose through the layer (October 1975 to April 1977) and after it was submerged. Ps values were 22.6 as the groundwater table went through the layer and 1.55 when the layer was submerged. The change in slope of Figure 6.7, layer 2-4, graphically shows how settlement almost stops when a layer becomes submerged.

Layer 4-6 had a Ps value of 10.1 prior to the groundwater table entering the bottom of the layer. As seen in Figure 6.7, the slope of the line for layer 4-6

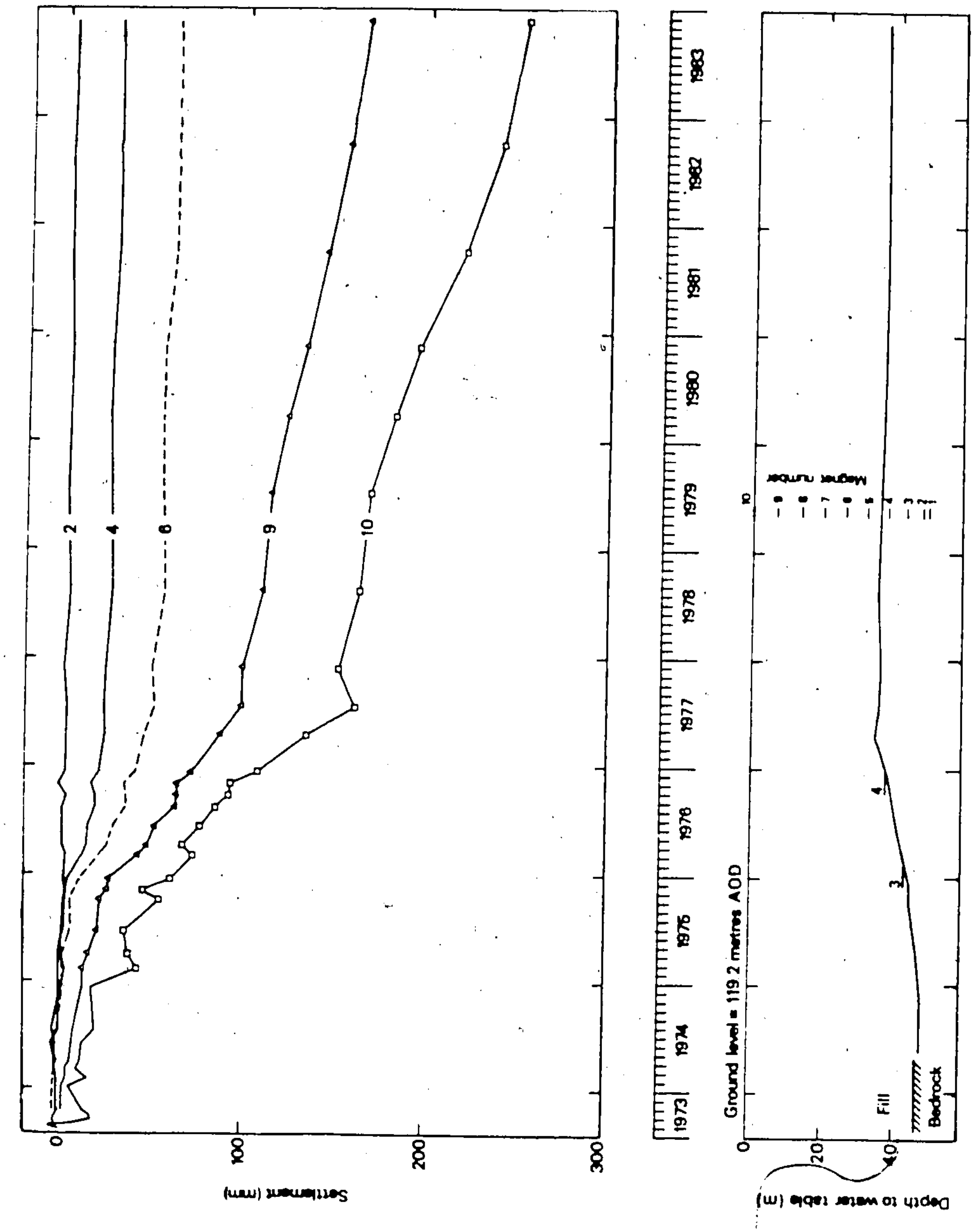


Figure 6.6 Settlement and Groundwater Table Recovery at Site D15, Horsley Mine (After Charles et al., in press)

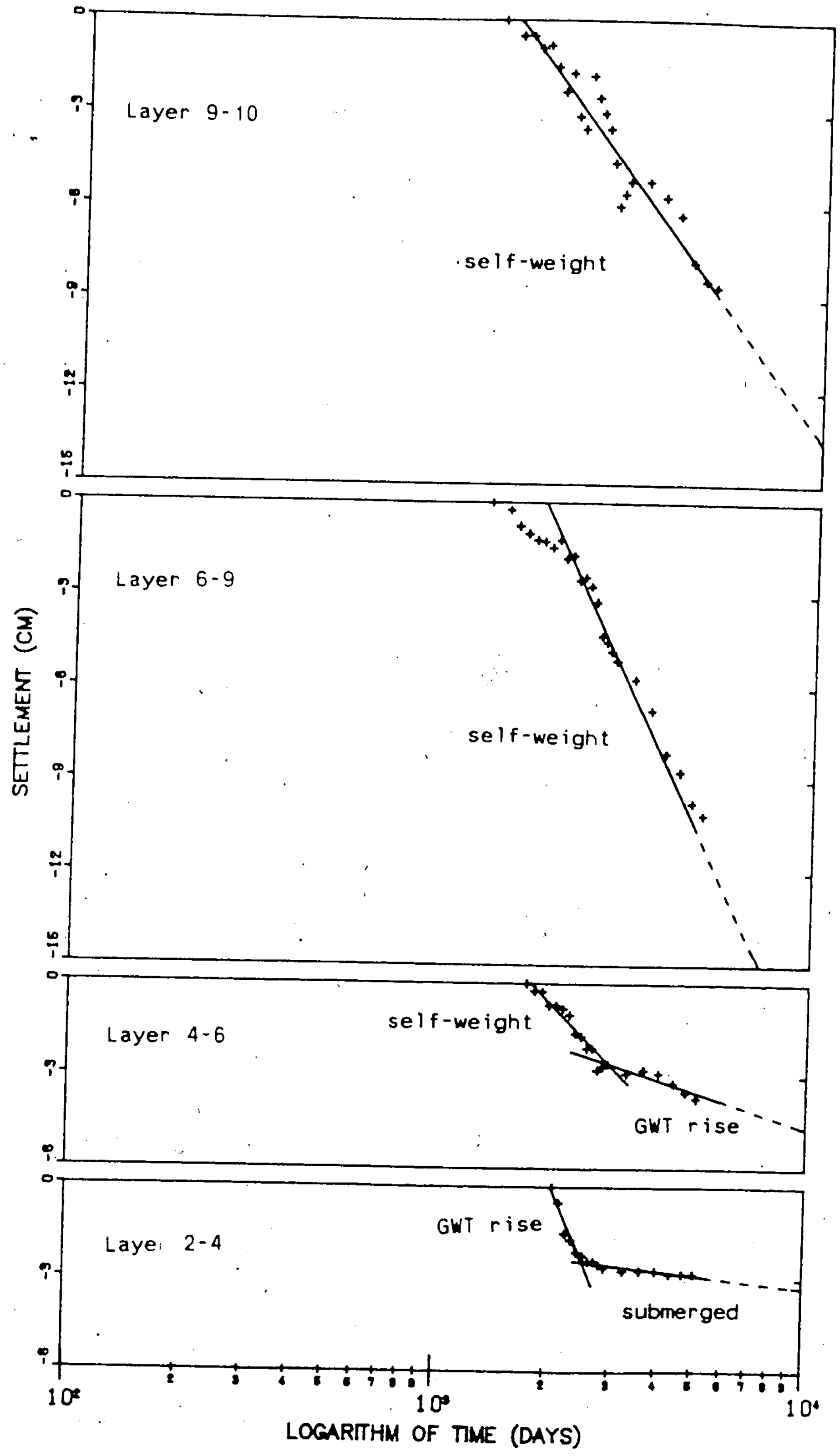


Figure 6.7 Settlement of Layers 2-4, 4-6, 6-9 and 9-10 at Site D15, Horsley Mine

changes (which occurred at the time the groundwater table entered the layer), with Ps becoming 3.25. Had the groundwater table not entered the layer, it is likely that settlement would have continued along the first slope of graph 4-6. It is not known why settlement almost stopped when the groundwater table entered this layer, or why the Ps values related to the groundwater table rise through the spoil (22.6 for layer 2-4 and 3.25 for layer 4-6) are so different.

The groundwater table did not reach and thus did not influence layer 6-9, indicating self-weight as the cause of settlement. Two slopes could be drawn through the data points for layer 6-9 (Figure 6.7) indicating the possibility of two settlement patterns. This site has been reclaimed less than five years which could explain the variation in settlement pattern.

It appears that the tendency of spoil at this site is to settle proportionally to the logarithm of time. Considering self-weight conditions, a simple prediction is made by drawing a line through data points from layer 6-9, from July 1975 to January 1978. This line is then extrapolated to November 1983, giving a value of 11.1 cm of settlement, close to the actual 10.1 cm measured. The data points for layer 6-9 in Figure 6.7 are recorded values of settlement and the line drawn through them is based on data from July 1975 to January 1978.

Therefore, if settlement data exists for a particular site, it is possible to predict settlement, assuming constant conditions. This is done by simply plotting the settlement-time data on semi-logarithmic paper, drawing a line through the points (using linear regression methods), and extrapolating the line to a desired time to find the related value of settlement. This is a graphical solution of the Predictive Settlement Method equation. If no settlement data existed for this site (D15), but Ps values for the strata did, settlement could also be predicted. The procedure for doing this is outlined in Chapter 4.

Layer 9-10 exhibited rather non-uniform settlement (Figure 6.7). However, similar to layer 6-9, the line determined by linear regression using data up to five years after reclaiming provided for a close approximation of settlement for November 1983. Actual settlement in November 1983 was 8.6 cm and the value extrapolated from the line described above resulted in a value of 8.9 cm. This verifies the tendency of spoil at this site, under conditions of self-weight, to settle proportionally to the logarithm of time.

The Ps value for layer 9-10 was 26.9, and for layer 6-9 was 13.8, using data from July 1975 to January 1978. The reason for the Ps value for layer 9-10 being two times as great as for layer 6-9 is that layer 6-9 is three times as thick (18 m compared to 6 m). More information is necessary to determine why these values are different. Possibly the stratigraphy is different. In other words, if the stratigraphy in layer 6-9 and layer 9-10 was the same, then the Ps values should have worked out to similar values. A possible explanation could be that at this site, long-term settlement tendencies are a function of depth. This means that more settlement at depth occurs soon after the material is spoiled, compared with spoil material nearer the surface. This would result in more settlement potential at the surface and less at depth.

6.3.3 Site C11

Prior to reclamation, this site (Figure 6.3), was the location of a lagoon during mining operations and exhibited rather unique settlement characteristics. The site is 45.7 m deep and was backfilled in 1965. Layers 5-6, 7-8, and 8-9 (Figure 6.8) were analyzed. For ease of analysis, the plot for extensometer 9 was assumed to curve from June 1975 to November 1976 rather than level out from June 1975 to October 1976, then drop 40 mm in November 1976, as indicated. This site in general did not show much settlement response to the rising groundwater table, except in layer 5-6. When the groundwater table had gone through layer 5-6 (or when it reached extensometer 6), settlement of this layer stopped. Layer 8-9 was undergoing self-weight settlement with a Ps value equal to 78.7 and

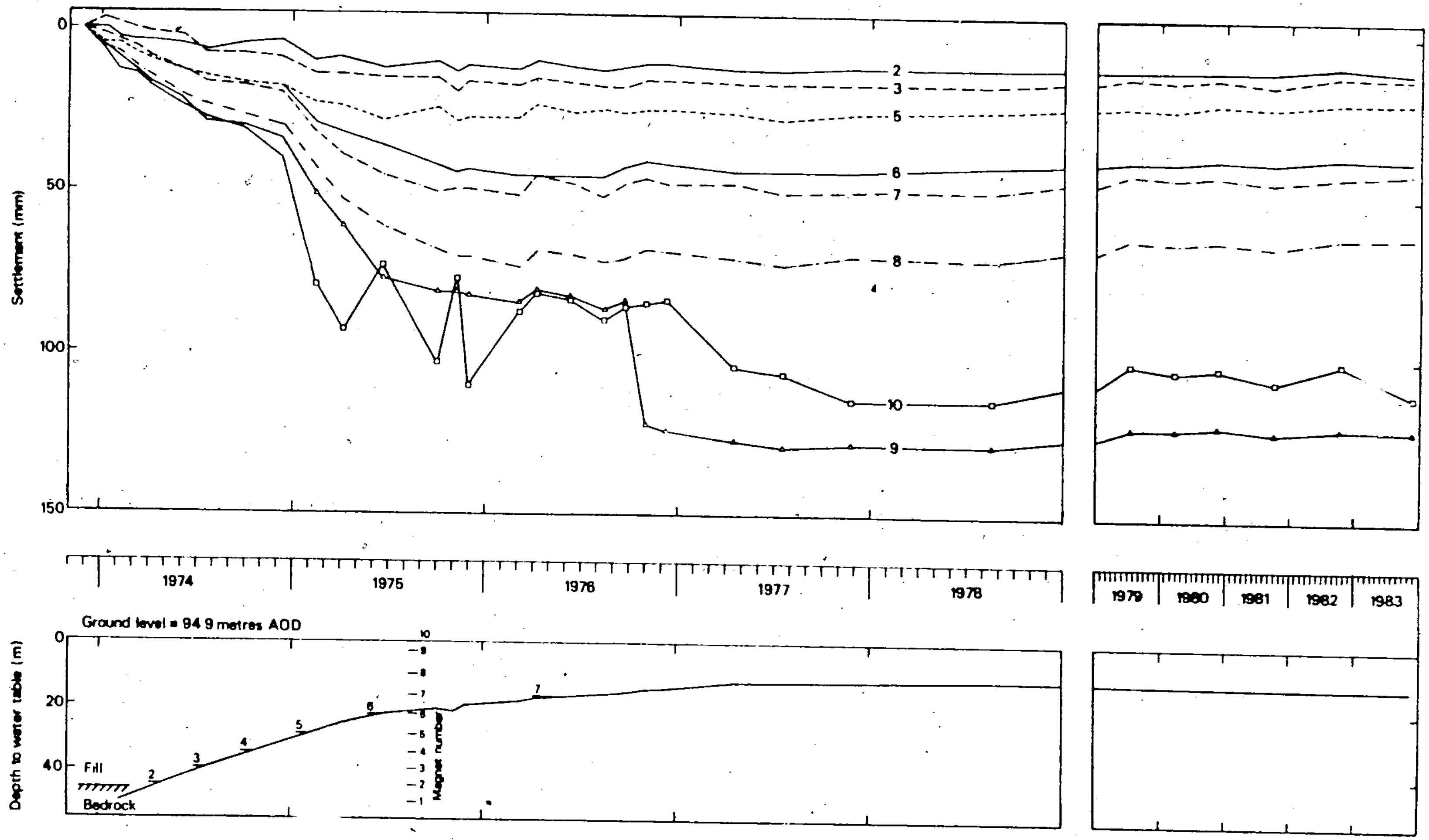


Figure 6.8 Settlement and Groundwater Table Recovery at Site C11, Horsley Mine (After Charles et al., in press)

after 5 years after reclaiming, settlement appeared to stop, with Ps equal to 3.01. The Ps value for layer 5-6 was 51.9 and for layer 7-8 was 36.7 as the groundwater table went through each layer. A slight heave is observed in layer 5-6 and a larger heave in layer 7-8 (Figure 6.9). It appears that settlement at this site levels off after about five years after reclaiming.

6.3.4 Site B2

This fill at this site (Figure 6.3) is 63.1 m deep, and was backfilled in 1964. Settlement and groundwater table elevation versus time plots for this site are seen in Figure 6.10. Only layer 10-11 has been unaffected by the groundwater table rising through the spoil and is thus the only layer where the settlement pattern does not change. Similarly to material at Site D15, this layer has settled more or less proportionally to the logarithm of time.

It is possible to compare Ps values for the various layers at this site before the groundwater table rose (self-weight settlement Ps values), as the groundwater table rose through successive layers (Ps values related to the groundwater table rise), and after layers were submerged (Ps values related to submerged conditions). Table 6.2 shows these values, related to the slopes of Figures 6.11 and 6.12. It is seen in Table 6.2 that Ps

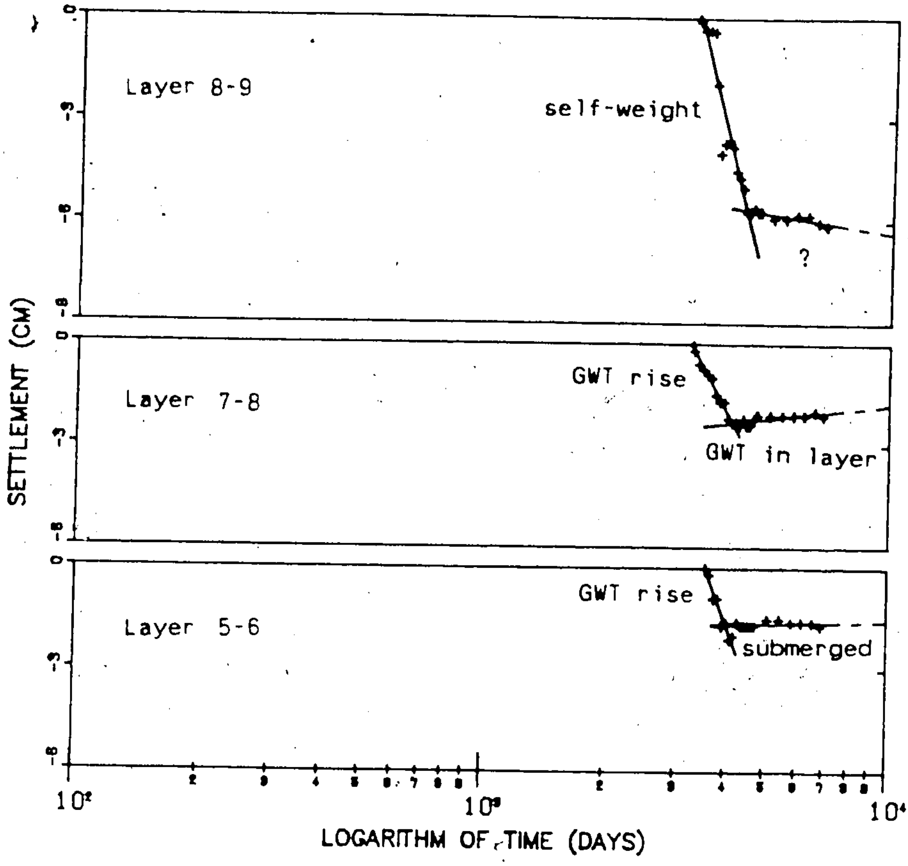


Figure 6.9 Settlement of Layers 5-6, 7-8 and 8-9 at Site C11, Horsley Mine

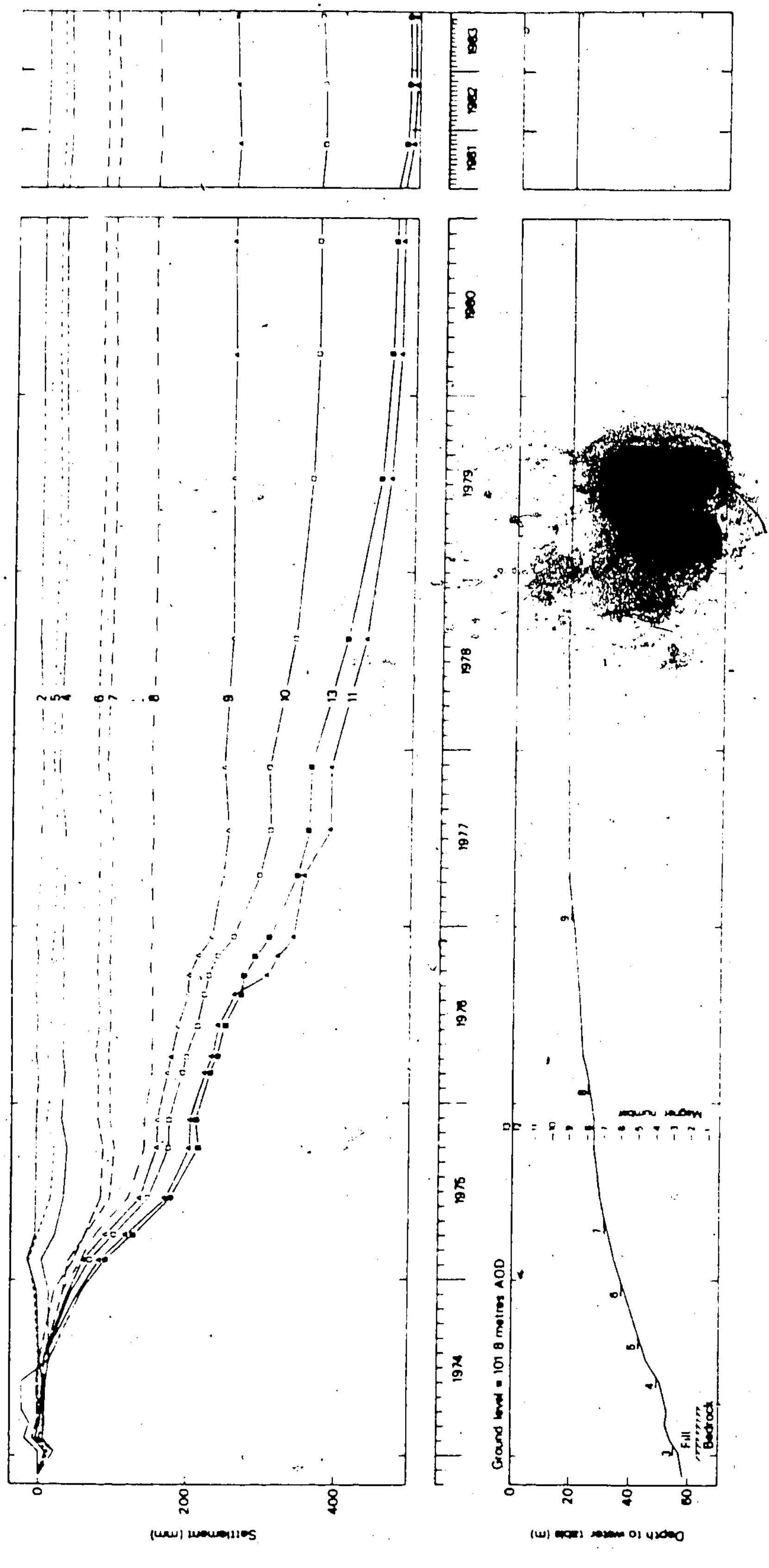


Figure 6.10 Settlement and Groundwater Table Recovery at Site B2, Horsley Mine (After Charles et al., in press)

SITE B2, HORSLEY MINE

SETTLEMENT RELATED TO SELF-WEIGHT		
LAYER	Ps VALUE	
10 - 11	85.7	
9 - 10	58.9	
8 - 9	69.1	
SETTLEMENT RELATED TO THE RISE OF THE GROUNDWATER TABLE		
LAYER	Ps VALUE	
9 - 10	163	(Water table just entering layer)
8 - 9	299	(Water table has gone through layer)
7 - 8	194	(Water table has gone through layer)
POST GROUNDWATER TABLE INFLUENCE (LAYER SUBMERGED)		
LAYER	Ps VALUE	
9 - 10	10.9	
8 - 9	14.9	
7 - 8	0.0	

Table 6.2 Ps Values From Site B2, Horsley Mine

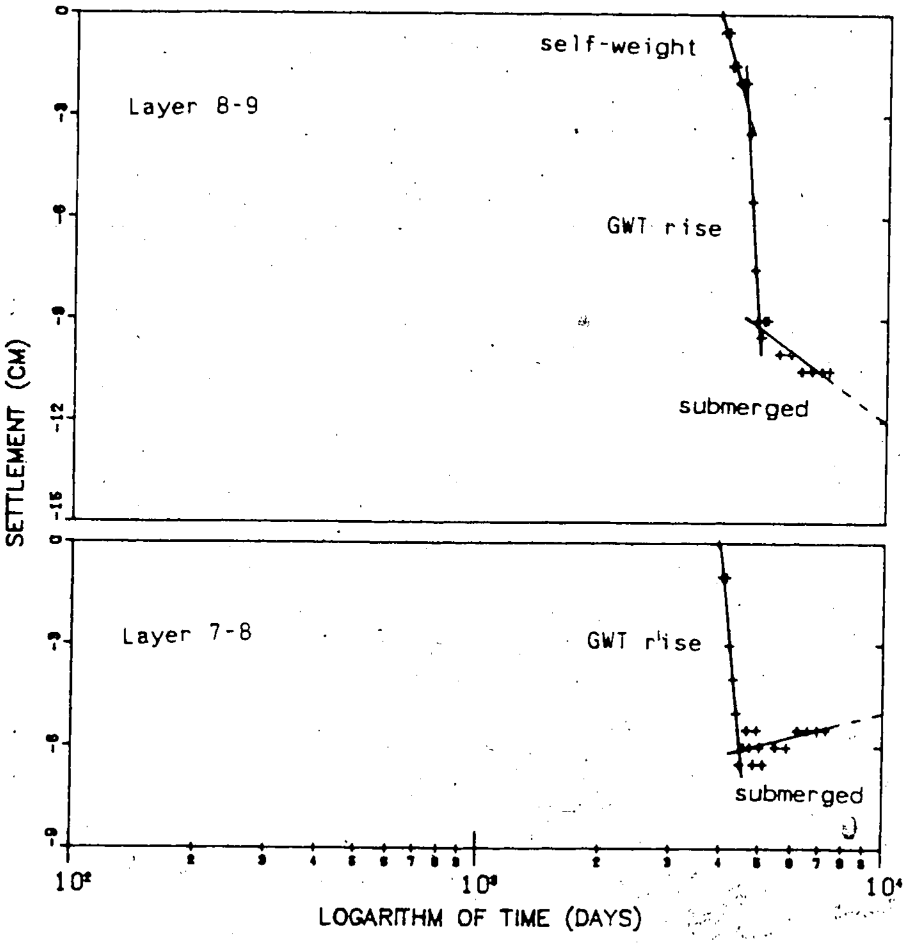


Figure 6.11 Settlement of Layers 7-8 and 8-9 at Site B2, Horsley Mine

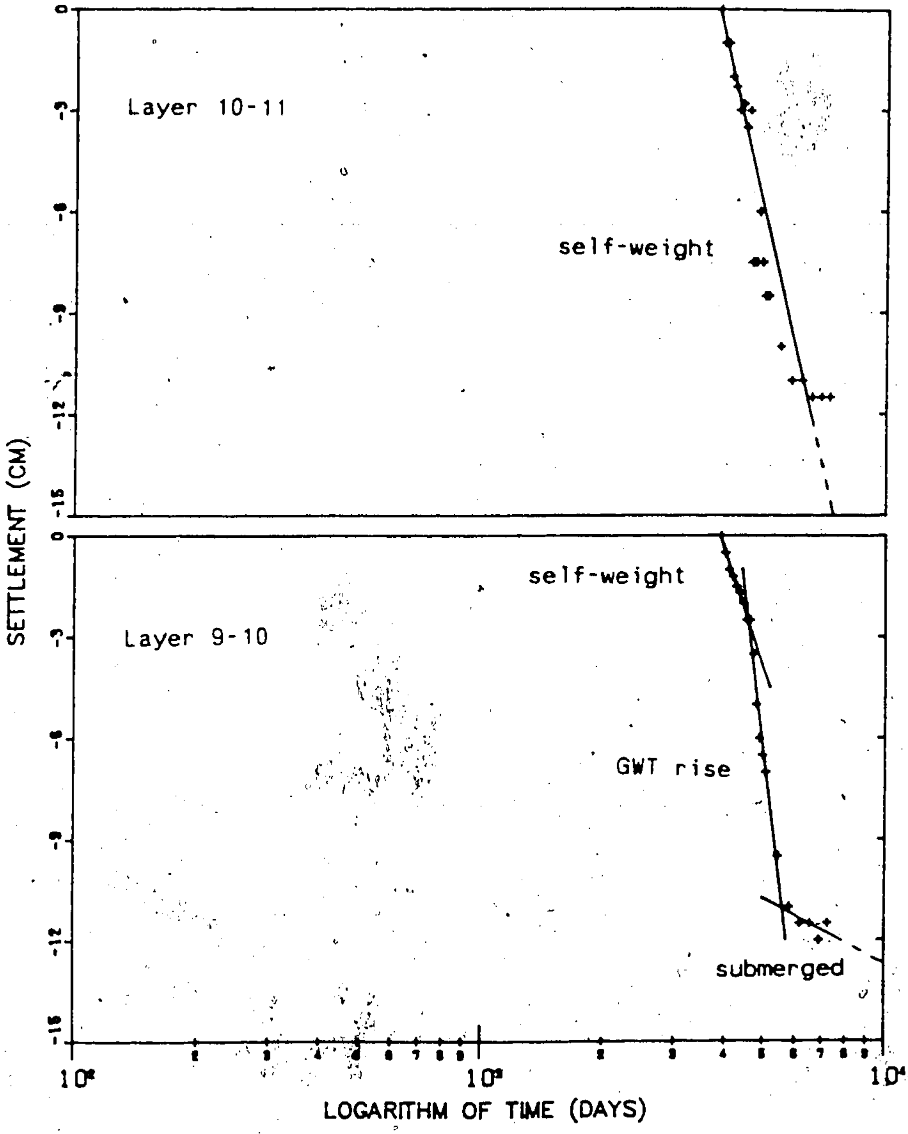


Figure 6.12 Settlement of Layers 9-10 and 10-11 at Site B2, Horsley Mine

values related to self-weight settlement are in a reasonably close range, as are those for groundwater table rise, and submerged conditions. Thus, for this site, or for a site of similar stratigraphy and history, it would be possible to predict self-weight settlement prior to the groundwater table rising using Ps values from 58.9 to 85.7. As the groundwater table rose, Ps values of 163 to 299 could be used. After a layer is submerged, Ps values of 0.0 to 14.9 are applied. More settlement data and information regarding the stratigraphy would result in refined Ps values and accurate correlations to other sites at the mine with similar spoil profiles.

6.4 Summary

The Predictive Settlement Method applied to mine spoil at the Diplomat and Horsley Mines derived a variety of Ps values related to various settlement conditions.

Ps values derived from settlement data from the Diplomat Mine were found to be similar to those at the Highvale and Whitewood Mines for conditions of a partially indurated crust, self-weight, capillary rise, submerged spoil, and heavy infiltration. For all of these conditions, other than the effect of a surface crust, settlement was observed to be proportional to the logarithm of time. It is emphasized, however, that Ps values should be used only at the mine where they have been calculated. This is due to the unique composition, material properties, and settlement behavior of mine spoil at each site.

Ps values calculated for the Horsley Mine gave a range of values for conditions of self-weight, groundwater table rise, and submerged spoil. For conditions of self-weight, groundwater table rise, and in some cases for submerged spoil, settlement was observed to be proportional to the logarithm of time.

It appears that the spoil at the Horsley Mine is not a slaking susceptible material. Settlement of spoil was observed to slow down dramatically or stop when the groundwater table submerged the spoil. By comparison, the spoil at the Highvale Mine is a highly slaking material, and continues to settle long after being submerged.

Because of unknown spoil stratigraphy at the Horsley test sites, and because of varying history, calculated Ps values cannot be applied to other mines [illegible] the Horsley region. If the spoil stratigraphy and history (e.g. inundation, surcharging, etc.) at another site were found to be the same, settlement predictions using the Ps values derived from the Horsley Mine, along with an estimation of the long-term groundwater table, could be made.

Table 6.1 (Diplomat Mine, Page 127) and Table 6.3 (Horsley Mine, Page 151) summarize the Ps values calculated from settlement data at these mines. When more

HORSLEY MINE

SITE	LAYER	Ps VALUE	CONDITION
D1	6-7	82.2	3 m GWT rise in 210 days
	5-6	85.8	6 m GWT rise in 420 days
	4-5	206	6 m GWT rise in [illegible]20 days
D15	9-10	26.9	Self-weight
	6-9	13.8	Self-weight
	4-6	10.1 3.25	Self-weight GWT rise through layer
	2-4	22.6 1.15	GWT rise through layer Submerged
C11	8-9	78.7 3.01	Self-weight ?
	7-8	36.7 0.0	GWT rise through layer Semi-submerged (heave ?)
	5-6	51.9 0.0	GWT rise through layer Submerged (heave ?)
B2	10-11	85.7	Self-weight
	9-10	58.9 163 0.9	Self-weight GWT just entering layer Submerged
	8-9	69.1 299 14.9	Self-weight GWT rise through layer Submerged
	7-8	194 0.0	GWT rise through layer Submerged

Table 6.3 Summary of Ps Values From the Horsley Mine

settlement and borehole data is available and analyzed from each mine, it will be possible to derive a range of Ps values. These values, in conjunction with estimated final groundwater table elevations, can be used at each mine site to predict long-term settlement.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

There are many variables that contribute to the settlement of mine spoil, and their interaction is a complex phenomenon. This thesis, by considering some of these variables, has derived a method to predict settlement of mine spoil, called the Predictive Settlement Method. This chapter will now summarize the development of this method and how it is applied. The major conclusions are discussed and recommendations for future study are presented.

7.2 Development of the Predictive Settlement Method

Settlement data of layers of spoil stratigraphy at the Highvale and Whitewood Mines were plotted with the logarithm of time. Plots tended to be straight lines indicating that settlement increased at a decreasing rate or that settlement was proportional to the logarithm of time. The slope of the line for any layer of spoil material was found to be a function of several settlement related factors such as self-weight, capillary rise, submerged conditions, and heavy infiltration. By analyzing the settlement response of spoil at twelve sites at the Highvale and Whitewood Mines under these conditions, it was possible to derive Ps (Predictive Settlement) values, where

$$Ps = \frac{\delta H/H}{\log(T2/T1)}$$

This is outlined in Chapter 4.

Ranges of Ps values were assigned to spoil materials subjected to various settlement conditions. Applying these values as they relate to specific spoil materials and settlement conditions, it was possible to show how settlement could be predicted. Based on an estimated future groundwater table elevation, settlement was predicted at the Highvale Mine.

The Predictive Settlement Method was applied to two other minesites, the Diplomat Mine near Forestburg, Alberta, and the Horsley Mine in the United Kingdom. Settlement data from both mines was plotted on semi-logarithmic paper and tended to result in straight lines. Ps values were calculated at both mines for various settlement conditions.

Ps values calculated for the Diplomat Mine were similar to those from the Highvale Mine, for similar settlement conditions. At the Horsley Mine, settlement rates increased as the groundwater table rose, and slowed down or stopped as spoil became submerged. At one site, the rate of recovery of the groundwater table affected the logarithmic rate of settlement. Ps values for the Horsley

Mine can be applied at each site at the mine where the data was obtained, or at other sites at the mine where the spoil material and site history are known to be the same. With the derivation of ranges of Ps values and an analysis of the groundwater hydrology, long-term settlement predictions can be made.

This thesis has shown that by developing Ps values based upon the analysis of settlement data of mine spoil, it is possible, along with an estimation of the long-term groundwater table, to predict approximate values of long-term settlement.

7.3 Major Conclusions

Many factors contribute to the settlement of mine spoil. Some of the variables that affect settlement are the formation of a partially indurated crust, capillary rise, slaking due to submerged conditions and collapse settlement related to heavy rainfall infiltration. Different types of spoil (clay, sandy clay, and partings) were found to have different settlement patterns when subjected to similar settlement conditions. By analyzing the settlement trends of mine spoil at ten sites at the Highvale Mine and two at the Whitewood Mine, it has been possible to derive a method for predicting long-term settlement. Using the formula

$$Ps = \frac{\delta H/H}{\log(T2/T1)}$$

a range of Ps values was determined for clay, sandy clay and partings spoil materials subjected to different settlement conditions.

Ps values for the three types of spoil material had some observable trends. Sandy clay and partings do not appear to undergo much self-weight settlement. It is likely that most self-weight settlement of these materials occurs shortly after being spoiled. Clay, if not near the surface and thus not influenced by the formation of a crust, settles by self-weight for long periods of time after it has been disturbed. All three spoil types appeared to be affected by capillary rise.

Little information exists regarding the submerged response of clay and sandy clay. Partings, when submerged, exhibited variable settlement response. All three spoil types settled significantly when subjected to heavy infiltration, particularly because the spoil was young at the sites where this phenomenon was observed. As spoil ages, heavy infiltration may not have as much of an effect, due to the development of an impermeable crust.

Total possible settlement at any site will likely be a constant, regardless of the sequence of settlement events. The settlement effect of static conditions, or of changing conditions such as a rising groundwater table, can be predicted. Due to the random occurrence of heavy infiltration events, the effect of these cannot be predicted. After such an event, the settlement trend of spoil will not be the same as before.

Several examples predicting long-term settlement of spoil showed ranges of possible settlement and where the major settlements likely would occur. This information is important because the depth of major settlement influences the possible amounts of differential settlement on the surface. In other words, if most of the settlement occurs at depth in a spoil pile, the resulting differential settlement observed at the surface will be less than if the majority of settlement in the spoil occurs nearer the top of the spoil profile.

Based upon estimated settlement conditions, (i.e. no groundwater table, or a rising groundwater table), and the estimated final groundwater table elevation, the examples demonstrated the process involved in predicting settlement. The location of the groundwater table, even if static throughout the period of prediction, can double possible settlement (Figure 5.3 and Figure 5.4). Heavy infiltration, even if no groundwater table exists in the spoil profile, can cause significant settlement (Figure 5.5). A rising groundwater table (Figure 5.6) in a 30 m spoil profile of clay, sandy clay and partings, can result in total settlements of from 8 to 31 cm from 5 to 20 years after spoiling.

At Highvale North Site 1, 10 cm of settlement was predicted from 5 to 20 years after spoiling, if conditions do not change (Figure 5.7). At the same site, if the groundwater table rises to an estimated 2.3 m below the ground surface, 12 to 18 cm of settlement, from 5 to 20 years after spoiling, are possible (Figure 5.8).

The Ps values derived in this thesis can be applied to any site at the Highvale Mine if the stratigraphy is known and the final groundwater table elevation can be predicted. A surface settlement gauge can be used as a check of the method.

The general format of the method can be applied at any mine where sufficient settlement data can be obtained, where the spoil profile can be determined, and where Ps values applicable to the site are calculated. Using these values, along with estimations of long-term groundwater hydrology conditions, long-term settlements can be predicted.

7.4 Recommendations

At the Highvale Mine, further analysis of the settlement of mine spoil is needed to more fully understand the variables that influence settlement. It is suggested that such factors as the variation of settlement with depth be analyzed as well as determining to what extent capillary rise is possible. This may provide information regarding the possible prevention of differential settlement of spoil subjected to these conditions. Also, the factors that contribute to the formation of a partially indurated crust need to be determined and analyzed as well as what thicknesses of crust are possible, and what the properties of the crust are.

More analysis is suggested as to why layers of similar material appear to settle differently under conditions of capillary rise and heavy infiltration. The capillary rise related settlement of a surface crust of different ages needs to be assessed, as well as the effect of overburden on collapse settlement. Further laboratory testing to ascertain slaking properties of spoil materials is suggested as well as laboratory testing that could produce a correlation between laboratory oedometer tests and in-situ field settlements.

When instrumentation is installed at a mine site, it is suggested that very detailed borehole logging be performed. Extensometers should be installed not at equal spacing throughout the spoil but at the boundaries of known layers of spoil, and at small, regular intervals throughout thick layers of the same material. This would allow for accurate assessment of settlement properties.

If construction is to occur on any reclaimed sites at the Highvale Mine, analysis of the spoil profile at the site is recommended and its settlement characteristics analyzed. If construction takes place, and the groundwater table has not risen to its highest possible level, then mining operations should be performed so that the groundwater table recovers at a slow rate. Further studies on the effect of the rate of groundwater table recovery are recommended. Prior to the recovery of the groundwater table, it is possible that heavy infiltration can cause significant settlement even 20 years after reclamation. Thus, it is suggested that buildings be constructed to withstand calculated possible differential settlement or that foundation materials at building sites be pretreated to prevent differential settlement. Landscaping should prevent the possibility of surface ponding of runoff. It is possible that a building could decrease evaporation of soil moisture caused by capillary rise, which could result in a possible increase in the moisture content of the soil below the building. The significance of this should be determined or at least taken into consideration when designing the foundation for the building.

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APPENDI[illegible] - FIELD INSTRUMENTATION DESIGN AND INSTALLATION

A.1 Multipoint Extensometer

A.1.1 Design

A schematic cross-section of a multipoint extensometer and the housing used in its installation are shown in Figures A.1 and A.2. The extensometer itself is a variation of the one used by El-Nahhas, (1980). The modifications incorporated were the shortening of the casing and utilization of a different type of foot. This type of foot was chosen to accommodate a borehole of variable diameter due to possible sloughing of the sides of the borehole in the spoil material.

A.1.2 Installation

1. Upon completion of drilling the borehole, if there is a possibility of the hole sloughing in, bentonite mud is placed in the hole.
2. A closed ended access tube is then inserted to the base of the hole. The access tube is made of PVC (Polyvinyl Chloride) and the lengths are bonded using PVC adhesive. If bentonite has been placed in the hole, the closed ended access tube is filled with

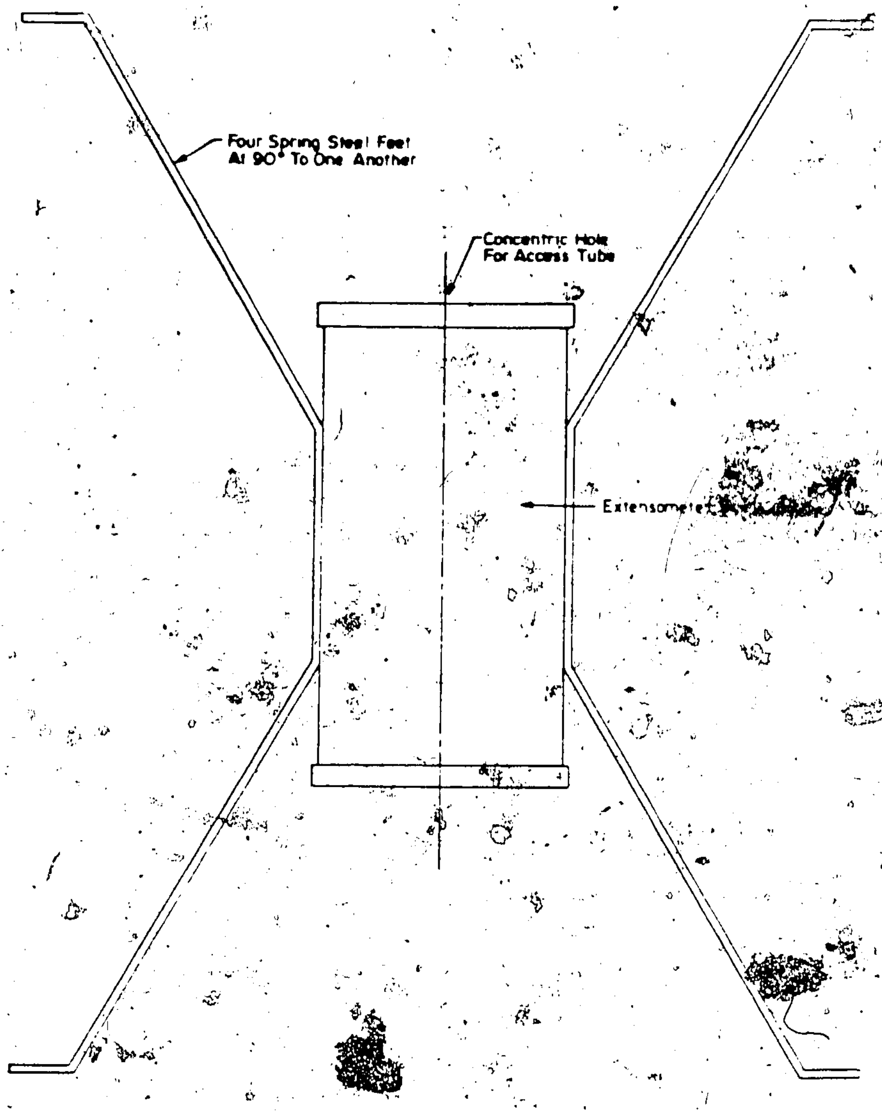

Figure A.1 Schematic View of Multipoint Extensometer

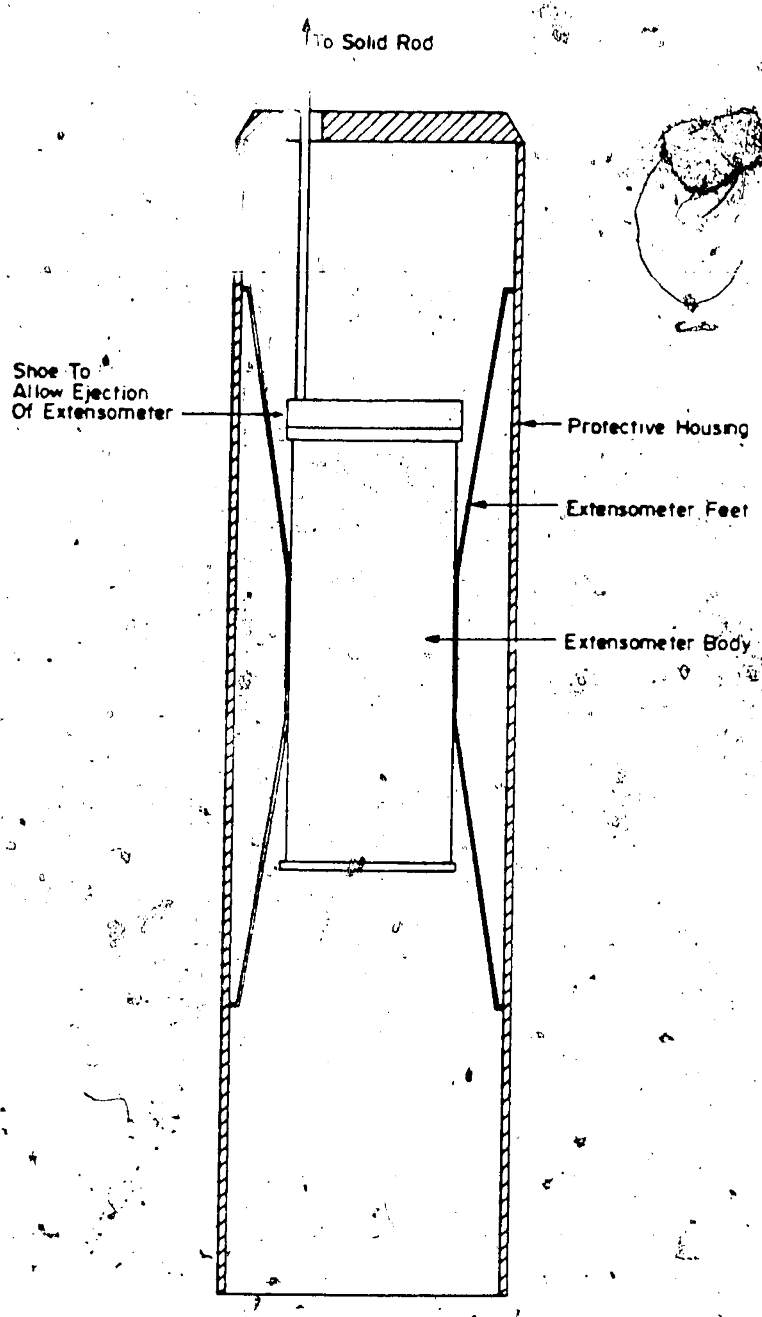

Figure A.2 Schematic View of Extensometer Housing water as it is inserted, to counteract the buoyant effects of the bentonite mud.

3. An extensometer is inserted into the protective casing and lowered down the hole with the aid of the lines on the drill rig. The extensometer and the casing fit over the access tube. As the extensometer casing is lowered, hollow tubing which extends up the borehole to the ground surface is attached to the casing. This tubing can be used to advance the casing if it catches on the side of the borehole or if borehole constrictions develop.

4. When the protective casing is at the desired elevation, solid rod is inserted into the hollow tubing. It extends slightly above the top of the hollow tubing.

5. By holding the solid rod fixed in position and raising the protective casing, the extensometer is forced out. As this occurs, the spring steel feet snap outwards and embed themselves in the wall of the borehole. (The lowermost extensometer is placed in the bedrock below the bottom of the spoil pile).

6. The casing is then brought to the surface, the hollow and solid tubing being removed at the same time, and another extensometer is placed into the casing. The extensometers were spaced approximately evenly within the borehole, the total number being determined by the

depth of the fill.

7. With the installation of the extensometers completed, a covering is placed over the borehole. An impermeable barrier is then formed using a mixture of Peltonite balls and water. More soil is then placed to allow positive drainage from the borehole. A small cap is placed over the top of the access tube.

To determine the position of the extensometer, a probe attached to a tape is lowered down the access tube. As the probe passes a magnet, a switch is closed in the probe and a beep is heard at the surface. The depths from the top of the access tube at which the second beep starts and stops is recorded and averaged. As indicated previously, the lowermost extensometer lodged in the bedrock is assumed to remain stationary throughout all measurements. The positions of the various extensometers relative to the lowermost extensometer (benchmark) are noted with time. In this way, the movement of the fill at the location of each extensometer is determined.

A.2 Settlement Gauges

A.2.1 Design

The design of a surface settlement gauge is simple. It is a small steel plate welded to the end of a piece of concrete reinforcing rod. The other end is machined to accept the end of a survey rod. A schematic diagram is shown in Figure A.3.

For the deep settlement gauges used at Whitewood Site 6, one inch steel pipe was fitted into a steel plate. A piece of angled steel was welded to the top of the pipe and was machined to accept the end of a survey rod. The deep settlement gauges were installed at depths of 3 to 18 meters.

A.2.2 Installation

1. For the [illegible] settlement gauges, a borehole extend[illegible] the level of frost penetration, about 3 meters, [illegible]s drilled and the settlement point lodged firmly in the base of the borehole. For the deep settlement gauges at Whitewood Site 6, boreholes were drilled to depths of 3 to 18 meters. The steel pipe was lowered into each hole, extending about half a meter above the ground surface.
2. A small amount of fine material is used to cover the steel plate and is then compacted with a tamping rod from the surface. This compaction ensures that the movement of the steel plate will be the same as the surrounding soil.
3. A loose fitting plastic tube is placed over the reinforcing rod or the steel pipe, and the hole is

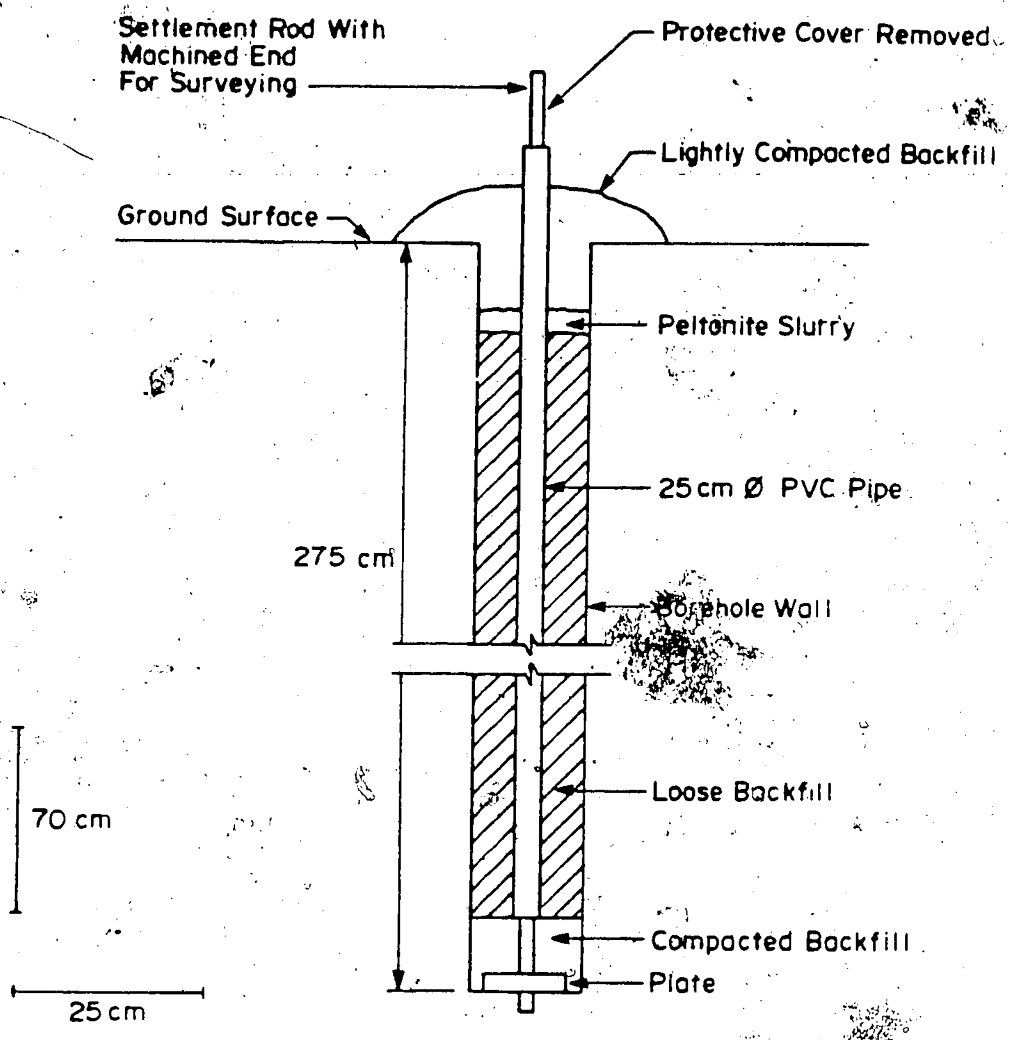

Figure A.3 Schematic View of Surface Settlement Gauge filled with the drill cuttings.

4. With the borehole almost completely backfilled, a mixture of Peltonite balls and water is dumped in. As before, soil is used to form a mound around the plastic tube fitted over the reinforcing rod or steel pipe to provide positive drainage away from the instrument. Again, a cover protects the top of the rod.

A.3 Standpipe

A.3.1 Design

The standpipe is simply a length of plastic tubing extending from the base of the borehole to the ground surface. The lowermost section is slotted hollow tubing while the remaining portion is unslotted. A schematic view is shown in Figure A.4.

A.3.2 Installation

1. With the borehole drilled, the lengths of tubing are connected and inserted into the hole. The lower end is capped to keep dirt from clogging the slotted length of tubing.
2. Sand is dumped down the borehole in sufficient quantity to surround the slotted length of tubing.

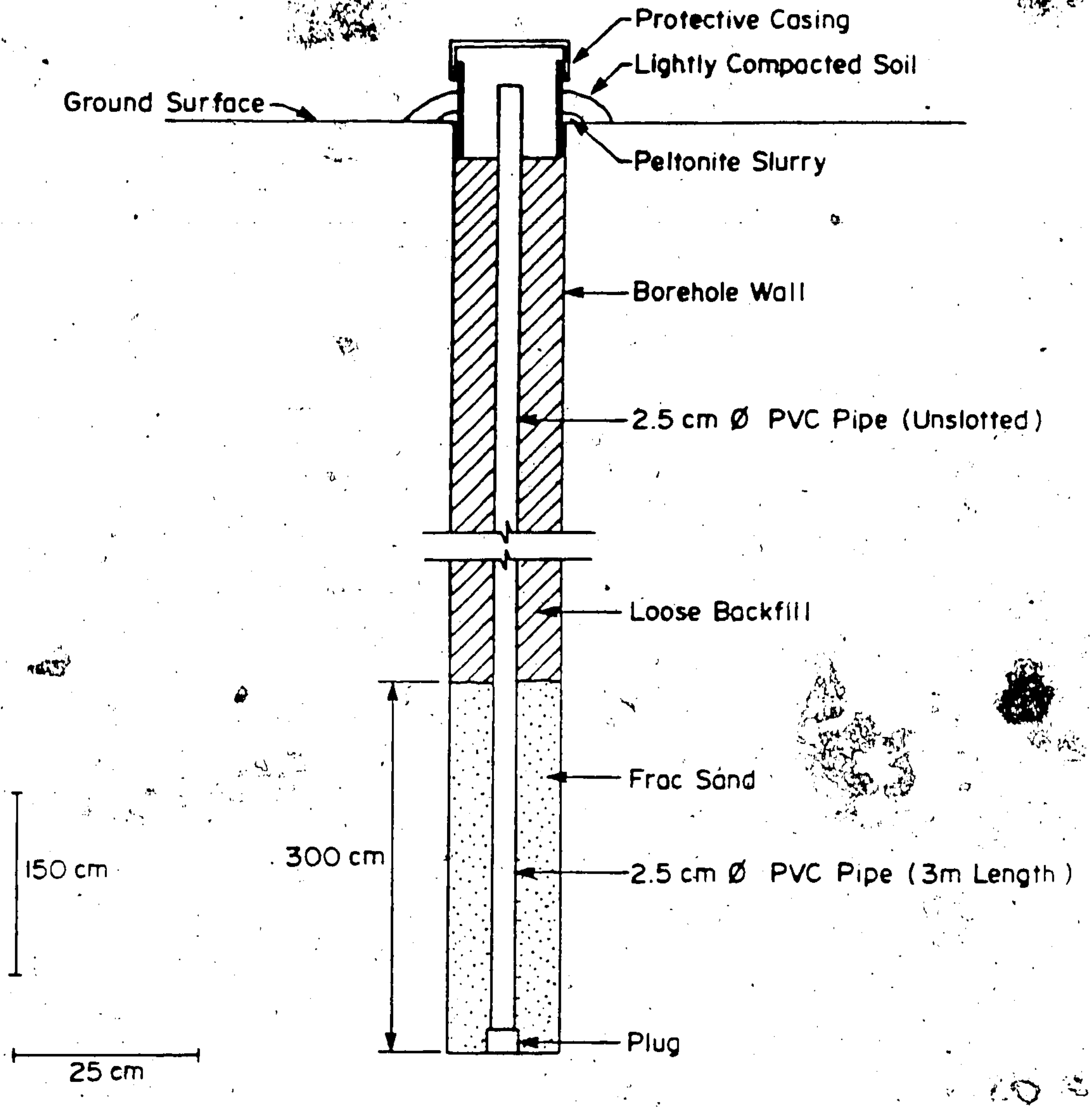

Figure A.4 Schematic View of Standpipe

3. The remainder of the borehole is backfilled with available material and an impermeable seal is formed near the surface using Peltonite balls and water. Soil is heaped around the tubing for positive drainage. A cap is placed over the top of the standpipe.

APPENDIX B - LARGE DIAMETER CONSOLIDATION TESTS

B.1 Introduction

Large diameter consolidation tests of one-dimensional compression were performed in the laboratory on spoil materials from the Highvale Mine. The purpose of these tests was to measure the settlement of the minespoil under load and when water infiltrated the spoil.

B.2 Sample Preparation

A 30 cm diameter cell was used for the large diameter consolidation tests. The inner walls of the cell were teflon coated. The height of the sample was governed by the amount of available material. Porous stones were used at the base and at the top of the sample, and filter paper was used to line the walls of the cell.

Samples 1, 2 and 4, (clay samples), were compacted dynamically in the consolidation cell with the standard compaction hammer. The intent was to achieve the same densities as in the field. Samples 1, 2 and 4 were compacted in 2, 2 and 3 layers respectively. Sample 3, the partings material, was not prepared in the same manner, as the compaction would have broken down the particles. Instead, the cell containing the sample was placed on a vibratory table for 15 minutes. Then the top porous stone and load cap were placed on top of the sample and vibrated for an additional 25 minutes in an attempt to achieve the in-situ density. After compaction was complete, the cell was assembled and mounted in a loading frame with a Belofram loading system. A linear voltage displacement transducer (LVDT) was placed on the load cap to monitor the settlement of the spoil material during the load application.

Samples 5-8 were prepared by adding [illegible] static load to represent 3.4, 5.1 and 17.8 m of overburden. Each of three successive layers of material comprising each sample were statically loaded. Then the consolidation cell was assembled in the same way as for samples 1-4.

B.3 Test Procedure

The test procedure was to place the sample in the test apparatus under conditions similar to those in the field and then load the sample and observe the amount of compression taking place. Samples were loaded to a vert[illegible]ure of 300 kPa (Samples 1-4), representing 20 m of overburden, and 60.5, 92.0, 320.0, and 320.0 kPa (Samples 5-8), representing 3.4, 5.1 and 17.8 m of overburden. When settlement was essentially complete, water was allowed to infiltrate from the base of the cell, modelling a rise in the groundwater table. During the saturation process, vertical deformation of the sample and the volume of water infiltrating the sample were measured.

Readings were continued until little change in strain occurred with time.

Figure B.1, a schematic view of the test apparatus, illustrates how the groundwater rise was modelled. At the base of the cell, there is a port with a valve through which water may flow. Connected to the port is a section of polyethylene tubing which is connected to a water reservoir. The water level in the reservoir is kept just below the top of the sample. During the initial part of the test, this valve is closed, and is later opened to allow saturation of the sample.

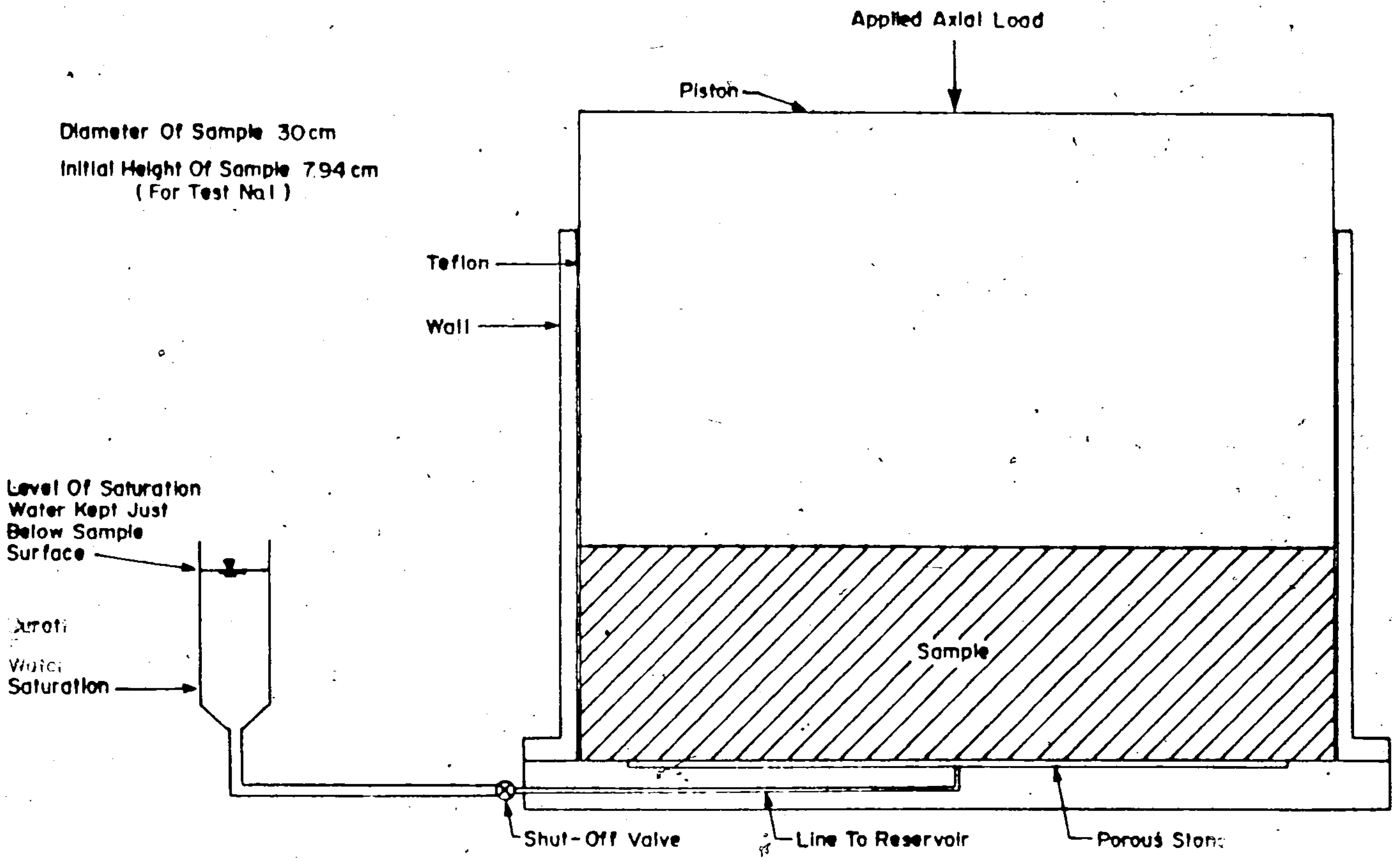

Figure B.1 Schematic View of Large Diameter Oedometer Apparatus

APPENDIX C - SLAKING TESTS

C.1 Test Procedure

Irregular lumps of spoil material from the Paleocene Paskapoo and Upper Cretaceous Wapiti Formation Bedrock at the Highvale Mine, having a dimension of about 2.5 cm, were dried to a constant weight at 105°C. The material [illegible] then placed in a funnel lined with filter paper and immersed in water. After two hours the funnel containing the sample was removed from the water, the excess water was allowed to drain, and the water content of the soil was determined (Eigenbrod, 1972). Atterberg limits were determined in order to find the initial and final liquidity indexes. Visual assessments of the material were made at elapsed times of 1 min., 10 min., 1 hr., and 2 hr. The sample condition is reported as a letter/number code in accordance with the classification for the static swell/slake test (after Dusseault et al., 1983).