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FIELD VERIFICATION OF A STOCHASTIC MODEL OF SOIL CREEP

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Thesis submitted to the University of London
for the degree of Doctor of Philosophy.

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July, 1985

Abstract

The research investigates random soil movement as suggested by Culling (1963), concentrating on the development of a technique for testing this theory. The technique employed dispenses with the need for continuous monitoring and avoids the inherent problems of soil disturbance arising from the use of soil probes. The theory assumes random and diffusive soil movement leading to a distinctive pattern of soil densities, through time, about obstacles of varying shapes. Solutions for circular and elliptical cylindrical obstacles have been calculated (Culling, 1981). The existence of a soil density pattern has now been investigated for circular obstacles by examining soil from around telegraph poles using photo-microscopy and image analysis to facilitate rapid calculation.

Soil samples were removed in brass tubes, dried with acetone, impregnated with resin, made into thin sections, photographed and analysed. From the soil:void ratios of each picture the changing micro-density of soil around an obstacle can be determined. Results indicate significant variations in the density values. Detailed inspection of the two-dimensional information reveals that under sloping site conditions there is a coherent pattern of soil density which reflects that predicted by the theory. Flat sites are also consistent in that there is no identifiable trend in the horizontal plane. The conclusion considers the adequacy of the research undertaken to evaluate the theory.

Acknowledgements

The author would like to express her gratitude to Dr. W.E.H. Culling and Professor J.B. Thornes for their supervision of the research recorded in this thesis and for their advice and encouragement throughout. Also to thank the technical staff of the Geography, Geology and Zoology departments and of the Science Workshop Bedford College, London for their valuable assistance and interest in the research project. Thanks to all fellow postgraduates of the Geography department, in particular Peter Vujakovic and the staff of the Computer Centre for their advice and supportive services, Bedford College. My thanks also go to Dr. E.R. Davies for his help and permission to use the image analysing facilities in the Physics department, Royal Holloway College, Egham.

Thanks are also due to the cartographic staff of the Regional Electricity Boards visited during the research who made available various maps showing the locations of posts in the areas of interest.

The work was supported by a Natural Environment Research Council postgraduate grant which is gratefully acknowledged.

Finally, it is a great pleasure to thank my parents not only for their financial support during the last year but also for their constant encouragement throughout the period.

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I INTRODUCTION

Soil creep is a widespread geomorphic process. It has been emphasized that it is an important denudational process (Kojan, 1967). Other geomorphic processes tend to operate at much faster rates but are of limited extent while soil creep is slow but occurs wherever there is a soil covering. Therefore there is a need to make measurements of its rate of operation in the long term and to investigate the exact nature of its movement (Finlayson, 1981). The following chapter begins by discussing the various mechanisms which have been put forward to explain slow soil movement. Rate process theory is considered with respect to the development of the Culling stochastic theory of soil creep (1963). Past and present direct measuring techniques and devices are critically reviewed with particular reference to their assumptions and the disadvantages of following such a line of enquiry. The chapter then concludes with a summary of the research objectives.

1.1 Theoretical Basis

The existence and nature of soil creep was first recognized in the 19th century, from field observations of outcrop curvature, plant roots, curved tree trunks and displacement of man-made structures such as fences, posts and walls. By the turn of the century, instead of merely observing end results, there started a more rigorous scientific enquiry into the exact nature and causes of movement (Davis and Synder, 1898; Gilbert, 1909).

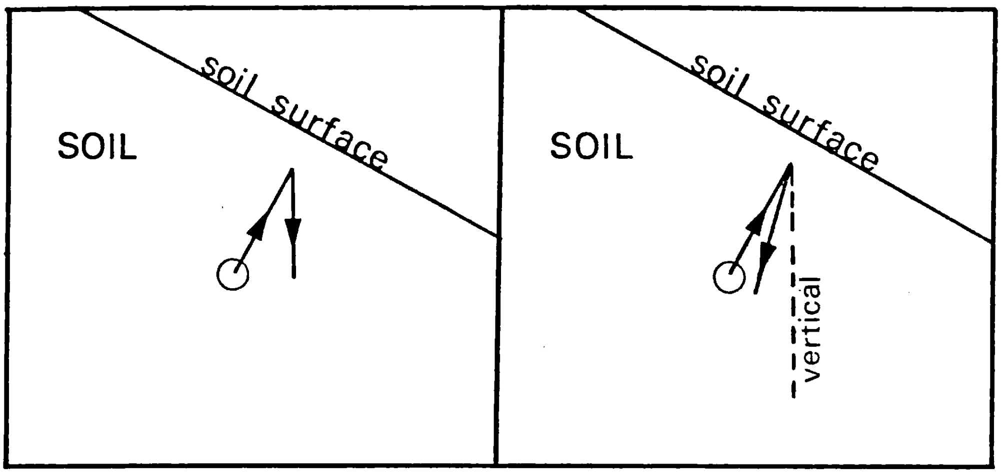
Davison (1889) considered that expansion of soil during cycles of freeze-thaw, should be exactly normal to the surface and that subsequent contraction should be exactly vertical (fig. 1.1 a). Following experimentation with slabs of stone and his monitoring of climatic conditions, he found that in a soil where ice needles were not present the expansion was indeed almost normal to the surface but that cohesion caused the contraction movement to take a line intermediate in direction between the normal and the vertical (fig. 1.1 b). The result was a zig-zag movement which produced a net displacement in the soil parallel to its surface. Davison, (ibid), nevertheless, developed a simple model of perpendicular expansion and vertical contraction with the total down slope displacement, measured in a horizontal direction, at a depth z in the soil given by :-

$$C(z) = k.\sin b.\int_{z}^{\infty} M(z).dz \qquad (1)$$

where C(z) is the horizontal creep movement at depth z, k is the soil expansion per unit moisture change (assumed to be constant), b is the slope gradient angle, and M(z) is the accumulated moisture change in the soil at depth z. A profile of the soil velocity is shown in fig. 1.1 c.

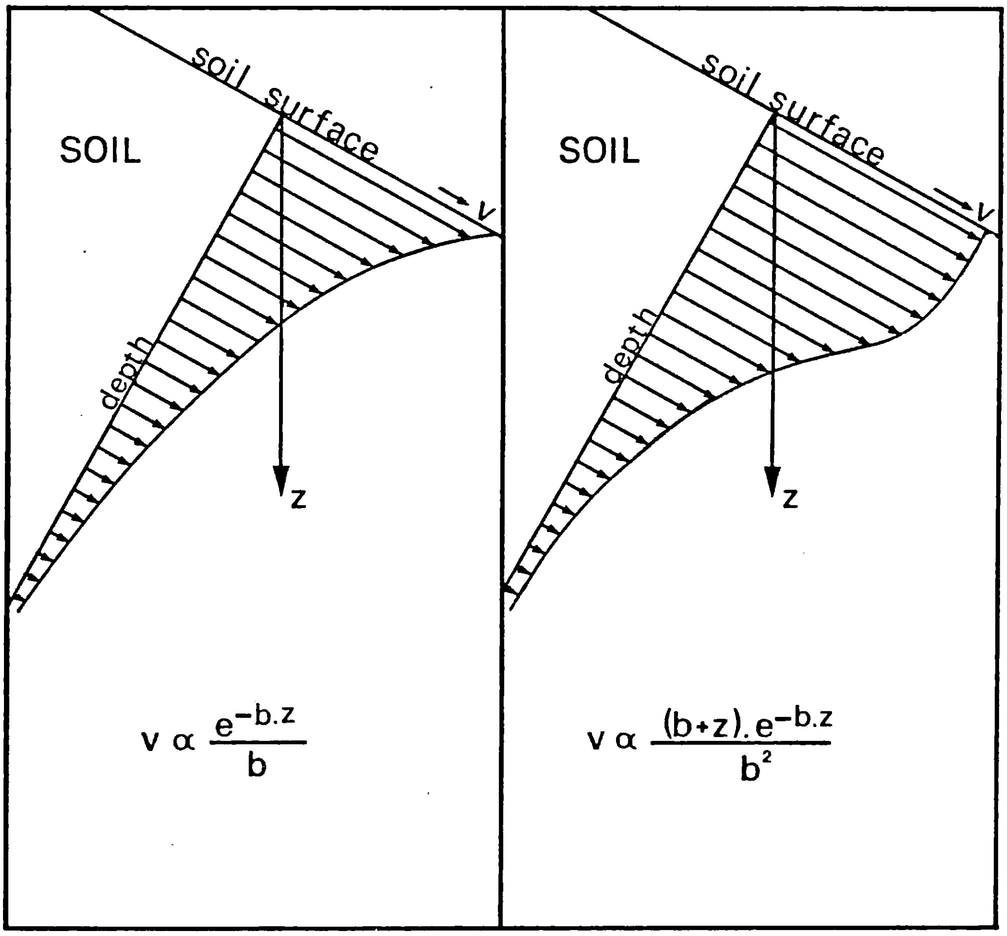
Kirkby (1967) developed a more realistic model of soil creep based on the theory that seasonal creep is produced by expansion and contraction cycles. These operate mainly at right angles to the soil surface and occur in response to soil moisture changes or the action of freeze-thaw. He pointed out that Davison's analysis left out of consideration the forces which are tending to move the soil downhill. The only force present which is able to do this is the

Path of soil partical - after Davison



a. theoretical *b.* observed

Predicted velocity profiles



c. after Davison theory *d.* after Kirkby theory

fig. 1.1

weight of the soil overburden. At the surface there is no overburden and so the soil cannot suffer a net shear, even though the amount of movement normal to the surface is at a maximum. At greater depth, the soil does not expand or contract, so that there can be no net shear component however great the overburden (provided that it is not great enough to initiate continuous creep). In between, at some finite depth, there will be a zone of maximum net shear rate.

Kirkby went on to express his analysis in mathematical terms in order to show the physical quantities involved more clearly. However, it must be emphasized that his theory only represented the average behaviour of the soil, and it was not a surprise when large random variations in the rate were obtained in field experiments. In order to simplify the theory, a number of assumptions were made. Firstly, the action of gravity was solely through the weight of the overburden above any point in the soil, although Kirkby recognized that there would be random variations about mean values in both direction and in the value in the overburden pressure. Secondly, the cyclic forces were alternately exactly opposed in direction, and in each case the force increased until the soil yielded. Thirdly, the direction of movement at failure was in the direction of maximum stress (ie. minimum work). Because Kirkby was dealing with mean movement of soil his theory does not adequately account for the fact, as shown by Kojan (1967) and Fleming and Johnson (1975), that soil movement may occur in any direction, at least in the short term, and that a small proportion may even move back up the slope.

Measurements were taken over a nine month period by Finlayson (1981) and from his results he concluded that :

> " movement in the soil occurs in seemingly random directions and . . . large total movement does not necessarily imply a similar large scale down slope movement".

Kirkby´s model leads to a shear rate which is proportional to the deviator stress and accumulated moisture change (Kirkby, 1967, p.362) :-

$$C(z) = k \,.\, \sin b \,.\cos b.\int_{z}^{\infty} z.M(z).dz \qquad (2)$$

The symbols used in the above equation represent the same parameters as used in the Davison equation (1). A profile of the soil velocity resulting from using Kirkby´s model is shown in fig. 1.1 d.

Subsequent to Davison´s analysis there followed a period in which both engineers and geomorphologists were engaged in field investigation of soil creep and it became clear that the process of creep could be subdivided into two. Terzaghi (1953) called these two types skin creep and mass creep. Skin or seasonal creep refers to movements occurring within the zone of seasonal variations in temperature and moisture. It also occurs within the zone of faunal and floral penetration. The depth of this zone will rarely exceed three metres and in fact is often much smaller than this, perhaps less than one metre. Mass or continuous creep refers to a more ´deep seated´ type of movement. It is present wherever shearing stresses produce slowly increasing shear deformations even if their intensity is considerably smaller than the shearing resistance of the materials involved.

Another classification, and one favoured in the following research, is suggested by Culling (1981). He divides the process of soil creep into engineering and geomorphic creep. The fundamental difference arises from the nature of the activating process which enables the soil to move :

> "Soil creep as studied by soil engineers and soil creep as understood by geomorphologists are two manifestations of the same basic phenomenon. Transparently the difference is one of time scale. More fundamentally the difference lies in the nature of the activating process."

Engineering creep is normally due to the constant action of gravity. Gravity is ever present throughout the soil but it is assumed to predominate below the depth at which seasonal agencies prevail. Engineering creep is thus typically continuous, regular and strong, in the rate process sense, and operates at the molecular level. Also it is a deformation or flow that is ultimately dependent upon the rupturing of chemical and physical bonding between particles in which bond renewal fails to keep pace with bond rupture. There is a random element to the spatial distribution of the making and breaking of these bonds but mostly the failure occurs along definite shear planes in the crystalline lattice. In contrast geomorphic creep is intermittent, random and in most cases operates under the influence of a weak external force (gravity). It operates at two levels - the molecular and the particulate. At the former the making and breaking of bonds across the mineral surfaces, at the inter-particle contact, is rapid and operates under the influence of strong, external turbatory forces (ie. freeze-thaw, hydration expansion etc.). Thus the shearing at the inter-particle contact is almost instantaneous. At the particle level the turbatory force acts as the internal vibration and the external force is now the acceleration of gravity. The frequency of vibration is low and the external force is weak. Consequently geomorphic creep is a slow, intermittent process (Culling, 1983, p.204).

In the above definitions Culling is using an alternative strategy for the description of soil creep, one which is based on taking a rate process view of the way that particles move. The rate process theory will now be briefly reviewed.

1.2 Rate Process Theory

The activated complex or rate process theory of Henry Eyring can be seen as the end product of a line of investigations into the rate of chemical reactions that extends back to Arrhenius at the end of the last century (Eyring, 1935b). In the late 1950′s rate process theory had been applied to soil creep (Culling, pers. comm., 1984) but such work did not appear in the literature until the early 1960′s. In engineering studies there was a re-direction of attention away from observable phenomena such as strength and deformation towards a molecular view and rate process theory was seen as an alternative approach to the interpretation of results.

Rate process theory views the arrangement of matter (e.g. in a gas) as the active translation of flow units from their initial equilibrium position, over a saddle region of a potential surface (energy-barrier), to a new state. A further factor which is not essential to rate process theory in general but pertinent to soil creep, especially geomorphic creep, is the availability of a vacant space to accommodate the dissolution of the activated complex. The use of rate process theory in soil creep studies was pioneered by Murayama and Shibata (1961) in their work on clays and developed extensively by Mitchell et al. (1968). The whole subject receives detailed treatment in Mitchell (1976, p.292-304). More recently Pusch (1977) and Feltham (1979a) put forward single energy-barrier rate theories of soil creep. Later they conclude that due to the structural heterogeneity of the soil (structurally sensitive aggregated clays), the assumption that the intrinsic barriers are all of the same type is scarcely appropriate (Pusch and Feltham, 1980). Some barriers may become enhanced due to local decreases in the deviatoric stress while others, somewhat dormant at first, may be rendered operative through the converse process of local rises of stress. They feel that :

> " An appropriate model must therefore take into account not only the existence of a distribution of energy barriers, but also its change with time in the course of the evolutionary creep process".

Culling (1981, p.180-231) gives a review of the use of rate process theory in soil mechanics with particular reference to the work of Mitchell; he also develops a rate process model of geomorphic creep (p.233-269) and he includes an in depth historical review of the origins of rate process theory in physical chemistry (appendix B, p. 368). In the application of the rate process theory to soil creep, there are four basic requirements :

1. An ever-changing, internal energy force whose distribution is random throughout the soil system.
2. An activation state sited at the saddle point (minimum potential threshold), the passage of which determines the rate of the process.

3. An external force (down-slope acceleration of gravity) imposing a preferred direction on an otherwise random activity.

4. Availability of spaces within the soil mass to accommodate the displaced particles.

The basic equation for the rate of the process at the molecular level :

$$v = \frac{KT}{h} \cdot e^{\frac{-E_0}{KT}} \cdot e^{\frac{f\lambda}{2KT}} \qquad (3)$$

where $\frac{KT}{h}$ = Eyring Universal Factor (frequency component)

$e^{\frac{-\epsilon}{KT}}$ = distribution of the internal energy

E_0 = activation energy

$f\lambda$ = external force which has the effect of increasing or decreasing the activation energy depending upon the direction

The theory was initially applied and developed in a physical chemistry setting to dilute solutions and gases. In soil mechanical applications there is a need to introduce an additional factor to represent the restrictions imposed by the soil structure. The basic equation at the particle level which is fundamental to the model of geomorphic creep is as follows :

$$v = A . S . e^{-\beta E_0} \cdot e^{\frac{1}{2}\beta f \lambda} \qquad (4)$$

E_0 = activation energy

f = external force

A = frequency

β = statistical mechanical quantity

S = structural component

We now go on to consider in more detail one of the instances in which a stochastic theory of soil creep has been used in the construction of a testable prediction of soil movement.

1.3 The Stochastic Theory of Soil Creep

Culling (1963) developed an alternative rationale to the analysis and measurement of geomorphic soil creep. He used a stochastic model for explaining particle movement. Soil is treated as being a particulate medium, not a continuum and in general as an activated process. Initially, we shall consider the simplest case of soil movement on a flat surface and then gradually build on the theory to include movement on a sloping site.

i. Soil movement on a flat surface.

The general physical model is that suggested in the 1960's (Culling, 1963). The major advance of the work since then is the use of a rate process approach to the movement of soil particles. This allows values to be given to parameters which in the original work were simply assumed, such as the diffusion coefficient. In the simplest case, we find that the four basic components required of a rate process approach are present to some degree. The third one, the external force (gravity), has a minimum affect on the direction of movement. The soil system is viewed as follows :

1. Soil particles are subjected to intermittent and independent forces (geomorphic).

2. It is assumed that these forces are randomly orientated and their magnitude is symmetrically distributed.

3. The forces are tending to displace particles but this is resisted in the majority of cases by neighbouring particles preventing them from moving.

4. The number of voids is assumed to be uniformly and isotropically distributed with respect to any one particle. The movement of particles is assisted by the occurrence of these voids and this introduces another random component on the movement.

5. The mechanical energy transmitted across the inter-particle boundaries is usually intermittent and of low frequency. (This is in comparison to engineering creep when the force is persistent).

6. The probability of a particle moving successfully is equal in all directions.

7. The particle movements are independent and execute random walks.

Following from the last point, it can be seen that the macroscopic soil movement behaves in a diffusive fashion and with the constant mixing the soil density becomes homogeneous and isotropically distributed throughout the system.

ii. Soil movement on a sloping site.

The same basic conditions, as outlined for a flat site, apply on sloping ground. The fundamental difference is that the external force of gravity now has a directed influence by reducing the amount of energy required for movement in the down slope direction (fig. 1.2). On a flat site a particle needs to have enough energy (A to Emax) to move over a threshold to a new position (B). This can be envisaged as a particles having sufficient energy to surmount a barrier produced by adjacent particles moving past them into a void, coming to rest at an energy level similar to that at which movement commenced (B). On a sloping site less energy is required to move a particle past another (A′ to Emax). Moreover the energy level, at which the particle comes to rest, is now lower than when it started to move (B′). Gravity is a persistent, ubiquitous and weak force which has the effect of lowering the threshold for movement in a down-slope direction. Therefore, superimposed on the random, diffusive soil movement there is a uni-directional drift in the down-slope direction.

iii. Introduction of a barrier into the soil.

We shall now consider the effect of placing a barrier, vertically down into the soil. In a flat situation there is an equal probability of movement occurring in any direction. A barrier will have a reflective effect with particles hitting it and randomly rebounding in all available directions. The soil density near the barrier will therefore be random and isotropic and have no systematic patterning. If a barrier was placed vertically down and at right angles to the drift in a sloping system, with time the drift will cause soil to move down slope until further movement is

Potential energy curves for particles subject to an external force

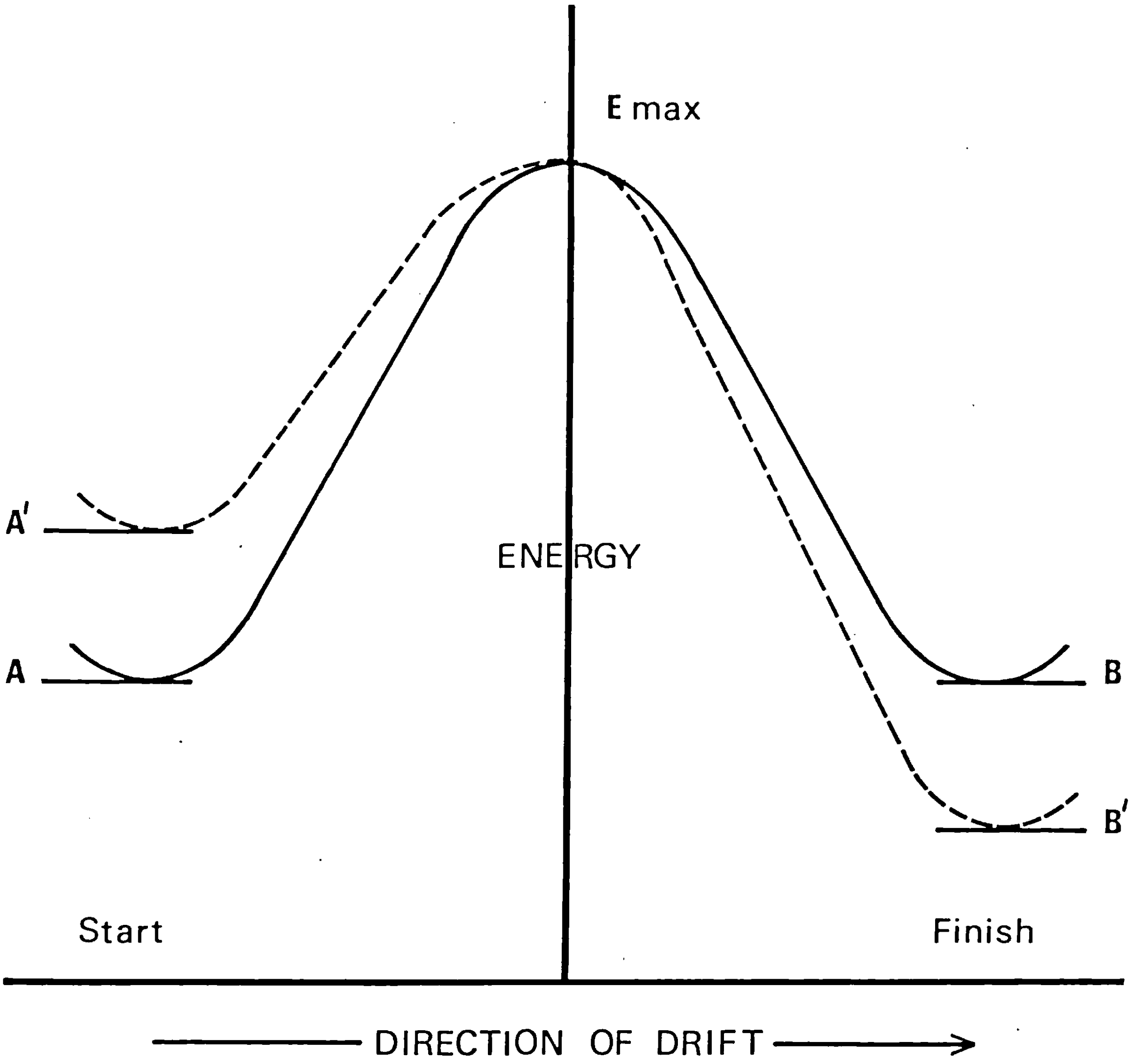


fig.1.2

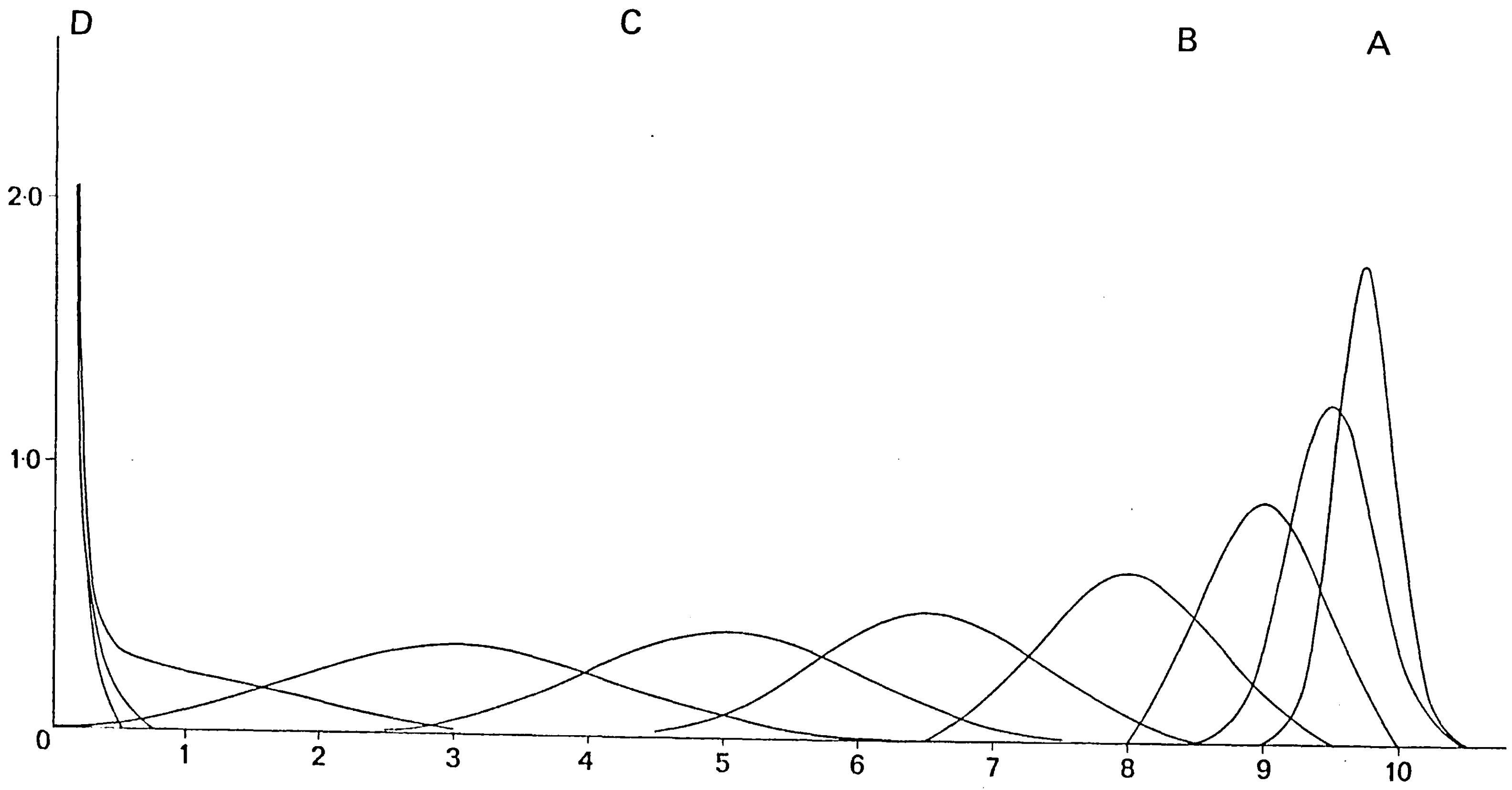
restricted on reaching the barrier. At this point there are four possibilities. If the soil supply is finite then for a finite barrier the entire source material will eventually slip past the barrier. If the barrier is assumed infinite the source material will pile up against the barrier where the counter effect of diffusion will produce an ′atmospheric layering′. On the other hand if the source is continuous then against an infinite barrier there can be no steady solution but if the barrier is finite, as is the case for a cylindrical obstacle, the possibility exists of a steady state solution distribution of the soil particles.

This can be exemplified by using finite source solutions (Culling, 1981 p. 275).

> " This method consists of the introduction of a finite quantity of recognisable particles into the soil aggregate and observing subsequent behaviour".

At point A (fig. 1.3) there is the introduction of a finite source of recognisable particles into the soil system. At B the diffusive nature of the soil movement is starting to disperse the particles from their point of introduction. At C the drift down slope, caused from the external forces, is dominating the process. Finally at the barrier (D) movement is halted and eventually an equilibrium distribution, if it exists, then comes into being.

One next step on from introducing a barrier of infinite dimensions is to consider a barrier of limited size, for example a circular cylindrical obstacle such as a telegraph post. It is assumed that soil movement in part A, B, and C of the diagram is similar to that mentioned previously. The major difference is in the soil movement near to the post. The post will still have a

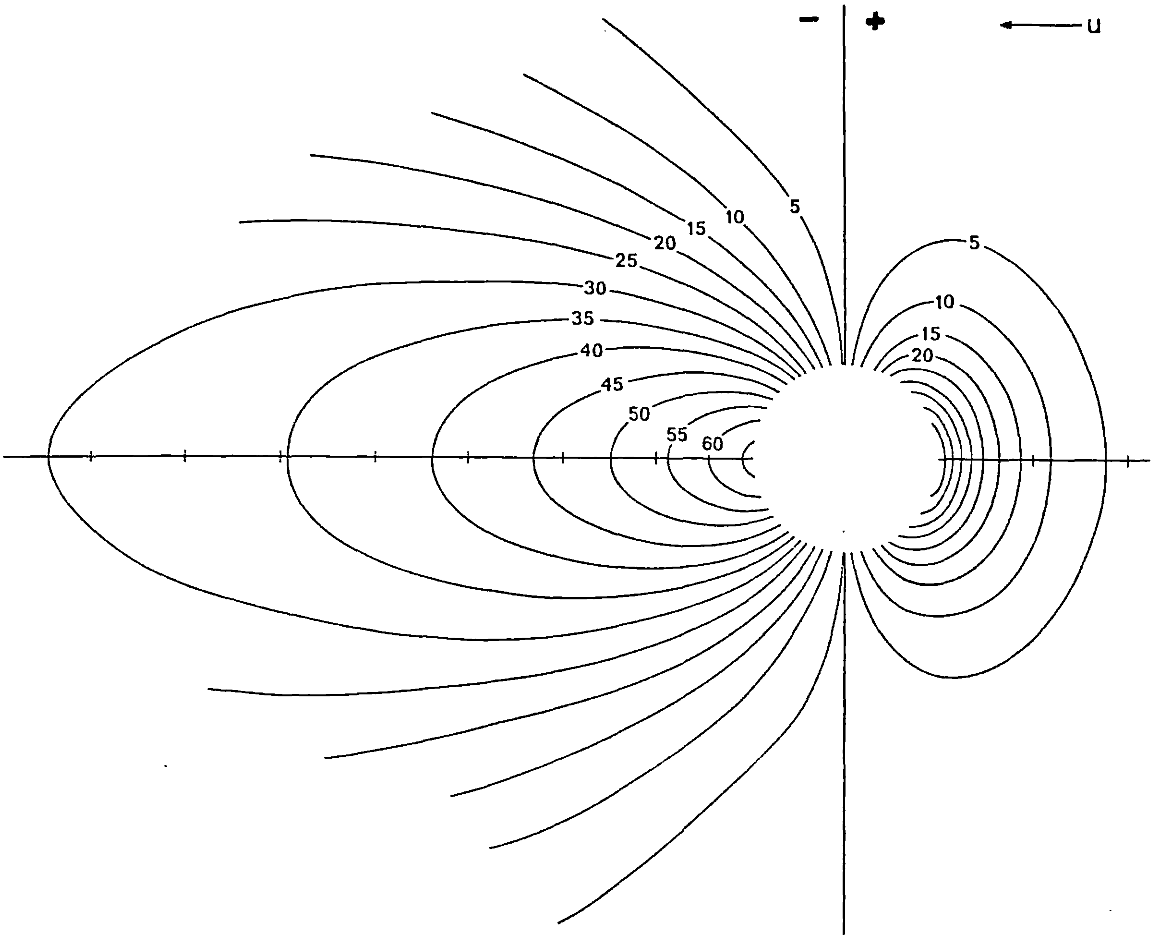


Diffusion, Drift and Steady State Distribution of a Finite Amount of Material

fig. 1.3

reflective effect but now particles will be able to escape to the down slope side of the post. Now if instead of a finite source of recognisable particles, the supply of particles were continuous, as is more likely in natural settings, there exists the possibility that an equilibrium or steady state distribution of soil particles will develop around the post. Culling has calculated the steady state distribution for a circular post situated in a soil system which is subject to uni-directional drift superimposed upon a diffusive type of movement (fig. 1.4). The equation for the steady state solution is outlined in appendix C. He has also calculated a similar solution for an elliptical, cylindrical barrier (Culling, 1983, p.217). This has the advantage of covering almost any shape that occurs in nature from a rectangle to a parabola. This research is focused on the simplest solution, that is the steady state density pattern around a circular cylindrical obstacle.

The objective of this research is to investigate the existence or otherwise of this pattern and the work has focused on geomorphic creep which occurs at or near the surface because of its intermittent habit it produces far slower overall rates than the engineering equivalent. A typical value from the engineering point of view is measured in cm/year (Chowdhury, 1978 p.302) whereas values for geomorphic creep are usually of the order of mm/year (Young, 1972 p.5). It soon became obvious that it is not practicable to introduce a quantity of marked particles, selected to simulate the whole or part of the soil aggregate, in order to provide a measure of the drift and diffusion coefficients. The problem with this line of enquiry is one of the time required between introduction of the particles and achieving an equilibrium state. It was decided therefore to use pre-existing datable sites



Steady State Solution for the Diffusion Equation with Drift

for the Region Outside a Circular Cylinder

fig.1.4

where an equilibrium state, if there is one, would already exist. Present techniques for measuring soil creep are now evaluated to assess their potential use in this enquiry.

1.4 Monitoring Soil Creep

Since soil creep was first recognized in the 19th century there has been a need to monitor soil movement in the field to acquire some data to test the models. There are numerous field investigations which have done just this, and many papers are in print summarizing the main techniques employed in field and laboratory investigation of soil creep (Selby, 1966; Statham, 1981; Young, 1974). There are many different criteria used to classify the techniques such as short or long term, or accuracy (Anderson and Finlayson, 1975). Auzet (1982), in her comprehensive bibliography called ′Measurement of Creep′, divided the methods up into those which enable creep to be measured directly and those which measure creep indirectly. Owing to the extensive literature reviews, the following résumé has been kept brief, and is divided into two main sections; qualitative and quantitative methods of monitoring soil creep.

i. Qualitative.

Qualitative survey and field evidence such as outcrop curvature, plant roots, curved tree trunks and displaced man-made structures were initially used to recognise the existence of soil creep (Thomsom, 1877; Keeping, 1878; Coppinger, 1881; Kerr, 1881; Davison, 1889; Gotzinger, 1907). A comprehensive qualitative survey of some of these causes is detailed in Sharpe (1938). Statham (1977) emphasizes the point that the validity of qualitative evidence for soil creep has been severely questioned in recent years. Phipps (1974) found no evidence to suggest that tree curvature was due to soil creep. Trees subjected to steady tilting should form a constant curve from ground level to canopy. All too frequently, Phipps found curvature approximating to a single bend close to ground level, with trees bending in different ways but on the same slope. Displacement of man-made objects are undoubted proof of local soil movement, but should not be used as evidence for more widespread movement. Bedrock curvature beneath a soil is probably a manifestation of soil creep, provided that the curvature increases steadily towards bedrock-soil interface

ii. Quantitative.

Quantitative evidence, for soil creep, appears in most of the modern literature but very often the limits imposed by accuracy and soil disturbance, due to the installation of measuring devices, are not fully recognized.

(a) Surface and sub-surface methods

One of the simplest methods is to place identifiable markers on the soil surface, and return after a known time interval to measure the magnitude and direction of any displacement. Fluorescent sand and coloured and magnetised stones are examples of the kind of markers that can be used (Davison, 1889; Selby, 1968; Young and Holt, 1968). The main problem with this technique is knowing which process, for example soil creep, surface wash or human/animal interference, is causing the displacement of the markers. It is perhaps more suited to the monitoring of scree rather than soil.

A slightly more advanced method involves driving stakes, pins or dowels vertically down into the soil (approximately 0-20 cms). The top of the objects used are aligned with a string or theodolite and subsequent deviations from this line are then measured and attributed to down slope creep (Washburn, 1960; Young, 1960, 1963; Schumm, 1964; Leopold *et al.*, 1966). Limitations arise from this method because the surface may move at a faster rate than the lower layers. The tops of the stakes will then be tilted down slope and the whole line of markers is susceptible to movement. They can be located by triangulation with a theodolite if bedrock is present on a nearby slope. When the annual movement is small, the error of location is often greater than the amount of movement.

Other more sophisticated surface devices have been tried out, with varying degrees of success. Kirkby (1967) developed a metal T-peg for measuring soil creep. The tilt of the rod, caused by soil movement, is detected by using a specially constructed spirit level, mounted on to the cylinder. The chief advantage of this method, is the ability to take frequent and sensitive measurements (to approximately 0.005 mm.), without disturbing the instrument while it is in the ground. The disadvantages are similar to those mentioned in connection with surface stakes and since they are exposed, they can easily be disturbed by weather conditions near the ground and by animals. Kirkby placed one of his T-pegs into a laboratory block of soil and found that after a series of wetting and drying, the tilt of the T-peg was too low by a factor of five, showing that the soil had moved, appreciably, relatively to the peg. Therefore, this device is reliable only for measuring relative movement to compare short periods with one another and not for long term measurements.

(b) Methods to monitor movement with depth

It is far more desirable to obtain rates at several depths rather than only at the surface. Young (1960; 1963) devised a method, now refered to as the 'Young Pit', that has been extensively used in temperate environments (Kirkby, 1967); tropical environments (Eyles and Ho, 1970; Lewis, 1974) and tundra locations (Dedkov and Duglav, 1967; Owens, 1969). It involves the excavation of a pit or trench, down to the bedrock, normal to the slope. Reference pegs are installed in the rock, at the bottom of the hole, and into the vertical soil face. The site can then be carefully back-filled with the intention of re-excavating the pit at a later date to observe the position of the pegs in the soil face. The main disadvantage of this method is the immense amount of disturbance that is caused to the soil system during the excavation and re-excavation of the pit. There is also a greater tendency for water to concentrate and seep down the sides of the pit compared with the rest of the surrounding soil. After the pit has been re-excavated it may be re-filled for future monitoring. Kirkby (1967) concluded that each installation of a 'Young Pit', is really a one off method.

Bricks (Zaruba and Mencl, 1969) and cones (Selby, 1968), and columnar pillars and tubes have been utilized to monitor soil creep at varying depths. Hollow objects are installed vertically down into the soil and can be left empty (Kojan, 1967; Owen, 1969) or filled with a variety of substances ranging from simple plastic pellets (Rudberg, 1958); glass beads (Schumm, 1964); coloured sand (Hadley, 1967); even quick setting cement or plaster ('Cassidy's tubes', Anderson and Finlayson, 1975) and white modelling clay

(Everett, 1963) to highly sophisticated strain gauges (Williams, 1957; Truesdale and Schwab, 1968); SGI rod inclinometers (Kallstenius and Bergau, 1961); and tilt meters (Fleming and Johnson, 1975). The inclination of flexible tubes in the soil can be measured by the angle of an ellipse etched onto a glass cylinder by hydrofluoric acid (Dury, 1966) or by the setting of heated paraffin wax (Anderson and Finlayson, 1975). The disadvantages of these methods are similar to those of 'Young Pits', that is the disturbance of the soil during installation and at a later date when it is necessary to remove soil, from around the device used, to enable observation of any movement. It is also assumed that tubes are infinitely flexible. If this is not the case then a slow moving horizon situated between two faster moving ones would be ignored because of the tendency to average the movement out. In the case of the strain gauges, there is the additional problem of the substantial cost with some models, for example, the Wheatstone Bridge and construction of probes costs approximately $1000. Some inexpensive strain gauges have been used quite successfully (Mercier, 1982; Mercier and Geissert, 1982) but further field results are required before an accurate assessment can be made of the technique. Everett (1963) made use of linear motion transducers. The transducer has to be fixed relatively to the surrounding soil, so this requires drilling of the bedrock. Other drawbacks are that only surface movement at a point is measured and the arm connecting the transducer to the plate on the surface of the ground, may be affected by wind movements.

Finally there is the possibility of using radioactive tracers which are thought to have great potential in geomorphology. Fallout radionuclides of Pb 210 and Cs 137 have been used in estimating denudation rates (Wise, 1977) but there has been little work done within the field of soil creep. The main problem is again that soil creep is far too slow a process. To be effective the radionuclides would have to have quite a long half life and this, of course, dramatically increases the risk of human and environmental contamination rising to an unacceptable level.

1.5 Summary of the Disadvantages of Present-Day Creep Measuring Techniques

The main problem is that there has been no change in the basic methodology used for monitoring soil creep. At present, the field investigation of creep involves the introduction of an identifiable and/or reference object(s) into the soil system for a known time period. The last decade has witnessed a ´technological explosion´ in such fields as electronics and the subsequent decrease in price of certain instruments. This has had the effect of bringing a lot of sophisticated equipment well within the price range of geomorphologists. New advanced instrumentation may have a higher degree of accuracy and permit measurements to be taken more frequently, without further disturbance to the soil, but the method is still subject to a number of crucial assumptions. These have been highlighted by Culling (1981) and can be summarized as follows :

1. Initial disturbance of the soil, from installing object(s) into the system, is minimal and with time will disappear, so that the soil returns to its former state.

2. The object(s), once they are in the soil, do not affect any of the processes, or for that matter flow patterns, existing in the soil; ie. The object(s) do not have the effect of creating a separate ´micro-environment´ around them in the soil.

3. Soil can be regarded as a continuum and that movement occurs en masse.

4. The object(s) respond(s) and moves in a similar manner to that of the soil. Thus accurately reflecting the soil´s behaviour.

5. The amount of time allowed before the first measurement (six or 12 months) is allowing sufficient time for noise from initial disturbance to have dropped to a negligible proportion of the result.

1.6 Summary of Objectives

The main objective is to test for Culling´s predicted density pattern around an obstacle which has been established in the soil for at least 20 years. A steady state distribution is assumed to exist. It is necessary to devise a method of looking at the soil, at the particle level, without interfering with the soil structure or the transport processes during the period of change. The methods mentioned above strive to do this but it is felt that more often than not they fail. A new approach is needed to consider the pattern. One that involves just one observation which can therefore be destructive. This requirement was satisfied by the following research strategy :

i. Locate suitable sites with datable obstacles.

A potential problem in the study is that the particles may accumulate in front of the post and limit further movement. Firstly, this has been avoided by only considering sandy sites. It is hoped that in adopting this situation any close packing of the particles next to the post will have the effect of increasing the effective diameter of the post on the up-slope side and thus merely blurring the pattern. Secondly, if the pattern is destroyed by close packing then the pattern on the down slope becomes more critical. Telegraph posts are readily found throughout Britain and they were chosen as desirable satisfying the criteria for the research. They are accessible, many being located on open ground, and datable. Finding sites with the required underlying geology and posts with a minimum age of 20 years, however, proved to be very difficult. Agricultural and human disturbance eliminated many potential sites. Eventually two sites were choosen on the Folkestone Sands, one a sloping site at Oberon Glade and the other flat site at Thursley Common.

ii. Devise a method to remove samples with minimum disturbance.

After a thorough search of the literature and discussion with soil science laboratories, it was concluded that there was not a suitable technique available whose main aim was to investigate micro-density patterns in the soil around obstacles. A technique was developed and used for investigating the existence of a pattern by considering the characteristics and changing percentage of voids around a telegraph post. Soil was removed with minimum disturbance by using Kubiëna tins and brass tubes. It was impregnated with resin and a fluorescent dye and then made into 30-40 micron thin sections.

iii. Analysis of the soil sections.

Various soil micromorphometric techniques were considered to extract the relative information from the sections with respect to their accuracy, replicability and the time involved. Photomicroscopy was chosen. The sections were photographed under ultra violet light and phase contrast conditions and digitized to facilitate calculation of the soil:void ratio.

The aim is to use the results to construct a picture of changing micro-density values around telegraph posts and compare these values to those predicted by Culling´s theory. Chapter two deals in greater detail with the requirements needed to test the theory; the problems encountered while searching for suitable sites, site descriptions and the sampling strategy used. Chapter three discusses the development of the technique of impregnation of the soil to enable thin sections to be made. Chapter four outlines the different micromorphological methods currently being used and the reasons for choosing photometry. Image analysers are briefly reviewed before describing the system used. Finally Chapter five presents a summary of the results and their implications to the stochastic theory of soil creep.

II SAMPLING STRATEGY

The selection of suitable sites to investigate the stochastic theory and the various constraints involved are discussed. Following preliminary work at Ockham Common, two main sites were chosen with contrasting local relief. The sites are described with respect to their geology, pedology, relief and line of posts. The collection of samples with minimal disturbance to the soil structure was critical to the research. Various available techniques are reviewed and the reasons for using the adopted field procedure are outlined.

2.1 Site constraints

A number of constraints were taken into consideration while searching for suitable sites. These will now be discussed in greater detail :

i. Geology.

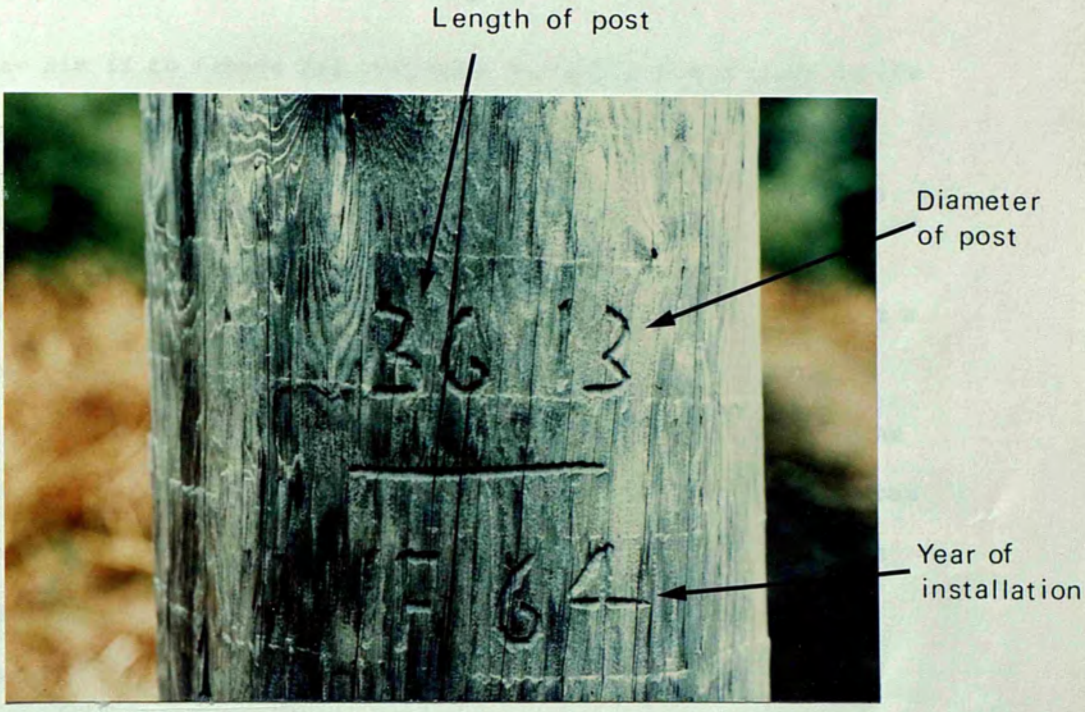
This research is aiming to produce field evidence to substantiate the existence of random diffusive soil movement. The theory is applicable to all types of soils. One important drawback of working with clayey soils is that internal cohesion, between particles, may have the effect of causing individual particles to cluster, break and recluster. These larger soil particles could react in the same way, but perhaps produce a coarse final density pattern. Nevertheless, it is not known whether or not there would be a significant difference in the density pattern. Following standard scientific practice we have chosen the simplest possible situation. That is a freely drained, sandy soil with a minimal clay and silt component. Soil structure and texture are partly a function of the underlying geology. A sandy lithology will tend to give rise to a sandy soil. Hence, after consulting the most recent 1 : 50 000 geological maps and their corresponding geological memoirs, interest was focused on the various sandy lithologies. It was decided to concentrate on the Folkestone Beds.

The Folkestone Beds complete the Lower Greensand succession and consist predominately of poorly consolidated, quartzose sands with seams of pebbles and clays. They are sometimes limonitic and sparsely fossiliferous, particularly in the eastern part of the outcrop. They grade from fine to medium sand but there are local variations. They exhibit well-developed cross bedding, including occasional dreikanter (wind faceted) pebbles which have led to speculation on the origin of the Folkestone Beds. Nearby land at the time of deposition was fringed with sand dunes which are probably, re-worked and incorporated into the present deposits. Like the rest of the Lower Greensand succession they are thought to be estuarine sediments, developed in shallow water under the influence of strong currents. The Folkestone Beds vary in thickness from 18.3 metres (60ft) at Folkestone, on the south east coast; thickening rapidly westwards to 79.3 metres (260ft) at Farnham, and then thinning again eastwards, along the southern outcrop, to less than three metres (10ft) at Eastbourne (fig. 2.1).

The Folkestone Beds give rise to characteristically acidic podzols. Under coniferous forest, on undisturbed heath, a surface accumulation of organic matter is underlain by grey sterile sand. This eluviated horizon loses iron and aluminium under the influence of organic compounds which are then deposited in two brightly coloured subsoil horizons, the upper of which is humose and very dark and the lower is rust coloured (Burnham and McRae, 1974, p. 600).

ii. Datable obstacles.

Datable obstacles, ubiquitous to the area, and of the required circular shape and size, then had to be located. Overhead electricity supply poles are approximately ten metre long wooden posts, of diameter 25.4 - 27.9 centimetres, which are spread over the country in a precise grid pattern. High voltage lines, (>33 000 volts), are usually set in concrete bases while low voltage lines, carrying domestic supplies, are located in hedgerows or in urban areas. In the middle of these two are medium voltage lines carrying 33 000 volts across rural areas from main distribution points. After the war, in the 1950's and early 1960's, a programme of modernisation commenced, not only to update present grid systems but to construct and install new ones. Therefore, a large number of new lines, with the exact date branded on the posts appeared throughout the country (plate 2.1). Twenty years is thought to be sufficient time for a soil to have returned to its steady state, following the installation of the posts into the soil. The regional electricity board offices, in the areas under investigation, were contacted, and large scale maps (1 : 10 000), showing the location and age of the posts, were obtained. All lines, introduced in the 1950's and early 1960's, and running across land on the Folkestone Beds, were noted.



Position of date on post

plate 2.1

iii. Minimum Disturbance to soil structure during removal.

The aim is to remove the soil with as little disturbance to its structure as possible. Therefore, the soil has to be as free of stones and roots as possible. This allows the containers (Kubiëna tins, tubes) used to collect the soil samples to be inserted with minimum disturbance to the soil structure. The soil needs to have a low faunal population (especially earthworms), to minimize the amount of horizon mixing from faunal activity. This is usually the case with acidic soils, such as podzols. Numerous complications can arise when dealing with heavy clay soils, mainly due to their high capacity for water retention. They are highly susceptible to swelling and shrinking in the field and great care has to be employed to prevent the development of cracks on drying at room temperature. This is another reason for avoiding clayey soils in preference to sandy soils.

iv. Slope.

The angle of the slope, on which the lines of posts run along, is important. If the angle is too steep the down slope drift component may mask out any discernible effect of random diffusive movement, and instead there could be a ´flow type´ pattern. The reverse could also be true ; on a flat site, the drift component would be at a minimum and the random diffusive element now dominant. This would lead to non-systematic density variation around the obstacle. Following some preliminary field work, it was found that posts on steeper slopes (greater than ten degrees) had surface scouring from overland flow around their base. For this study it was calculated that a slope angle of between three and seven degrees would be suitable. It was also the intention to have a control site of a post in a flat area.

v. Open access.

Most private land investigated has been ploughed at some time in the past. There are often animals grazing in the vicinity of the posts, and although permission was usually granted to work on the land, it was often for a limited time period only. In contrast, common ground and Nature Reserve land investigated has generally not been grazed in recent years. The lines of posts were not visible from the public footpaths and therefore not subject to frequent human interference. It was also felt that any area to be considered as a potential study site should be readibly accessible so that it could be freely visited as the need arose.

To summarise, a suitable site needed to have an acidic, sterile soil containing very few stones, roots and minimal faunal activity (especially earthworms), a datable obstacle, such as an electricity supply post, preferably introduced into the ground more than 20 years ago, and a slope not greater than about seven degrees.

2.2 Locating a site

A period of reconnaissance field work was undertaken to assess the local surface and subsurface conditions around the posts on the Folkestone Beds. At first there seemed to be a profusion of potential sites but it soon became clear that finding a site which fulfilled all the constraints was going to be difficult.

Hurtwood Common (TQ 085 435) has an extensive grid of posts. This whole area, running east from Wonersh to South Holmwood and south of the chalk escarpment associated with the Hogs Back, has Lower Greensand deposits out cropping at the surface. Permission was given by the estate mangers to dig in the area, and work began on the line of posts nearest to Winterfold Cottage (TQ 064 431). The posts were put in the early 1950's and there is very little surface vegetation around them. A small trench was dug about one metre away from a post but unfortunately the soil was found to be full of weathered fragments of bedrock. It was impossible to remove soil without causing disturbance to the structure. Each time a Kubiëna tin or tube was pushed into the soil face contact was made with fragments of rock and caused any container used to rotate about the point of contact. This problem re-occurred with posts in other parts of the forest and hence the area was abandoned.

At Chobham Common (SU 965655) there is a line of posts dating back to the 1950's. The soil is very sandy but the area is over grown with Pteridium aquilinum and Calluna sp. It was impossible to get close to most of the posts and even when there was a pathway near to one, it was found to be totally impossible to remove soil without disturbance because of the shallow and extensive root system. In another section of Chobham Common there was an extensive line of posts but unfortunately these fell within the governmental F.V.R.D. area (TQ 965653) which is out of bounds to the public.

At Ockham Common all of the constraints were met but the line of posts was in the area being developed for the new M25 motorway. The soil around a great many of the posts had been disturbed and therefore deemed useless. This proved to be fortunate as it was not possible to gain permission to work in the area.

A lot of the older lines of posts now need treatment to prevent rotting at the base of the post near the soil:air interface. This involves coating a section of the post, just above and below the ground level, with a mixture of pitch and tar or with creosote. Obviously, during the process, the soil around the post is totally disturbed. Therefore, any post found to have been treated in this way was immediately disregarded.

Eventually two sites which fulfilled the constraints were located. One a sloping site at Oberon Glade (TQ 051454) and the other a flat site at Thursley Common (TQ 914408) both in Surrey (fig. 2.1). Because of the extreme difficulty in finding suitable sites one other site, at Ockham Common, Surrey (TQ 085587), was chosen as pilot study area to perfect unfamiliar techniques before using them on the two main sites.

2.3 The sites

i. Ockham Common TQ 085587 Geology sheet 285 (Aldershot).

This area was used as a pilot study site to perfect certain techniques before using them on the two main sites. Ockham Common is situated near Boulder Mere, Surrey (TQ 083586) to the south east of the A3 road. The area is a Nature Reserve and therefore open to the public. The main landuse is mixed woodland (*Pinus sp.*, *Quercus sp.* and *Betula sp.*). The relief is gently undulating with a general height of 35 - 40 metres, rising up to 62 metres at Telegraph Hill. The actual study site was situated in a clearing in the middle of the trees. The main vegetation here is *Betula sp.*, *Ericaceae sp.*, Location of research

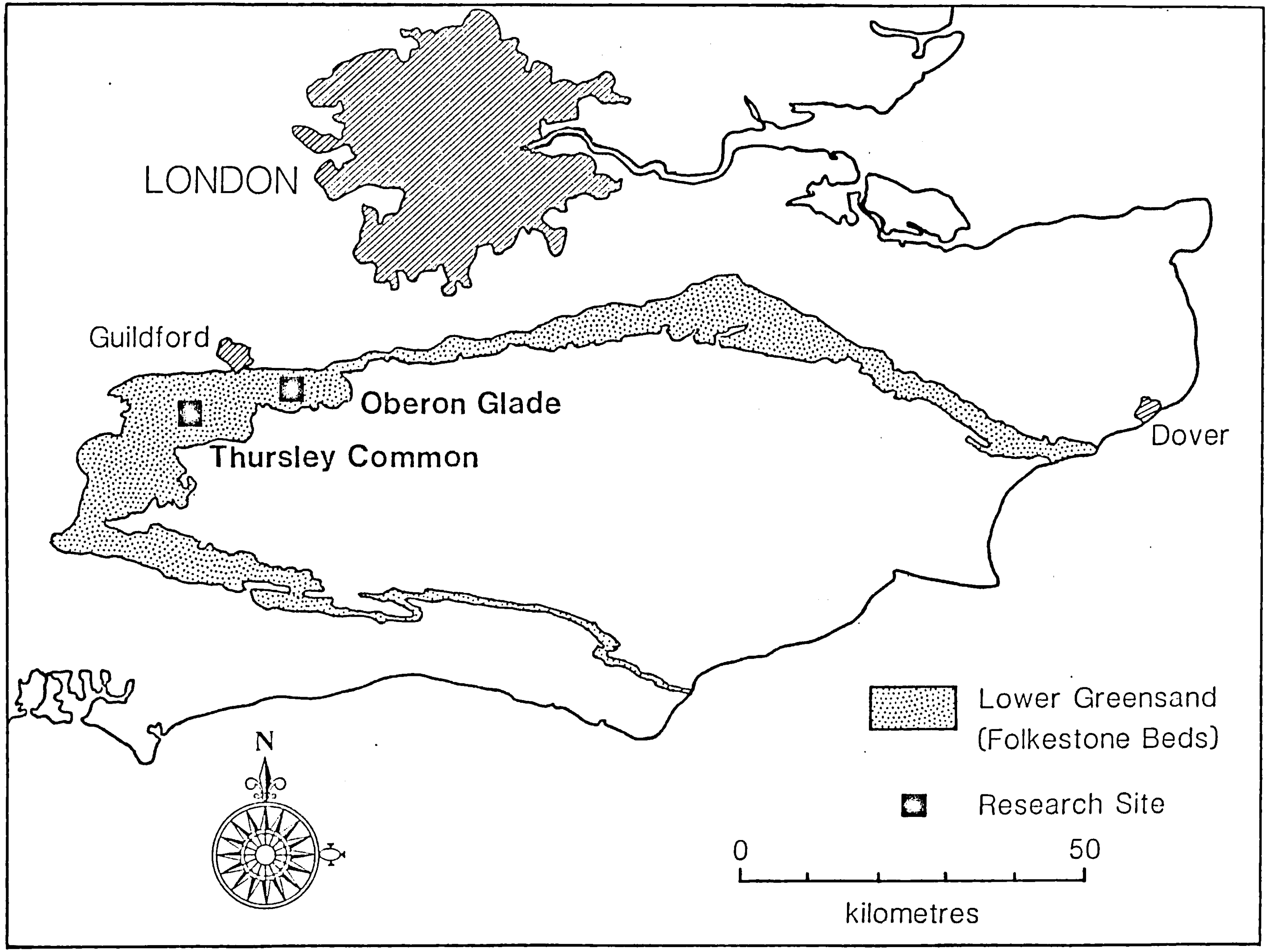


fig. 2.1

and Pteridium sp. The area is freely drained.

The underlying geology is the Bagshot Beds. They form two outliers of fine buff coloured sand with flint pebbles and is separated from the London Clay by 3.7 metres (12ft) of transitional sand and clay, namely the Claygate Beds (Gallois, R.W., 1965). This lithology generally gives rise to heath and woodland, for instance Bagshot Heath and Hampstead Heath. Outcrops run in an east-north-east direction, preserved in an axial syncline. The Bagshot Beds were laid down as a consequence of the shallowing of the London Clay sea. They are poorly fossiliferous and higher ground, such as Telegraph Hill, correspond to patches of plateau gravel.

The soil at Ockham Common is podzolic, very sandy and structureless with distinct eluviated and illuviated horizons. There is a well developed LFH horizon underneath the trees but in the clearing it is very skeletal. The pH of the Ae horizon ranges from 3.64 to 4.16 (Yam, O.L., 1979) and there is an iron pan approximately 45 centimetres down from the surface. There is hardly any surface vegetation and no evidence of faunal activity thus allowing for the removal of soil with minimum disturbance. There are a few small flints in the lower part of the profile (below 20 centimetres) but this area was not important to the study.

Although there is a line of posts on the far side of the Common, these were inaccessible due to road construction. Nevertheless, there are a number of small fence posts, about six centimetres in diameter. It was decided to use these to practise removing soil from around circular, cylindrical obstacles in the field, rather than running the risk of ruining a main site due to technical inexperience.

ii. Oberon Glade TQ 051454 Geology sheet 285 (Aldershot).

This study site is a small patch of heathland dominated by Pteridium aquilinum; Pinus sp.; Quercus sp. and Betula sp. Oberon Glade is suitated on Farley Heath to the north west of Farley Green, Surrey. The area is open to the public and mainly used for recreational purposes. The relief is gently undulating with a general height of 80 metres and rising to about 110 metres. The slope around the post was surveyed using an Abney level and it was found to be 4.5 degrees. There was nowhere evidence of surface accumulations of water and the area was very well drained (plate 2.2).

The outcrop of the sandy Folkestone Beds covers about 31 square kilometres to the south and east of Farnham and it forms hilly wooded country and heath. Further east, four miles south-east of Guildford at Farley Heath, the sandy Folkestone Beds are represented by a large but thin outlier similar to that of Albury Heath and Blackheath. On the Farley Heath outlier exposures are few. The only pit of note is 185 metres north of Upper Woodhill. This exposure shows a face of 3.7 metres (12ft) high, the upper 2.7 metres (9ft) of which is normal current bedded ferruginous sand (Dines, H.G. and Edmunds, F.H., 1929, p.38).

The soils of the area are podzolic, very sandy and structureless. Results of grain size analysis (appendix D) show that the soil is a sandy loam (U.S.D.A., 1951, p.209). The upper horizon sampled in the study is composed of 50.3 percent sand, 39 percent silt and nine percent clay. A definite horizon of amorphous organic matter exists near the surface. There is a distinct LFH layer, eluviated bleached A horizon which has a pH of 3.9 and this

Oberon Glade - general view plate 2.2

Oberon Glade - the post plate 2.3

grades down into a Bh horizon where there is evidence of a weak argillic layer at 20 centimetres down from the surface. There is little evidence of faunal activity, hence the horizons have very sharp, clear cut boundaries with each other. The only vegetation near the posts was some short grass which proved to have quite shallow roots. There were a few stones in the lower part of the Bh but none in the upper part of the profile where the sampling was to take place. There were no characteristic features of water-logging in the Bh horizon such as mottling or gleying and therefore as suggested the soils of the area are well drained.

The overhead electricity supply line, running down into the glade, consists of four posts, all of which were erected in October, 1960. They are medium sized posts, 25.4 - 27.9 centimetres (10 - 11 inches) in diameter. One of the posts, at the top of the slope, was originally set in a concrete base. The two near the foot of the slope had evidence of surface scouring around them and one had been treated for rot. Therefore, only one of the posts, undisturbed since its introduction into the soil in 1960, could be used in this study (plate 2.3).

iii. Thursley Common TQ 914408 Geology sheet 301 (Haslemere).

Thursley Common is a Nature Reserve area, covered with heathland and large patches of mixed woodland in which the *Pinus sp.* areas have been artificially planted. The Common lies to the south west of Milford, Surrey and just off the A3 road. Thursley Common is open to the public and mainly used for its numerous ancient bridle-ways. The relief is gently undulating with a general height of 60 metres and rising up to about 100 metres in the south of the Common. The immediate area around the posts was surveyed using an Abney Level and the angle of the slope was found to be less than one degree and therefore regarded as flat. The drainage for the most part is free except for marshy areas, in the north of the Common, coinciding with the Sandgate Beds (plate 2.4).

Up to 45.7 metres (150ft) of Folkestone Beds are present beneath Thursley Common. To the south of the Common, the Folkestones outcrop eastwards from the Cosford Valley for 27.4 metres (30yd) and are then faulted against the Sandgate Beds (TQ 914396). On the north side of the Common, the basal feature is lacking. Exposures here are rare and marshy, together with seepages, mark the base of the formation. Current bedding is ubiquitous and Allen and Narayan (1964) interpreted typical features of the cross-stratified units in terms of large scale ripples, formed in a shallow sea under tidal conditions. Small patches of the third Blackwater terrace cap the Folkestone Beds to the west of Hammer Pond (TQ 911401) to the south of the study site (Thurrell, R.G. *et al.*, 1968, p.94).

Thursley Common - general view plate 2.4

Thursley Common - the post plate 2.5

The soils of Thursley Common are podzolic, sandy and structureless. Results from grain size analysis (appendix D) show that the soil is a sand (U.S.D.A., 1951, p.209). The upper horizon sampled in the study is composed of 94 percent sand, one percent silt and two percent clay. There is a one centimetre organic layer at the surface. The bleached Ae horizon has a pH of 4.2 and extends down to 130-140 centimetres from the surface. There is nowhere evidence of faunal activity. The posts are far enough away from the trees to avoid interference from the rooting systems and any grass had very shallow roots. There were no stones in the Ae horizon and no signs of water logging in the Bh horizon. The area is therefore freely drained.

The overhead electricity supply line runs west to east across the Common from Truxford Cottage (TQ 898406) to Warren Mere (TQ 918408). There are twenty posts, all medium sized, 27.9 - 30.5 centimetres (11 - 12 inches) and introduced into the soil during the winter of 1951-1952. The posts in the extreme west are surrounded by vegetation and inaccessible whereas the posts in the east are situated in cultivated gardens (Silkmill Cottages). In the coniferous woodland, near Warren Mere, a post was found to satisfy all of the constraints (plate 2.5).

2.4 Collection of soil samples

To establish the technique of carefully collecting soil samples, with minimum disturbance to the soil structural characteristics, a pilot study was carried out at Ockham Common. The standard procedure was to use Kubiena tins (8.0 x 6.5 x 4.0 centimetres). Numerous problems arose when manually inserting them and subsequently a tool was developed to overcome this. In most of the final sampling brass tubes (6.5 x 2.5 and 6.5 x 4.0 centimetres) were used and found to be far more efficient than tins for our purposes. Two methods were used to collect the soil, the first necessitates trenches dug at right angles to the post whereas the second involves tins or tubes pushed down from the surface of the soil. The latter method causes the least disturbance to the soil but its use is limited by the amount of surface vegetation.

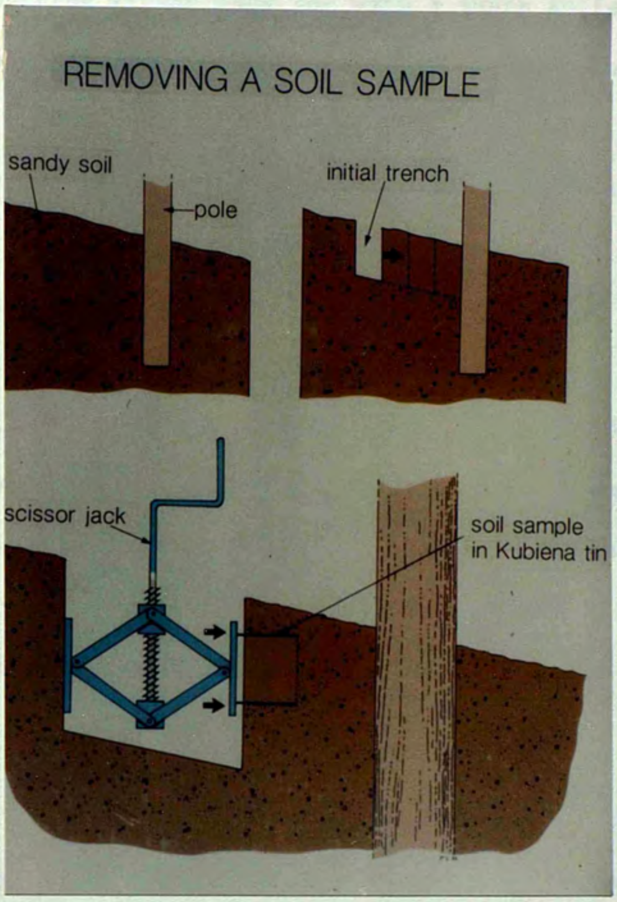
The full extent of the density pattern was not known. It may extend to a metre or more or only a few centimetres. Sampling was carried out to 60 centimetres from the circular boundary of the post. A great deal of patience is needed to ensure that absolute minimum disturbance is caused to the soil structure when excavating the samples. All of the sites were on public ground and therefore no sampling could be left unfinished and returned to at a later date. It may take up to five hours to remove 40 samples and for this reason each post was treated in two sections. For instance the soil on the down slope side was collected one day and the following day the up slope side was sampled.

It was intended to space out the tins or tubes evenly relative to each other and place them in at a constant depth (three centimetres). This proved to be impossible, especially with the tins, due to the heterogeneity of the soil, even though the sites had been chosen for fulfilling the constraints such as a minimum amount of vegetation and fauna in an attempt to eliminate this problem. In the first method the only practical solution was to push the tins/tubes into the soil profile at varying depths. The second method overcame the problem but it was hampered by the fact that there must be very little surface vegetation before it can be used.

i. Using trenches.

A shallow trench (35-40 centimetres) was excavated approximately 60 centimetres away from the post on the down slope side. The soil profile face nearest the post was cleaned and aligned to the vertical. Manual insertion of the Kubiëna tins proved to be very difficult because of the lack of room for adequate leverage to push them smoothly into the soil. Sharpening one end of the tins to facilitate easier insertion was found to be impractical. In most cases the tins rotated about one of their corners and it was felt that this caused significant disturbance to most of the soil. Wooden guides were fitted to a one-ton scissor jack and this tool enabled a tin to be pushed into the soil with a constant, smooth action and even pressure (plate 2.6).

Between five to eight tins were inserted along the trench and only when they were all in position was the scissor jack removed. This ensured that the minimum amount of soil was lost during the excavation. Each tin was fitted with a lid before they were



Using a modified scissor jack

plate 2.6

carefully removed by cutting around each one with a sharp knife. A small amount of soil was left projecting out of the back of the tin and this needed to be carefully levelled off before the second lid was fitted. In the event of a pebble or decaying piece of organic matter projecting out of the tin the sample was rejected. The samples were sealed with sticky tape and labelled with respect to position from the post and orientation. After all the samples had been removed, the soil face had to be re-cleaned and re-aligned to the vertical. The procedure was repeated about five or six times until the final trench was almost adjacent to the post. Once all the necessary samples were removed, safely sealed and labelled the area of ground was back filled. The procedure was completely repeated on the other side of the post.

When brass tubes (6.5 x 2.5 and 6.5 x 4.0 centimetres) were used the method was identical to that above for tins. The major difference was that tubes could be inserted manually. A small plastic bung was fitted over one end to allow the tube to be pushed into the soil profile. The tubes were usually cut a little longer than was required so that it was not necessary to completely push them into the soil face. This ensured that soil was not compacted at the exposed end on insertion. A 60 degree chamfer was put on to one end of the tubes to produce a sharp cutting edge. Parafilm sealing tissue was used to seal the ends of the tubes before they were finally labelled.

ii. Direct insertion.

This method was only used with tubes. They were manually pushed down into the surface of the soil to a constant depth. Care was taken to ensure that they were inserted vertically and if any obstruction was encountered, such as roots or stones the sample was rejected. Tubes to be inserted on the one side of the post were all carefully pushed in before any were excavated (plate 2.7). They were removed individually with a sharp knife and any soil left projecting out of the bottom was levelled off (plate 2.8). Again, if there was a pebble or root projecting out, the sample was automatically rejected. They were sealed with Parafilm and each sample was labelled with respect to distance from the post and orientation.

2.5 Summary of conclusions

A number of conclusions can be drawn from this initial field work. The tubes were a far more efficient way of collecting soil. Firstly, they were much easier to insert manually. The 60 degree chamfer meant that they entered the soil quite smoothly. Secondly, there has been very little work published on the ´edge effect´ of a tin or tube on soil micro-structure. After investigating the problem further, the Soil Science Department at Rothamstead did make a comment saying that they felt the effect was only a matter of a few microns (Murphy, personnal communication, 1982). From subsequent experience of studying hundreds of sections, this view is borneout. A cylindrical shape helped to minimize the problem because it gave the maximum volume for amount of edge. Thirdly, brass tubing was used because it was readily available and its

plate 2.7 a

Collection of soil samples using tubes

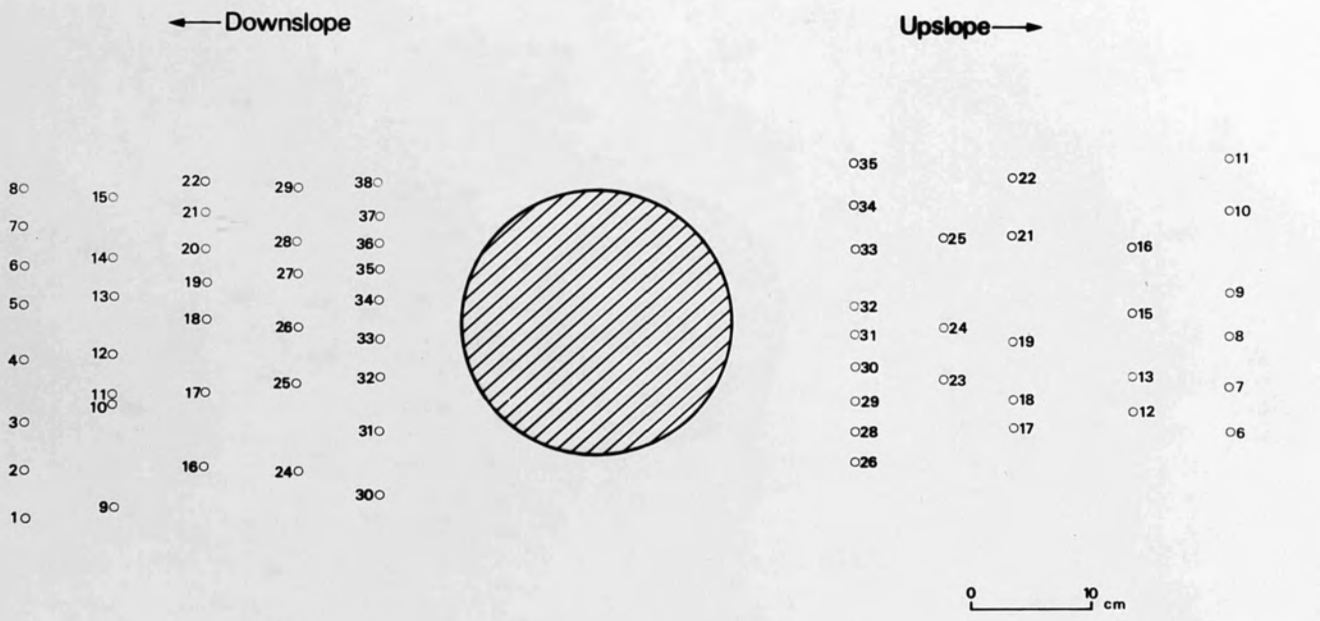
plate 2.7 b

properties enabled quite a small gauge of metal to be used (16 gauge, 1.626 millimetres) while maintaining a good deal of strength. Kubiëna tins require a workshop and special tools to be made properly. If this service is not available then they have to be purchased from an outside source. It was found that these often have a policy of a minimum order which can be as large as 500. The tubes are therefore far cheaper in terms of money and in time.

Of the two methods investigated for inserting the tins or tubes, the one which did not involve the excavation of trenches was thought to be the most successful. Digging a trench and cleaning and aligning the soil profile face meant that a lot of the potential sampling area was lost because of irreversible disturbance. The tubes can also be inserted at equal distances from the post in a semi-circular pattern when direct insertion is used. It was difficult digging straight trenches at right angles to the post and curved trenches would have posed a severe problem. The major drawback of the direct surface insertion method is that it is not practical when there is a lot of surface vegetation.

At Oberon Glade there was a small amount of surface vegetation hence the area around the post was divided into two sections, up slope and down slope, and then soil was removed in tubes by means of digging a trench and working towards the post. 35 samples were collected from up slope of the post and 38 on the down slope side (plate 2.9). At Thursley Common, the same method was used on the east side but on the west side tubes were pushed directly down into the soil. 47 samples were collected on the west side of the post and 42 on the east side (plate 2.10). In all cases tubes were used in preference to Kubiëna tins. The samples were immediately returned to the laboratory and prepared for impregnation on the day of removal from the field.

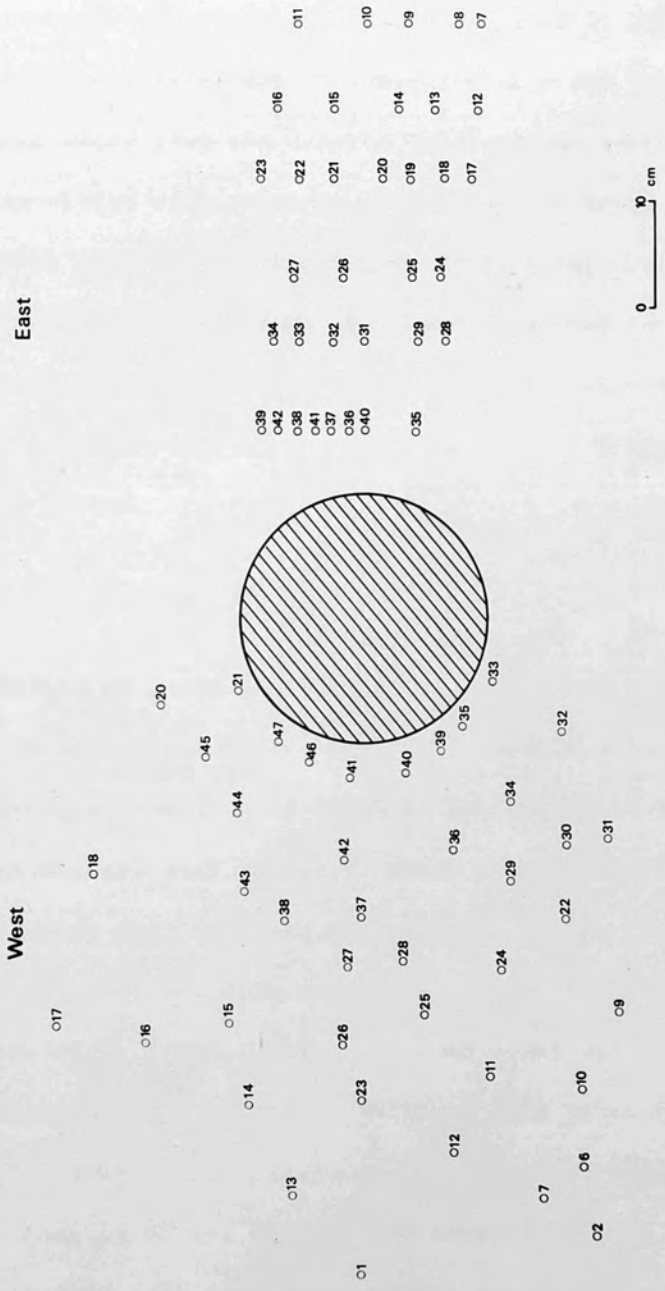
OBERON GLADE - sloping



Relationship of sample points to post

plate 2.8

THURSLEY COMMON - flat



Relationship of sample points to post

plate 2.9

III LABORATORY TECHNIQUES

Soil samples collected from Oberon Glade and Thursley Common had to be impregnated before thin sections could be made. Resin was found to be the efficient way of achieving this but it was necessary to remove any water from the samples prior to impregnation. The problems associated with removing water from the samples are discussed with particular reference to certain techniques. There is a brief résumé of the materials that have been used to impregnate soil, the modern plastics now available and the reasons for choosing the particular resin used in the research. The impregnation method used is then listed.

3.1 Drying the Samples

If a sample is loose and friable it is necessary to consolidate it before sections are made and processed using manual and automatic rock sectioning equipment. It is usual to impregnate with a low viscosity substance, such as resin, which hardens on the addition of a catalyst. Most soil has some water in the pores. There are no resins that are miscible with water that are sufficiently hard when cured (FitzPatrick, 1980). There are some waxes but these have their limitations. For instance, Carbowax 6000 tends to crystallize in the form of spherulites, although this can be greatly reduced by ultra-rapid cooling of the impregnated sample in Freon 22 (Gillott, 1973). It is also liable to show surface smearing during grinding and very little is known about the mechanism of its exchange with water or the possible complex formation with clay (Greene-Kelly, Chapman & Pettiffer, (1970). It was therefore necessary to remove any water prior to impregnation with a resin. There are two main ways of doing this, complete removal of water from the interstices and water replacement by a liquid which is miscible with resin.

i. Complete water removal.

The most direct way of overcoming the problem of water in a sample is to simply remove it from the soil. There are various ways of achieving this and they are now discussed.

(a) Air and oven drying

The simplest method is to allow the sample to dry out at room temperature (20 degrees) or in an oven (40-50 degrees). Although these are not drastic treatments sample cracking and shrinking is often inevitable due to surface tension forces at the air/water interface. The actual orientation of the mineral particles may also be altered (Gillott, 1973). Oven drying of silty soils appears to increase the porosity, causing an increase in the size of all pores (Murphy, 1982). In general, air or oven drying can be used for routine thin sections but they should but avoided when quantifying structural components from thin sections.

(b) Freeze drying

When dealing with small samples (5 x 5 centimetres) the basic technique is to immerse the soil in liquid nitrogen (temperatures can be as low as -180 degrees). Quick freezing occurs in a few minutes and then the samples are placed in a freeze dryer for a few days. They are now ready for impregnation. For larger samples, such as slabs or cores, Crevello, Rine and Lanesky (1981) suggest that the samples are further treated by inserting them into a precooler dryer with the shelves and condenser below 0 ^{o}C. The chamber is evacuated to 100 microns of mercury and the condenser further cooled to -40 degrees. Maintaining the condenser at this temperature, the shelves are heated in 25 degree increments to 125 degrees within two to three hours. They are left in the chamber for eight to twelve hours at 125 degrees. Crevello et al. also feel that freeze-dried samples should be impregnated as soon as they are dry because they are then less susceptible to damage. If this is not possible the soil is best stored in an oven at 100 degrees or in an airtight chamber with desiccant.

Shrinking of the sample by surface tension forces is minimized in this method because ice is removed by sublimation and a meniscus is not formed in the pores. One of the problems with freezing the water is that there is a nine percent increase in specific volume when water in bulk is converted to ice. Gillott (1973) thinks this only becomes significant in soil which has water in relatively large void spaces. The main problem with freeze drying is to prevent the growth of ice crystals. Ice nucleators (amino acids, metaldehyde) have been added to pore solutions because this promotes small ice crystals to form in the interstitial spaces. This is thought to have less effect on the fabric than allowing large crystals to grow. The most effective way to prevent structural damage from ice crystals is to convert pore water to ice glass by rapid cooling (-120 degrees), high viscosity in the liquid near the freezing point and depression of the freezing point by the addition of appropriate solutes. It is a long and complicated process and care must be taken to ensure that the sudden drop of temperature does not cause the soil sample to shatter. Many of the above problems can be reduced if the water is initially replaced with an organic compound such as amyl acetate (Boyde and Wood, 1969) before freeze drying. Another view is to not remove the ice but examine the soil in its frozen state. Some stereo-scans (Cambridge) allow this but it can be a very expensive way to solve the problem. Murphy (1982) found that :

> ". . freezing of samples prior to impregnation is somewhat unsatisfactory if samples greater than a few millimetres thickness are taken."

FitzPatrick noted that considerable disturbance to the soil structure, from the formation of ice crystals, is caused when freeze drying samples as thin as one millimetre. Freeze drying is a successful way of drying soil. It tends to be a long and tedious method if carried out properly but then it does produce results of a high standard. It has been used extensively for studying clays and this seems to be the area where it is of most value.

(c) Critical point drying

Greene-Kelly (1973) pointed out that if it can be assumed that shrinkage is principally due to capillary forces, reduction or elimination of the liquid-vapour interfacial tension should result in reduced shrinkage. The addition of surfactant solutions to kaolin have been shown to linearly decrease the drying-shrinkage as the surface tension of the solution decreased (Kingery and Francl, 1954). When remoulded clay was dried under n-octoic acid (surface tension - 0.80 newtons per square metre (N/m^2)) it was found that total shrinkage was about half that of a similar sample in air (Greene-Kelly, 1973). The problem with these procedures is that it is often difficult to remove the additives and therefore they are deemed to be not suitable for sample preparation. Shrinkage has been found to be markedly decreased when samples are dried at temperatures greater than the critical temperature of water which is 374 °C (Diamond, 1970).

The principle which underlies this techniques is that at a temperature and pressure above a certain critical point the physical properties of a liquid and its vapour become the same. With the removal of the boundary layer the surface tension forces disappear and the possibility of structural damage on evaporation of pore fluids is greatly reduced. Anderson and Holland (1960) were amongst the first researchers to investigate the use of such a method for sample drying and a similar approach has been used by Gillott (1969) and Horridge and Tamm (1969). The most direct method is to place the samples in a suitable sealed container and remove any water at a temperature and pressure above the critical point of water (374 °C, 22.52×10^6 N/m^2). Alternatively, the water can be replaced with other miscible liquids which have critical points at lower temperatures and pressure and then the procedure repeated as before. Anderson and Holland (1960) used liquid CO_2 (31 °C, 50.33×10^4 N/m^2). Unfortunately, liquid CO_2 is not miscible with water and a series of replacements had to be employed.

One of the major disadvantages is that the conditions for critical point drying are similar to the hydrothermal conditions that favour rapid synthesis and alteration of clay minerals (Grim, 1953). Gillott (1973) felt that there are few inherent drawbacks to the critical method when water is replaced first. He concluded that samples dried with a non-polar liquid may be theoretically superior to those dried with a polar fluid such as alcohol. Although he found that samples critically dried from alcohol did not differ in external appearance or fabric from sample dried by the more involved CO_2 method. Greene-Kelly (1973) discusses in detail critical point drying from replacement liquids. He does not like the use of alcohol for two reasons. First, he feels that the critical temperature of ethyl alcohol is too high (243 °C) and for the method to be of general application a critical temperature below 100 °C is needed. Second, when water is replaced by alcohol in the diffuse double layers there is risk of clay aggregation. He concludes by favouring a series replacement of water with carbon dioxide and its removal above its critical point.

ii. Water replacement.

Instead of completely removing the water it may be advantageous to replace it with a volatile liquid which has a lower surface tension than water (7.28 N/m^2) and is miscible with resin, for example acetone (2.37 N/m^2) or ethyl alcohol (2.28 N/m^2). There are two ways of achieving water replacement namely liquid and vapour phase replacement. The liquid or vapour exchange can either use progressively more concentrated aqueous solutions of the solvent or the pure solvent itself. Both methods will now be briefly discussed with respect to pure acetone but the procedure is the same for other liquids.

(a) Liquid phase replacement

The wet sample is placed in a xlon box and covered with acetone. The container is sealed and left to stand for 24 hours. The acetone is carefully syphoned off and fresh acetone is poured in once more to cover the sample. This is left for 48 hours and then the procedure is repeated for the following week. After approximately five or six treatments the acetone is tested for the presence of water by shaking 10ml of it up with 40ml of petroleum spirit. If water is still present there will be some turbidity and layering since acetone is miscible in petroleum spirit while water is not (FitzPatrick, 1980). Greene-Kelly (1973) assumed that the exchange was complete if the density of dry methanol placed in contact with a sample for a few days was not appreciably altered. Whichever method is employed the acetone treatment is continued if there is evidence of water otherwise the acetone is syphoned off and the sample is now ready for immediate impregnation.

There is a possibility of fluid migration and ion interaction with this method. The liquid replacement is accomplished with minimum effects from concentration gradients if the samples are covered successively in graded solvent and water mixtures of increasing concentration.

(b) Vapour phase replacement

The wet specimen is placed on the metal gauze of a desiccator containing 200ml of acetone. There must be a reasonable space between the sample and acetone to allow for efficient vapour exchange. The desiccator is sealed and left for three days. The acetone is syphoned off and replaced with fresh every three days for two weeks. The acetone is tested for the presence of water as in the previous method. If water is still present the acetone treatment is repeated until the test shows that there is no water. The sample is ready for immediate impregnation.

Vapour phase replacement is preferable to liquid phase since none of the soluble material is removed especially if acetone is graded with water and the replacement uses mixtures of increasing concentration (FitzPatrick, 1980). He also found that this technique is only recommended for samples not thicker than two centimetres.

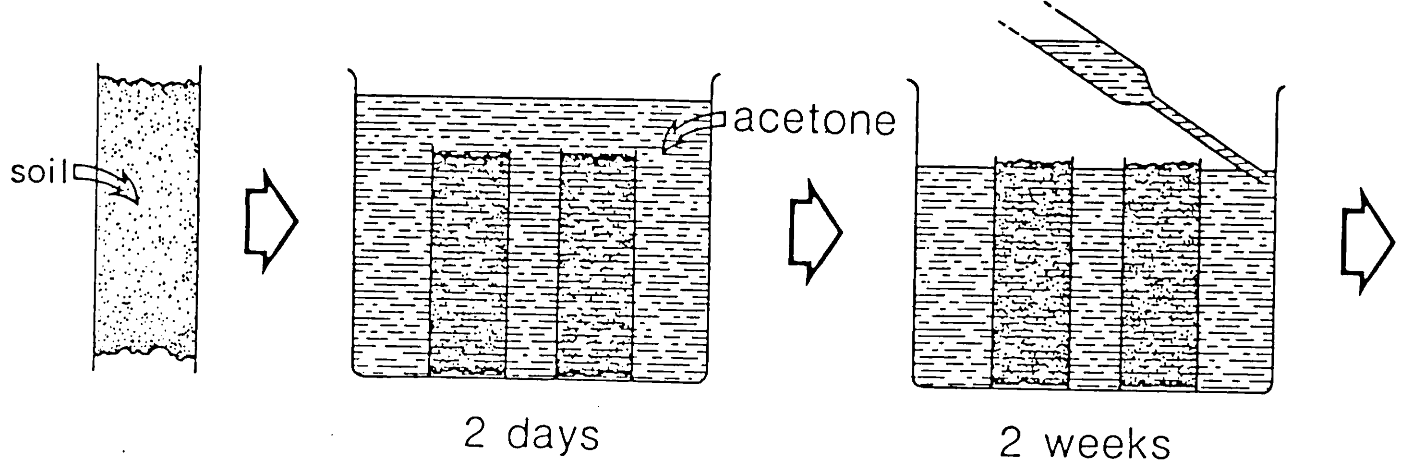
Because the research is concerned with investigating the micro-structure of soil from the examination of thin sections, it was imperative to minimize disturbance at all stages of the technique. The samples from Oberon Glade and Thursley Common were very friable and had to be impregnated before thin sections could be made. Air, oven and freeze drying techniques were not considered because with the former there is a high risk of sample disturbance and with the latter the recommended thickness, a few millimetres, is felt to be too small. The soils had very little clay and a small proportion of silt hence it was decided to use a method involving water replacement. Critical point drying was first considered but it was felt to be rather elaborate and time consuming for soils composed mainly of sand. The two phase replacements were tested and vapour phase replacement was found to result in poor impregnation because of the thickness of the samples (maximum of four centimetres). The soil samples were all collected from the bleached, sterile, eluviated horizon. Most of the soluble material has already been leached out of this part of the profile to a lower horizon. Therefore it was felt that liquid phase replacement with pure acetone would be the most suitable way of removing the water in this study.

The samples were treated with acetone on the same day as collection. This was to minimize the risk of drying out overnight. Parafilm and sticky tape were removed from every sample before carefully placing them in xlon boxes. The number in each box varied depending on the size of the tube. Pure acetone was used in each replacement. It was slowly poured down the side of the boxes until all the samples were covered and then lids were fitted to prevent the acetone from evaporating off. The solution was tested for the presence of water after approximately seven treatments. When the test showed that there was no water present, the samples were assumed to be ready for impregnation with resin and the remaining acetone was gently syphoned off (fig. 3.1 a).

3.2 Impregnating Materials

Impregnation is when a liquid is used to fill the pores and voids within the specimen; the liquid then sets solid binding the friable specimen together to form a hard workable material. There are two basic types of impregnation, surface and thorough. Surface impregnation is often all that is needed when a specimen is strong enough to withstand normal cutting and grinding but not strong enough when reduced to 30 microns. The same principle is used in the field for peels and impressions when resin is sprayed or brushed onto a surface. The soil used in this research was non-cohesive and friable and in all cases it was necessary to impregnate thoroughly. The following discussion therefore concentrates on techniques and materials associated with thorough impregnation but many of the resins mentioned are also used in surface impregnation.

a WATER REPLACEMENT



b IMPREGNATION

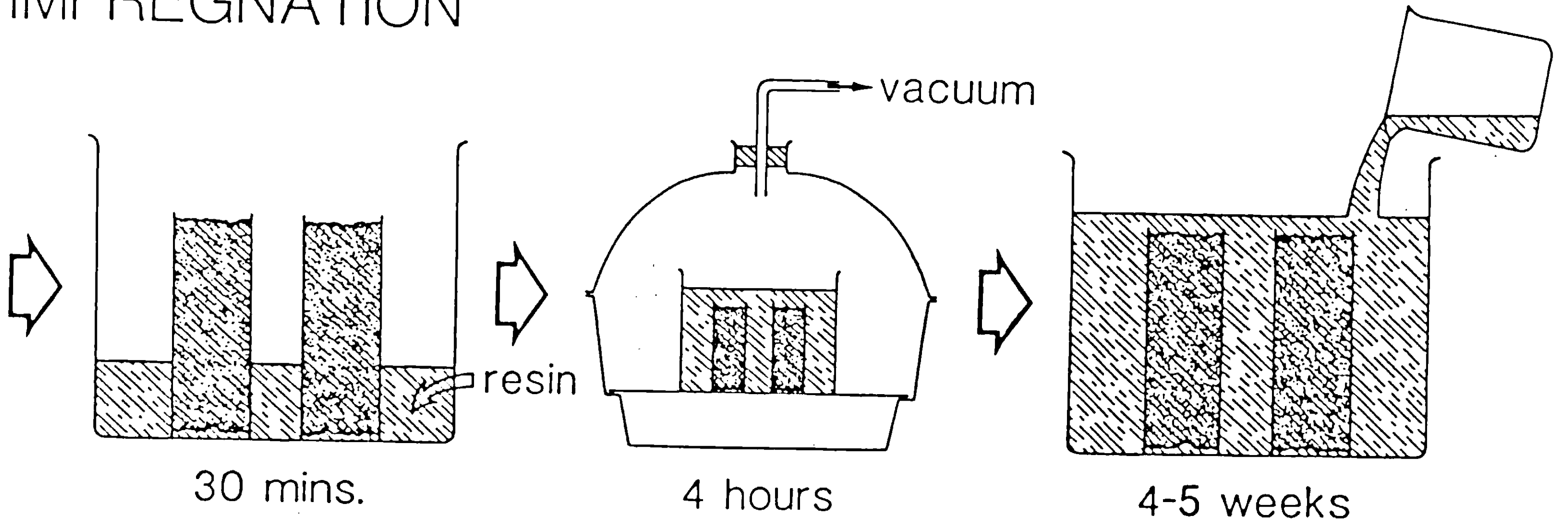


fig. 3.1

The ideal impregnation material should have low viscosity under the impregnation conditions, it should set with a minimum change in volume and it should be non-polar. The actual conditions of impregnation should not be so extreme as to risk any changes in optical properties and arrangement of the constituents of the soil material. When finally hardened the impregnation material should be relatively hard at room temperature, colourless, isotropic in thin section and have a refractive index as close as possible to that of Canada balsam, the classic medium for thin sections of rocks. The ideal resin has so far not been produced and at the best of times impregnation is a compromise (FitzPatrick, 1980). The various substances used for impregnating soil and rock samples are now outlined.

i. Natural resins.

One of the first impregnation materials to be used was Canada balsam dissolved in xylol. Together with Kollolith (Ross, 1924) and Dammar resin they have been the most popular natural resins. They require prolonged heating or "cooking" to reduce their viscosity to ensure thorough impregnation and this increases the possibility of sample disturbance. Dammar resin is likely to become brittle and craze with time and balsam is easily overcooked (115 ^{o}C) during the hardening process which causes it to darken. Allman and Lawrence (1972) feel that natural resins have fallen into disfavour in recent years because it has been realised that the degree of penetration into many specimens is very low. Cutting and grinding can be a problem since many non-polar lubricants, such as kerosene, cannot be used because they dissolve the resins. Water cannot be used because it may cause dispersion of the fine-grained parts of the soil material. Therefore grinding must often be done dry which is a time consuming procedure because it requires the grinding plate to be cooled with an ice-salt mixture to prevent the heating up and consequent flowing of the resin. Natural resin, especially Canada balsam, is now very expensive when compared to modern synthetic equivalents, which are easier to use (FitzPatrick, 1980)

ii. Plastics.

The use of polymerizing plastics such as polystyrenes, polyesters and epoxy resins has helped to overcome some of the difficulties encountered with natural resins. Polymerization is effected by mixing the resin with known quantities of a paste or liquid catalyst and a liquid accelerator. The resin first sets, then gels and finally cures into a hard and relatively inflexible material which is strong enough to be thin sectioned. Gelling time is dependent on the amount of catalyst and accelerator used and temperature. Some of the earliest work was done by Kubiëna (1938) who introduced thermo-labile plastic material for the preparation of soil thin sections. Unfortunately later workers did not achieve similar success with his method. Bourbeau and Berger (1947) developed a method using Castolite, a polyester resin, which became a standard for subsequent workers for many years to come. Most of this following work was mainly concerned with experimenting with various resins and polymerizing rates. Marco resin was used for impregnating soil prior to thin sectioning (Alexander and Jackson, 1955). This procedure was greatly simplified by using Bakelite, a polymeric resin (Hepple and Burges, 1956). Allman and Lawrence (1972) outlined some of the main materials and associated techniques that have been used for impregnating soil samples. In general, most of the epoxy resins and Santolite, Bakelite and Lakeside 70C need to be cured. This has the effect of reducing their viscosity (ie. Araldite MY778 viscosity of four poises at 21 °C but only 0.2 poises at 100 °C) and thus allows for more thorough impregnation. Araldite epoxy resins show exceptional strength and adhesion properties while hardening very quickly, for example, from as little as 30 minutes to four days depending on the variety and recipe used. Epoxy resins now have widespread use in the preparation of rock sections for mineralogical work even though the Araldite resins exhibit a high refractive index of 1.59. It is felt that the exothermic process of hardening together with the necessity to cure to high temperatures of 80 °C to 120 °C is very likely to cause structural disturbance to loosely consolidated, friable soil. Recent research is tending to favour the use of cold cure resins for impregnating soil samples, when the aim after thin sectioning is the quantification of soil structures (Bullock, Murphy & Waller, 1982).

Some epoxy resins (Araldite CY219) and polyester resins (Crystic 17449) fall into this category of being able to cure at room temperature. The main problem is that materials often need to be thinned to reduce their viscosity. Therefore, the hardening process must allow time for the thinner to slowly evaporate off, without causing structural disturbance, otherwise the soil will not be sufficiently hard to allow for sectioning. This means that the amount of accelerator used is greatly reduced if not excluded to slow down the gelling time. And it also has the positive effect of lowering the exothermic heat peak during hardening. The extra time involved (4-8 weeks) is thought to be justified when considering using the thin sections for structural investigation.

iii. Polyethylene glycol (Carbowax).

Carbowax is one of the few substances that will impregnate wet samples. Its melting point is at about 60 ^{0}C and viscosity is quite high but impregnation action takes place by diffusion through the water contained in the sample. It is manufactured in a series of molecular weights with Carbowax 6000 (a polyethylene glycol fraction of average molecular weight 6000) found to be the most useful. There are several disadvantages when using it for impregnation, the most important being that it is not isotropic. The birefringence is variable, perhaps depending to some extent on the water concentration and it sometimes tends to crystallize in the form of spherulites. Allman and Lawrence (1972) pointed out that it has been reported that there is a reaction between pure montmorillonite and Carbowax when the amount of montmorillonite in a sample exceeds 50 per cent. Carbowax does not become as hard as natural resins and plastics. It has a value of 1 on the Mohr scale of hardness and consequently it tends to smear on grinding. Mitchell (1976) was one of the first workers to successfully use Carbowax to produce sections 40 microns thick of moist clay. Greene-Kelly, Chapman and Pettiffer (1970) discussed advantages and disadvantages of using Carbowax and they felt that it´s use was undervalued by pedologists. They concluded that polyethylene glycol fractions of molecular weight 6000 are satisfactory embedding agents for preparing thin sections soil containing different amounts of clays. They went on to apply the technique to a study of the effects of swelling and shrinking on clay orientation (Greene-Kelly and Mackney, 1970). There has been a lot of subsequent use of Carbowax by engineering geologists to impregnate cores at field moisture content without the need of special apparatus and complex techniques. Nevertheless, the researcher must be aware of the problems and make allowances for them in the final analysis.

iv. Latex sols

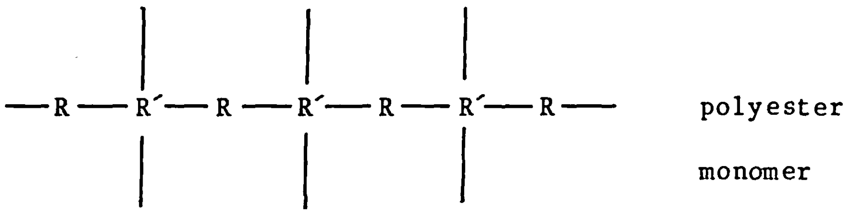
Brewer (1964, p.408) briefly mentioned a method using latex sols to stabilize soils prior to impregnation. The soil is placed on a wire mesh grid with the base in contact with the sol thus allowing it to take up latex by capillarity and diffusion. It is necessary to leave it for several days before drying. The method does not seem to have been adopted by subsequent researchers perhaps because the soil sample still has to be impregnated with one of the plastics or resins mentioned.

3.3 Impregnation

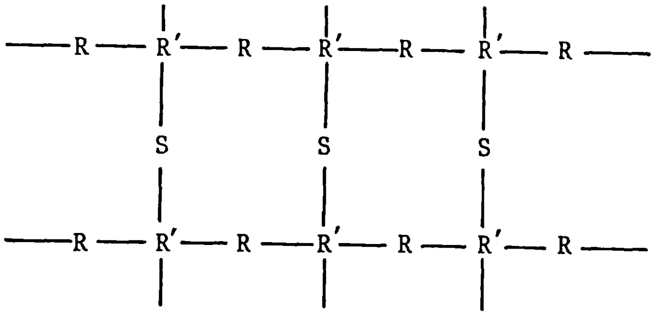
Impregnation can proceed once all the water has been replaced by a suitable liquid. The soil was very soft, friable and liable to collapse once removed from the collecting tubes hence the brass tubes remained in place until the cutting and grinding phase. The most satisfactory impregnation was obtained by using a cold cure, low viscosity resin and subjecting the samples to a partial vacuum. It was decided to use a polyester or epoxy resin. Polyester resin needs thinning to reduce its viscosity. Acetone is an ideal substance but it has a low boiling point so care must be taken when impregnating at high vacuum. There is evidence that polyester resins react with some alkaline soils to form black droplets. These accumulate in the pore spaces and impair the quality of the thin section. The soils being considered in this research were acidic in nature (Oberon Glade pH - 3.9, Thursley Common pH - 4.2). The viscosity of epoxy resins drops rapidly on heating and therefore thinning is not necessary. They have a high boiling point so that impregnation can take place at a high vacuum. The main problem is that some epoxy resins, whether hot or cold, can react with highly weathered minerals causing them to swell. This can cause massive disturbance to the soil micro-structure. It was felt that the heating up of epoxy resin and samples would in the long term cause more disturbance than using a thinner and a polyester resin. Acetone was already in the samples and the extra time needed to allow for gelling and hardening was thought to be justified. Crystic resin 17449 was chosen as the impregnating medium.

i. Crystic resin 17449.

Crystic resins are unsaturated polyester resins which mainly occur as liquids. They consist of a solution of a polyester in a monomer which is usually styrene. The styrene enables the resin to cure from a liquid state into a solid form by crosslinking the chains of the polyester without the evolution of any by-products. They can be moulded without the use of pressure and are regarded as being contact or low pressure resins.



In the presence of a catalyst or initiator (FitzPatrick, 1980) and an accelerator the styrene crosslinks the polymer chains to form a highly complex three dimensional network.



The polyester is then said to be cured. It is now a chemically resistant and hard solid. The crosslinking or curing process is a form of polymerization. Three stages can be observed in the curing process after the catalyst is added.

1. Gel time - period from the addition of catalyst to the setting of the resin to a soft gel
2. Hardening time - period from the setting of the resin to the point when it is hard enough to allow the sample to be removed from the container
3. Maturing time - time require for the block to acquire its full hardness, chemical resistance and stability

A methyl ethyl ketone peroxide was used as the catalyst for the Crystic resin. The cure of a polyester resin will begin as soon as the catalyst is added. The rate of cure is slow at room temperature and the manufacturers recommend the addition of an accelerator (based on a cobalt salt or tertiary amine). The cure reaction is exothermic and the temperature of the resin can rise to 150 °C and higher in an unfilled casting (Scott-Bader, 1980). Therefore it was decided to not add any accelerator so that the volatile thinner (acetone) can evaporate off slowly with minimum disturbance to the soil's structure. This ensures a thoroughly hardened end product.

It also reduces the stresses and strains on gelling to a minimum (Bullock et al., 1982) by decreasing the rapid rise to the exothermic heat peak in the early stages.

When soil sections are viewed under plane and polarized light, it is often impossible to distinguish between some mineral grains, such as quartz, and voids. Various dyes were added to the resin prior to impregnation to assess their potential in marking the voids. A fluorescent dye was found to be the most successful. This will be discussed in greater detail in a later section.

Finally, any medium used must permeate and harden the soil without altering its natural fabric, and for petrological studies it should have, ideally, a refractive index of 1.54 (Dalrymple, 1957, natural filtered Canada balsam - 1.538). Allman and Lawrence (1972, table 11, p.74) have listed refractive indices of various mounting and impregnating materials but at that time the resin used in this research was not on the market. It was decided to assess the refractive index of a mixture of Crystic resin and fluorescent dye using an Abbe Refractometer. The instrument makes use of a standard prism made of a medium high refractive index, in this case dense flint glass. It measures refractive indices of solids and liquids over the range of 1.3 - 1.7. The most important use of the instrument is for the measurement of refractive indices of liquids. The instrument is well documented in standard physics text books (Worsnop and Flint, 1951). The refractive index of the mixture (resin, catalyst and dye) was found to be 1.52 at 24 °C. Araldite, frequently used by geologists for thin sectioning, has a high index of 1.59. Although Crystic resin has a lower index than the required index of 1.54, it is thought to be acceptable for this research especially as the main reason for examining the thin sections is not petrological.

ii. Impregnation technique.

The procedure used was based on the method outlined in one of the Soil Survey´s technical monographs (No.6, Bullock et al., 1982) with some modifications. All the samples were impregnated under the same physical conditions and following the method outlined below fig. 3.1 b) :

1. Place a 2000ml xlon beaker containing a magnetic pellet on to an automatic stirrer.
2. Measure out the required quantities of resin, catalyst, acetone and fluorescent dye (table 3.1)
3. Dissolve the dye in about 20ml of the acetone. Pour the resin into the beaker and start the stirrer. Slowly add the acetone and dye and leave for five minutes or until the dye is throughly mixed with the resin.
4. When the dye is completely dissolved, add the catalyst and leave for another five minutes. Prepare the samples for impregnation.
5. Switch off the stirrer. Transfer some of the resin mixture into a 250ml beaker (it is much easier to manage when pouring the resin). Carefully pour resin down the side of the sample containers until it reaches approximately half way up the sample tubes. Leave the samples stand for 30 minutes to allow the resin to gently move up the soil by natural capillarity action.

Impregnation materials and quantities

	Standard Impregnation	Replenishment	Reimpregnation
Crystic resin	1500ml	2000ml	480ml
Acetone	200ml	---	20ml
Catalyst	11.5ml	14ml	1ml
Accelerator	---	---	0.5ml
Uvitex OB	6g	6g	0.5g

Table 3.1

6. Top up the resin mixture in each container until the level of resin is at least one centimetre above the soil. Transfer all the samples in their containers into a desiccator and leave to stand for another 30 minutes.

7. Place a lid on the desiccator and evacuate with a small vacuum pump for four to five hours. Seal the outlet of the desiccator and then turn off the pump. Leave over-night.

8. Slowly increase the pressure inside the desiccator to room pressure, remove the samples and transfer them to a well ventilated room or preferably a fume cupboard for four to five weeks.

9. During the first week the acetone will slowly evaporate off. It is therefore crucial to keep topping up the resin with a replenishment mixture (table 3.1) to ensure that the level of the resin does not fall below the top of the soil. This would permit the re-entry of air into the soil and lead to poor impregnation. It is also thought to prevent cracks from forming after the block is cut open although the reason is not fully understood ((FitzPatrick, 1980).

10. Leave the samples until the resin has reached the gelling stage then transfer them to an oven at 40 °C for two weeks to allow for hardening.

11. Remove the samples from their containers, checking that they are still adequately numbered and leave them to cool at room temperature for about a week.

Once the samples have attained their maximum hardness the next stage is take a representative slice from each sample and prepare it into a 35 micron thin section.

3.4 Cutting and Grinding

The soil sections were made following standard geological procedures. One modification was that a new chuck with semi-circular holes was used to hold the samples during cutting. This prevented them from rotating while being cut.

The top 1.5 centimetre of each sample was cut off with a diamond wheel on a vertical spindle, general purpose rock cutting machine (Mottacutta) using a water soluble oil as coolant. The tops of the samples were marked with respect to site and orientation with an indelible pen before removing a one centimetre slice from the centre of the soil columns. The remaining sample was labelled and kept in case the initial slice was destroyed in some way and rendered useless. In all cases the slice was cut from a similar position down the tube. The brass casing was still around the impregnated soil column. Therefore, a trim saw was used to cut away the outer ring of superfluous resin and brass casing. One of the stages in preparing a thin section is to adhere the specimen in question to a glass slide. Hence it was necessary to ensure that one side of the soil slice was as flat as possible to promote good adhesion. The unmarked side of the slice was ground smooth with two progressively finer carborundum powders (grade 400 and 600) on two automatic laps. Each sample was ground for exactly one minute with grade 400 and 30 seconds with grade 600. They were then washed and polished on a felt pad with grade 800 aluminium oxide for 30 seconds or until the resin exhibited a glass-like finish. Any scratches or marks in the resin would have led to considerable difficulties when examining the sections microscopically. After polishing the samples were washed and then cleaned ultra-sonically for three minutes. They were finally manually dried and placed into a desiccator with desiccant over night to ensure that they were perfectly dry before the next stage. Damp samples will not adhere to glass slides.

An accelerated mixture of Crystic resin and catalyst was initially used to adhere the polished slices to glass slides but it was found to be most unsuccessful. Numerous slices came off during the removal of the excess soil on the slide. Many developed bubbles beneath them and separated during the final grinding down to the required thickness. In all about a third of a trial run of samples was lost. A cold setting resin based on two fluid epoxy components called Epofix (Struers) was investigated and found to give excellent adhesion. The resin is specially developed for mounting, where low shrinkage and good mechanical properties in the cured state are required. Owing to its low viscosity (550 c.p. at 25 ^{o}C) Epofix is claimed to be able to penetrate all porosities and cracks in a specimen. Also after curing it can be cut, ground, polished and even drilled. To attain the maximum amount of adhesion, irrespective of which resin is used, it was necessary to de-grease all the glass slides with methylated spirits. Epofix was prepared by mixing 16 parts by volume of Epofix resin with two parts by volume of Epofix hardener and stirring the two for at least two minutes. The hardening process begins as soon as the two liquid components are mixed. A small spot of the mixture was placed on the centre of a polished soil slice. A clean glass slide was carefully lowered down onto the soil with a hinged action to prevent air bubbles from being trapped underneath the glass. Once the Epofix had spread over the whole surface of the soil the sample was put aside and the procedure was repeated for every sample. Epofix is quoted as taking about eight hours to harden at 25 ^{o}C, so the samples were left overnight.

The excess soil projecting from the slide was removed with a diamond wheel on a horizontal spindle rock cutting machine (Woco). The glass slides were held in position with a vacuum clamp while the soil was trimmed to approximately 200 microns thick. The sections were ground down further by hand using grade 400 and 600 carborundum on glass plates. Each section was continuously checked with a petrological microscope to ensure even grinding until it was 30 to 35 microns thick and the quartz exhibited first order, pale yellow interference colours. Finally the sections were cleaned and polished with a soft cloth and then transferred into a desiccator to completely dry out. A liquid vinyl cover was sprayed over the sections to protect them in preference to using glass cover slips. It was easier to apply onto the larger sections, it did not impair the visual quality of the sections and it can be removed, unlike cover slips, with xylene if at a later date the sections were require for electron microscope work.

IV PHOTOGRAPHING AND ANALYSING THE SECTIONS

Delgado and Dorronsoro (1983) distinguish two stages in every micromorphometric study. First, the methods used to differentiate the components to be analysed from all other components in the soil and second the technique of measurement itself. The following sections deal with methods used in these two stages and the reasons for adopting them. Randomly selected central areas within each section were photographed. Black and white high contrast photographs were produced and an image analyser was used to facilitate quantification of the soil to void ratio.

4.1 Differentiating the Voids

The next stage in the procedure was to extract the relevant information from the thin sections concerning their micro-structure. The sections were examined with a petrological microscope and it was found that quantification of the voidage by direct microscopic examination (point counts and other such techniques) was not only very tedious but also prone to error due to the large sample size. It was decided to take photographs of the sections and then use an automated procedure for analysing them. Thereby, minimizing the error from human fatigue.

A major problem arose when trying to photograph thin sections because of the difficulty in separating individual components for measurement. In normal transmitted light both voids and quartz appear transparent. In cross polarized light any minerals at extinction and voids appeared black. Also, because of the anisotropic nature of some mineral grains, such as quartz, not all grains are at extinction at the same time. Accurate image analysis depends on achieving a sufficient contrast between the voids and the rest of the soil matrix. Various techniques have been developed to overcome this problem and these will now be briefly discussed.

i. Use of dyes

Various dyes have been added to the resin before impregnation of the samples. Jongerius et al. (1972, p.247) added a green organic stain (BS 1172) to the resin. On polished surfaces or in thin sections of samples treated with this dye, voids appeared dark on a light coloured background (the soil mass) when incident dark field illumination was used. Jongerius felt that the method was not sufficiently accurate in the preparation of silty and sandy soils. Various coloured dyes were investigated for this research but many showed differential adsorption properties. A red dye (Sudan IV, Gurr, 1981, p.20) coloured everything from resin in the voids to organic matter and even some quartz, making it impossible to clearly distinguish the voids from the rest of the soil matrix. An orange dye (Sudan II, Gurr, 1981, p.18) was very patchy perhaps because of its poor solubility in alcohol. A blue dye (Sudan blue, Gurr, 1981, p.24) initially seemed successful until microscopic examination showed the colour to be made up of tiny spots. Fluorescent dyes have been used successfully for void detection (FitzPatrick, 1970; Murphy, Bullock and Turner, 1977). It must be remembered that fluorescent dyes are adsorbed by organic matter. Ismail (1975) recommended that they are best used for void detection in preparation of mineral soil materials. The soil collected in this research was very sterile and composed mainly of quartz grains with very little organic matter. Uvitex OB (Ciba-Geigy) a fluorescent whitening agent was added to the resin before impregnating some of the soil samples from the pilot site (Ockham Common) and it was found to give excellent results. The dye dissolved readily into acetone and then mixed evenly into the resin. Microscopic examination of the subsequent thin sections showed that the dye was evenly adsorbed and it was decided to add this dye to the resin prior to impregnation.

Uvitex OB is a yellowish-green powder which has a melting point of 200 to 201°C. It is a high purity fluorescent whitening agent which is particularly suitable for the optical brightening of polymers at all stages of the process. It has good light fastness, excellent heat resistance, a high tolerance to chemicals and it is readily soluble in a wide range of solvents. For instance, its solubility in acetone at 25°C is 0.5 g/100ml.

ii. Photographic techniques

One of the simplest photographic methods was employed by Murphy, Bullock and Turner (1977) using high contrast developing. Photographic prints were produced by placing thin sections directly into the enlarger. The section is then treated as if it were a negative and enlarged down onto high contrast paper. Care had to be taken to ensure that the correct exposure was used. Over exposure would have resulted in over estimation of the voids because some mineral grains would appear as voids. Likewise, under exposure would have meant that many of the smaller voids would have gone undetected. Murphy *et al.* (1977) found that the most suitable prints were obtained by slightly under exposing. It was necessary to compare the print with the original sample to check for odd quartz grains which had appeared as voids. When this was found to have happened the area was simply inked in. It is felt that this latter stage is highly subjective and open to error. The technique is recommended for studying voids larger than 150 microns in diameter. This research is also interested in voids smaller than 150 microns, therefore it was decided to concentrate on photomicroscopy techniques.

Jongerius et al.(1972) developed a method of void detection by means of porosity photograms of the thin sections. The method was discussed by Ismail (1975) and described as a photographic overlay technique for soils containing mineral grains. The pictures were produced at a two times magnification on Polaroid P/N film (4 x 5 inches). The thin sections were placed on a Zeiss 'Makrotisch' (macro-stage) in which there were polaroid filters. The crossed polarised filters were turned during exposure to a locked position in steps of 10° over a total of 50°. On the polaroid negative the anisotropic transparent minerals were black; ferruginous or humose clayey ground mass was grey and opaque minerals, organic matter and voids were transparent and came out white. The procedure was repeated in transmitted light. The second polaroid negative was exactly the same as the first the only difference being that the voids were now black. A positive transparency was made from the second negative and overlain over the first negative. When a final print was then made from these two, only the voids appeared black (table 4.1). The technique produced some reliable results but the method suffers from procedural errors during the overlay process.

Photographic overlay technique (after Jongerius _et al._, 1972)

	1st negative		2nd. positive		final print
transparent anisotropic minerals	black	+	black	=	black
plant fragments	transparent	+	black	=	black
opaque minerals	transparent	+	black	=	blank
fine ground mass	grey	+	grey	=	grey
voids	transparent	+	transparent	=	transparent

Table 4.1

In the early 1970's the use of two quarter-wave mica plates in the microscope was developed. Pape (1974) used them to convert linearly polarized light to circularly or elliptically polarized forms. Ruark, Veneman and Waldron (1982) developed the principle of circular polarization on soil thin sections to distinguish voids from mineral grains. They obtained cross polarization by rotating the analyser until there was maximum extinction of the transmitted coloured light. The quarter-wave plates were then rotated so that their axes were precisely 90 degrees to each other. Voids in the thin sections appeared completely black while mineral grains emerged coloured. Thirty three soil thin sections were all photographed under crossed and circular polarized light. Their findings showed a significant reduction in void area which was most pronounced in the 64-320 microns void size category when the latter method was used. They concluded that the application of crossed polarized light to soil thin sections resulted in images that over estimated the void area due to the extinction of a small percentage of anisotropic mineral grains in the slide which had their optical axes exactly parallel to the plane of polarized light. And they felt that :

> " ...circular polarized light is a viable means of eliminating extinction of anisotropic mineral grains when examining thin sections of soil for various void parameters."

The latter method produced reliable results without the need of the complicated overlay process of Jongerius, which increased the risk of procedural errors.

Ruark et al. (1982) described in great detail the construction of the circular polarization system from wood; PVC pipe (10 centimetres diameter); a green filter; plastic polarizing sheet;

two quarter-wave plates and a single lens reflex camera equipped with polarizing filter. The main concern was that it was mandatory to achieve correct alignment of the optical components. FitzPatrick (1980) has stressed that when considering microphotography :

> " ... the optics of the microscope must be of a high standard. Whereas somewhat poor optics may suffice during visual examinations, when unevenness of focus may not be a serious handicap, it is essential to have an absolutely flat field and even illumination for photography."

This research investigates changes in soil micro-density from photographs of soil thin sections taken at quite high magnification, so the method of using sections as negatives and enlarging them on to high contrast paper was eliminated because it is for voids greater than 150 microns. It has been clearly demonstrated that photographing under crossed nicols will lead to errors in the estimates of void areas. The method of Ruark et al. (1982) using circular polarized light was choosen as being the most accurate way to produce photographs of thin sections but the equipment used was not felt to be of a high enough standard to allow the production of quality photographs. Phase contrast microscopes, widely used by biological sciences, are based on a principle which uses two quarter-wave plates. One such microscope was available for the research. It had transmitted and ultra violet light sources, a Zeiss camera and necessary filters already built into the one structure. It was therefore decided to use a combination of techniques namely fluorescent dye in the resin so that void area would fluoresce under ultra violet light but also photograph under phase contrast conditions. The method has produced excellent, high contrast black and white photographs. The essential principles behind phase contrast will now be discussed in further detail.

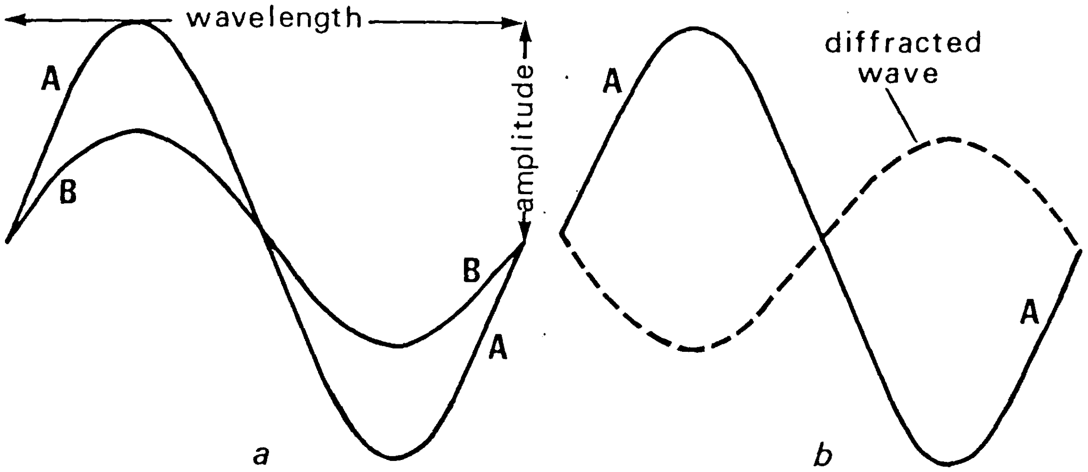
4.2 Phase Contrast

Most living cells are virtually transparent. To overcome this problem Zernike (1934) developed a process called the ′phase-strip method for observing phase objects in good contrast′ or phase contrast for short (Zernike, 1955; Zeiss, 1936; Kohler and Loos, 1941). This formed the basis of phase contrast microscopy (Pluta, 1975). The procedure is to convert phase changes into amplitude changes which are visible to the human eye. The method is now in widespread use particularly for the examination of delicate living structures, enabling objects which are almost transparent to be observed clearly and their details revealed often in sharp contrast without staining or interference with their delicate structure. There is very little evidence for the use of these methods in the study of rock and soil thin sections.

Biological specimens transparent to the human eye, because they do not change the intensity or amplitude of light passing through them, do change the phase of the light waves relative to the general illumination but the human eye is not sensitive to these changes. These specimens are made visible by phase contrast techniques. It is difficult to give a rigorous explanation of phase contrast without elaborate mathematics (Barer, 1956). Consider light passing through two contrasting objects (fig. 4.1), the first partially absorbing and the second completely transparent. In both cases curve A represents the incident wave falling onto the object and curve B the emerging wave. The intensity of the light is proportional to the square of the amplitude of the wave. When light passes through a partially absorbing object the intensity is reduced and amplitude lowered (fig. 4.1 a). The emerging wave can also be

Optical Transparency

Partially absorbing



Transparent

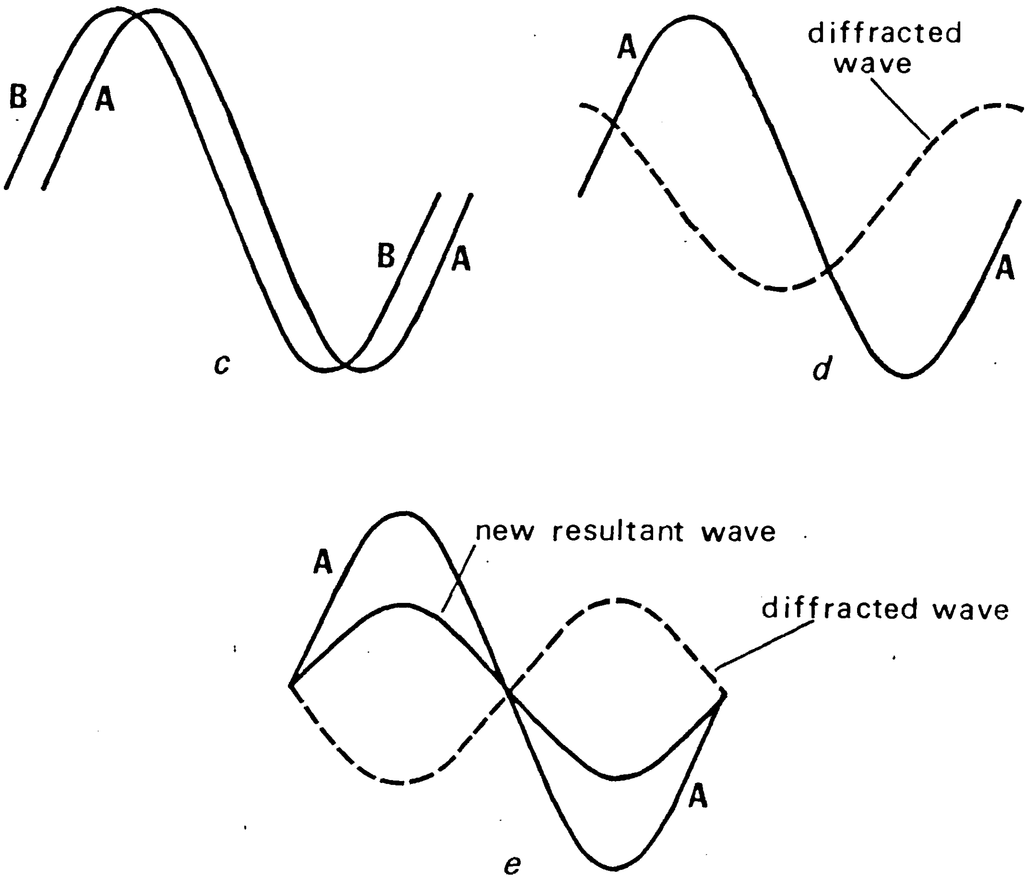
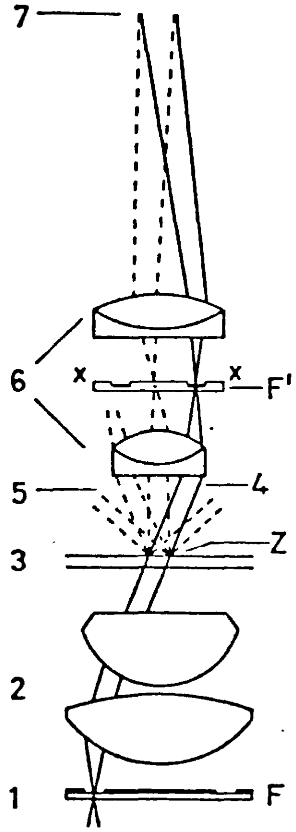


fig. 4.1

viewed as the sum of the original incident wave and the diffracted wave (fig. 4.1 b). These two waves when added together will result in a wave similar to B. When light passes through a transparent object (such as quartz) no energy is lost, so the amplitude is not altered. Nevertheless, due to the refractile properties of the object, the transmitted wave will either be advanced or retarded in phase relative to the incident wave (fig. 4.1 c). Once again, the emerging wave can be represented as the sum of the incident wave and the diffracted wave (fig. 4.1 d). There is an important difference between the two diffracted waves which is fundamental to the principle of phase contrast. In the case of an absorbing object the diffracted wave is exactly half a wavelength (180^0) out of phase with the incident wave. A wave diffracted by a transparent object is out of phase with the incident wave by a variable amount - it depends on the refractile properties of the object in question. For a weakly refractile object, the wave is diffracted by approximately quarter of a wavelength. Here is the essential feature of the technique. By means of an optical device the phase difference between the diffracted and incident wave is increased from about 90^0 to 180^0, so that the two waves cancel each other out as far as possible. Crests of the diffracted wave correspond to troughs of the incident wave (fig. 4.1 e). The sum of the incident wave and the altered diffracted wave is a resultant wave B similar to that in (a). To the eye and the photographic plate an otherwise transparent object would appear to be a partially absorbing one.

The phase contrast microscope is very similar to the normal petrological microscope (fig. 4.2). A diaphragm with an annular aperture is mounted in the anterior focal plane (F) of the substage condenser so that the slide is illuminated by a hollow cone of light. The direct image of this bright annulus is formed by the objective in the back focal plane (F′) together with the diffraction images (due to the structure in the objective) which are displaced from the optic axis. In the plane F′ is placed the phase plate (x--x) which carries another annulus exactly matching the dimensions of the direct (or zero order) image of the condenser annulus. This plate is designed to introduce a phase difference of a quarter of a wavelength of green light between the beam which is directly transmitted, and the light diffracted by the object and passing through the entire area of the back aperture of the objective not covered by the annulus. Separated wave trains originating from the same point (coherent waves) when recombined interfere to produce maximum darkness (destructive or subtractive interference) when they differ in phase by half a wavelength. The nearer the difference approaches this value, the greater the effect becomes. Consequently, when the phase difference is zero, two such waves combine to give maximum brightness (constructive or additive interference). It has been found that for the great majority of colourless objects examined by the microscope a phase plate which adds a phase difference of quarter of a wavelength, to that which already exists by virtue of the action of the object, will produce the maximum effect. According to the design of the phase plate, destructive or constructive interference effects can be introduced. If the former, then a particular object with a refractive index higher than its surroundings will appear dark on light. If the latter, then an object will appear light on dark. In terms of the phase plate if the annulus (x--x) accelerates the wave by quarter of a wavelength such a object will appear dark (positive contrast) and if the plate retards the light the object will be bright (negative



1. Annular diaphragm.
2. Condenser
3. Object plane
4. Direct light
5. Diffracted orders
6. Objective with phase plate
7. Image plane (eyepiece omitted)

F: anterior focal plane of the condenser
z: object
F': posterior focal plane of the objective
x–x: phase plate (positive form)

Basic Lay Out of a Phase Contrast Microscope

(after A. L. E. Barron)

fig. 4.2

contrast).

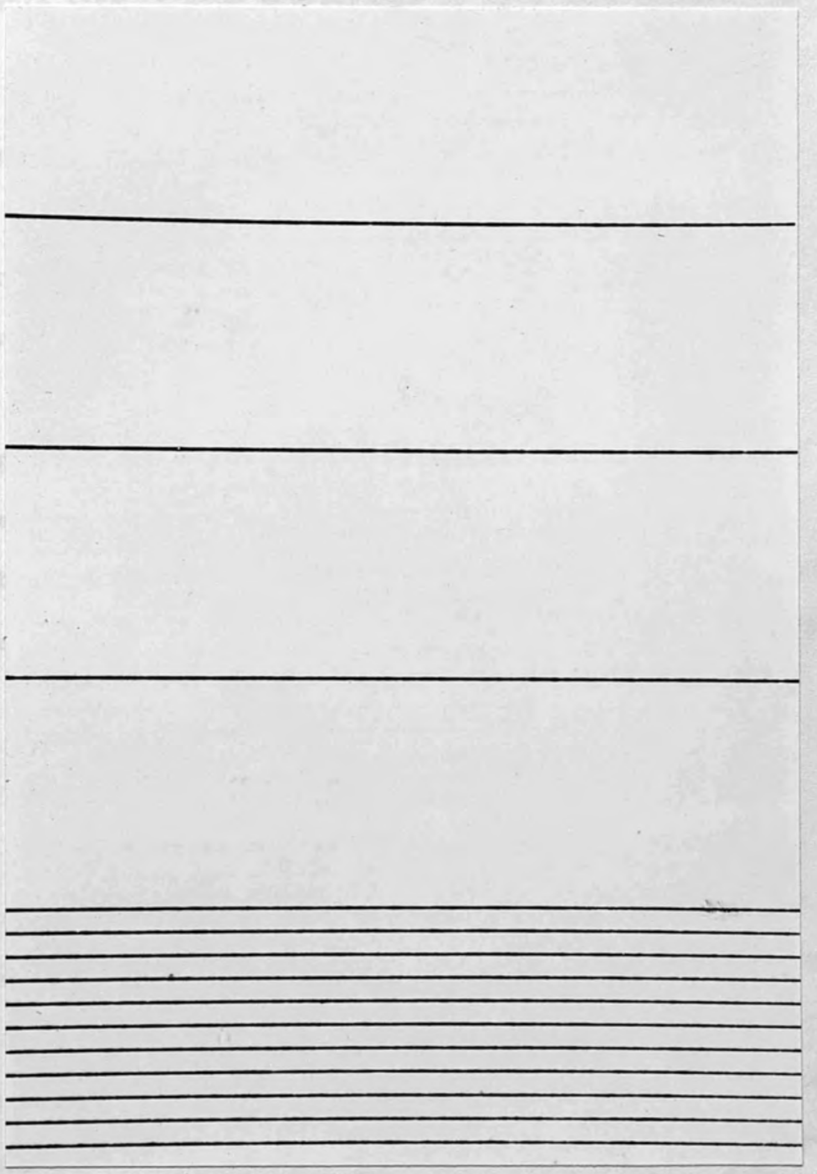
The method has distinct advantages when used on transparent objects but less satisfactory images result when it is used on objects which predominately vary the amplitude and not the phase of the transmitted light. Therefore, phase contrast does not help in the examination of light absorbing material, such as well stained specimens, although it may benefit the examination of faintly stained objects. All the thin sections to be used in the research contained a fluorescent dye. This did not seem to impair the final results as perhaps would a coloured dye or stain.

4.3 Sampling

To calculate the minimum number of photographs needed to represent each thin section to a specified acceptable level of accuracy a slide was chosen at random and the central area photographed 36 times. Each print was then analysed to assess the percentage of the total area photographed which were voids. A simple statistical procedure, based on the Student's t distribution, was followed to calculate the required sample size (Silk, 1979, p.163) :

$$\text{sample size} = \left[\frac{t_{n-1,\alpha/2} \times s}{e} \right]^2$$

Where s is an estimate of the standard deviation of the population of measurements and e is the maximum tolerable sampling error. To simplify the arithmetic, the initial t value is set at two and the



Scale Lines - magnified x320

plate 4.1

sample size is then calculated. A new t value (d.f. = n-1) can now be replaced in the above equation and the procedure is repeated until the sample size value levels out. For calculating the percentage voids of a thin section from black and white photographs, the ideal sample size is nine photographs of each thin section (appendix B. 1).

A graduated slide with 10μm and 100μm intervals was also photographed developed and enlarged in exactly the same way as all other photographs. The subsequent print enabled the total magnification, not only due to the microscope but also the photographic treatment, to be accurately calculated (plate 4.1). The final magnification is estimated to be times 320. Therefore each print represents and area of 515μm by 365μm of the thin section. A few voids larger than 500 μm were found in some sections but this research limited itself to quantifying voids less than 500 μm.

Various size classifications have been suggested (table 4.2) but there is no universally accepted system. Jongerius (1963). devised the simplest classification but it fails in having too low a cut-off for macropores. Johnson , (1980) overcame this problem by introducing an additional two classes but they changed the nomenclature in the procedure. Brewer (1964) also revised the size classes making more divisions within the smaller sizes but he termed a macrovoid or pore as anything greater than 75μm. FitzPatrick (1980) proposed a classification which is suitable for classifying not only pores but also other features in the soil such as detrital grains, organic materials and faecal remains. The classes range from the very small (<2μm) up to very large sizes (> 10 mm). This

Void size classifications

Jongerius(1957)	Johnson et al(1960)	Brewer (1964)	FitzPatrick(1980)
micropores < 30μm	micro < 75μm	crypto < 0.1μm	micro < 2μm
mesopores 30 - 100μm	very fine 75μm - 1 mm	ultramicro < 5μm	very small 2 - 60μm
macropores > 100μm	fine 1 - 2 mm	micro 5 - 30μm	small 60 - 200μm
	medium 2 - 5 mm	meso 30 - 75μm	medium 200μm - 2 mm
	coarse > 5 mm	macro > 75μm	large 2 - 10 mm
			very large > 10 mm

Table 4·2

system was adopted in the research. Hence the pores being quantified range from medium to very small.

4.4 Photographing and Printing

i. Photographic procedure.

The use of a phase contrast microscope has implications for the type of film used in order to maximize the contrast between the voids and the rest of the soil, retaining only the particle outlines. The best contrast was obtained by using an ultra violet filter and light source. The voids, filled with resin and the dye, fluoresced strongly and appeared bright blue while mineral grains, organic matter and the rest of the soil matrix appeared black. Ilford FP 4 and Pan F and Eastman Fine Grained Positive (blue sensitive) films were investigated. The two Ilford films produced very thin negatives and subsequently poor photographs while the Eastman film resulted in excellent high contrast photographs.

Photographing was limited to the central area of the slide to avoid the peripheral areas that may have been disturbed by the tube edges. Initially six areas were photographed. They were randomly chosen by slowly moving the stage in any direction but always staying within the central area. Two decisions were possible; whether or not to take a photograph where the objective came to rest. There were two occasions when it was decided not to take a photograph. If the objective was filled by a large mineral grain or void the ´scene´ was rejected. This occurred only seven times in 1450 photographs.

ii. Developing the prints.

To ensure consistency throughout the developing stages and considering the large number of high contrast black and white photographs to be produced all developing was done manually by the researcher. Each stage of the process was tried and tested before the main negatives were developed and printed. The Eastman film was developed in PQ Universal (dilution of 1:4) for 19 minutes. It was fixed (dilution of 1:4) for twice the clearing time which was about 40 seconds before being washed in clean running water for 20 minutes. All negatives were printed on Ilfospeed Multigrade II (12.7 x 17.8 centimetres) glossy, medium weight paper to produce a ′deeper black′ print compared with the matt equivalent. All prints were exposed for nine seconds at F4, using filter 7 to give maximum contrast. Prints were developed in a standard paper developer (dilution of 1:4) for one minute; dipped quickly into a stop bath; placed into fresh fix (dilution of 1:7) for 30 seconds and finally washed in clean running water for 15 to 20 minutes. The paper developer was changed after every 50 prints and the fix after every 100. Each potential print was numbered in pencil as soon as it had been exposured. When it had been dried it was re-numbered in indelible ink. Some photographs were exposed for twice the original time. These were photographs which had a lot of organic matter in them. Closer inspection of the negatives showed these areas to be dark grey and not black. The extra exposure time overcame this problem. Prints were stored until complete sets were ready for analysis.

4.5 Analysis of the Photographs

The second stage in a micromorphometric study is the technique of measurement. Picture or image processing, pattern recognition and scene analysis are some of the terms used to describe methods of extracting information from (usually) two dimensionally distributed data (Fabbri, 1984). The image can be derived from thin sections, polished blocks and drawings. Images can be then produced directly through a television camera, through a microscope or via photographs. In this research, the soil:void ratio was quantified from photographs using a procedure with a high degree of replicability and automation. Various workers have summarized the early conventional micromorphometric methods as a necessary background to the more recent advances (Ismail, 1975, p.8-11; Delgado and Dorronsoro, 1983, p.72). The most conventional methods, as suggested by Delgado and Dorronsoro (1983), are :

1. Line measurement. Measuring the lengths of components by moving the sample relative to parallel lines (Redlich, 1940; Swanson and Peterson, 1942; Kubiëna, 1943).

2. Point counting. A grid is placed over the image and components or features situated at numerous points are measured. Also, components under the eyepiece cross-hair are counted during vertical and horizontal traverses of a section (Jongerius, 1963; Swietochowski and Jablonski, 1964).

3. Drawing and weighing. Drawings of the components are made on paper of constant density. Selected ones are then carefully cut out and weighed (Kubiëna, 1961; Buol and Hole, 1961; Gadgil, 1963).

4. Planimetry. This is similar to the latter method but the selected components are measured using a planimeter (Kubiena <u>et al.</u>, 1962a; Guardiola and Delgado, 1969).

5. Photometry. A photograph with the selected components already clearly distinguished is used. These components are measured using a photo-electric cell (Kubiëna <u>et al.</u>, 1963; Beckmann and Geyger, 1967; Kubiëna, 1967).

6. Particle-size analyser (Zeiss TGZ3). A circle of light of variable diameter is altered by a diaphragm to be equal to the width of each component to be measured. The measurements are automatically recorded by 49 counters each corresponding to a set width (Kubiëna <u>et al.</u>, 1963; Jongerius and Jager, 1964; Bouma, 1969; Palan, 1972)

Several optical methods were considered for extraction of information from the black and white photographs produced in this research. Initially a digitizer was used to trace around the void areas but the digitizer was a small bench top model and instrumental error was such that often a reading was produced before a circuit around an area was complete; it was particularly inaccurate when tracing around small voids. This led to an underestimation of the percentage voids. The technique was also highly prone to human error. With increasing time from the start of a batch there was an increasing tendency to become fatigued.

Jongerius' (1963) photogram analyses were investigated including the TGZ3 and the grade of blackness method (Kubiëna <u>et al.</u>, 1963) but both would be very slow and laborious to use given the larger size required in this research. Delgado and Dorronsoro (1983) point out that the ideal procedure should be rapid, accurate and based on area measurements. They feel that the technique comes quite near to the ideal with Television Image Analysis Systems (TVIAS) in which an image is displayed via a television camera onto a monitor, from here it is transformed into an electrical impulse in a detector module. The instrument is then set to detect a particular grey level, corresponding to the component of interest, and the level relates to the strength of the signal. After the setting has been made the image signal is analysed in the computer. Delgado and Dorronsoro (1983) used the Zeiss Micro-Videomat but this research dealt with a similar system called a Quantimet.

In the early 1970's a sophisticated point counter, the Quantimet, was established as being the major break-through in rapid quantification of soil structure. Early models were large in size and inflexible in their ability to perform other tasks but subsequent improvements in technology has enabled the Quantimet to become a far more compact and versatile machine. The principles of the Quantimet 720 are discussed in detail in a number of papers, in particular Fisher (1971) and the Imanco Operating Manual (1971). A Quantimet 720 consists of two main parts. The first is either a microscope or an epidiascope. The second consists of a scanner; system control module; standard detector module and computer module; variable frame and scale module and finally a display monitor. An optical image is formed directly from thin sections or photographs using the microscope or epidiascope respectively. The image is scanned by a 720-line plumbion scanner 10.5 times per second. Each line contains 910 picture points thus making a total of 655,200 picture points per frame. The output is relayed to a detector where components can be selected measurements according to their common grey level characteristics. Grey level limits are variable and components which have different grey values to their surroundings can be discriminated and detected. When the computer has detected the required components a number of features can be measured such as area (A); perimeter (P); horizontal intercept (I); number (N); end count (Nec); full feature count (Nff) and Feret´s diameter. A ´sizer´ allows the parameters to be submitted to chord size criteria.

Various researchers have adapted their techniques to include the use of a Quantimet in the study of soil structure characteristics from thin sections and photographs (Jongerius et al, 1972a; Ismail, 1975; Murphy et al., 1977a,b). The Soil Survey, Rothamsted, machine was considered but it provides a higher level of information than is required here which is simply the percentage of white areas (voids) in the photographs. An image analyser, working on the same principles as the Quantimet but at a simpler level, was chosen to extract the relevant information.

4.6 Image Analysis

The photographs were all digitized, to facilitate rapid quantification of soil structure characteristics, using the Image Analysing System belonging to the Pattern Recognition Group, Physics Department, Royal Holloway College. Light energy is converted into electrical impulses. An object, picture or photograph is placed under a television camera and the resulting electrical signals are relayed to a frame store where they are digitized and stored. The subsequent image is scanned in a raster of 128 horizontal active lines. Each line is digitized into 128 picture points or pixels : these are approximately square and are contiguous in the horizontal and vertical directions. Thus each image is sub-divided into a total 16,704 pixels. The intensity of each pixel depends on the grey value of the original image. A white point will have an intensity value of 63 while a black point will have an intensity value of 0 hence there are 64 grey levels per pixel. These can be manually thresholded into a two level binary picture under software control with the aid of a joystick. A PDP-11/34 DEC computer has access to the stored information via a computer interface.

After numerous trial runs and the development of a program by Dr. E.R. Davies (appendix F) which permitted the efficient use of operator time the procedure for analysing the photographs was as follows :-

1. A photograph was precisely placed between two cardboard guides beneath a television camera and lit with even illumination from a 100 watt spotlight bulb. Non-reflective glass was used to keep the photograph flat and to eliminate glare from the glossy paper.

2. The computer program was started and the photograph was scanned, digitized and stored in the frame store.

3. A threshold was set to produce a two level binary picture which was felt to represent the original photograph with resonable accuracy. The total area higher than the threshold value (ie. the sum of the white corresponding to voids) could then be measured.

4. The binary picture was limited in size (14,384 pixels) so that only pixels covering the photograph were quantified. This total area was then kept constant throughout the analysis.

5. Once the borders were fixed the computer processed the digitized picture and printed out the results as a percentage of the total area.

To ensure replicability the first photograph was used throughout as a standard. It was re-processed every six photographs to check that the threshold value was still the same. This was necessary to take account of the changing daylight conditions during the day. It was thought that this procedure was preferable to standardizing all the results at the end because small changes, that otherwise would have been overlooked, could be monitored and the results adjusted accordingly.

The accuracy of the results is influenced by a number of parameters. External errors from changing light conditions were monitored as far as possible and adjustments were made. The whole setup was carefully noted and measured so that results could be reproduced exactly within the limits of experimental error. Instrumental error, for instance noise from current variations of the electronic system, was estimated to be about 0.1 percent. Care must be taken to avoid errors from poor resolution associated with some television cameras and their signal. Some cameras can produce geometric distortions of the image because of the method of scanning, the level of magnification and the position of the component on the screen. Dorronsoro et al. (1978) found that measurement was most accurate when the object was placed in the centre of the screen and maximum error occurred at the edges. Photographs were always placed in the centre of the screen and then a border was placed around the area to be quantified. This avoided measurements in the peripheral area of the screen. Also, hard copies of a number of the pre-digitized pictures were taken to assess the accuracy of the television camera. A simple point count exercise was performed on the hard copies and their corresponding photographs. A 10 by 15 grid was placed over each one in turn. It was noted every time a grid corner lay on a white area and percentages were calculated. It was found that percentages from the camera pictures were comparable with the photographs, to an accuracy of one percent.

It was necessary to check the results to ensure that the image processing was giving realistic answers. 41 photographs were choosen at random and the percentage voidage calculated from point counts (16 x 16 grid). The percentages estimated by the image processor were then compared to the point count percentages by plotting them on a graph. The corresponding correlation coefficient was found to be 0.98 and is significant at the 99.99% level (appendix B.2). Bearing in mind possible sources of errors and the alternative methods it was concluded that the automated procedure used in this study, to extract relevant information from the photographs, gave results with the required standard of accuracy and replicability.

V Results

The following chapter considers the results and their implications for Culling's theory. The percentage voidage values are plotted on scaled plan drawings and generalised by using mean values perpendicular to a line drawn through the centre of the post in the direction of maximum slope. They are represented by three dimensional block diagrams and finally expressed as trend surfaces.

To recapitulate, soil samples were taken from around two posts, one a sloping site - Oberon Glade and the other a flat site - Thursley Common. The percentage of voids was estimated from nine black and white photographs of soil thin sections. The aim is to investigate the predicted density pattern around an obstacle, as suggested by Culling (1981) and use empirical data to assess whether or not there is any field evidence to support his theory. The complete set of results is listed in appendix A but for the following discussion the mean of the nine photographs for each sample is used (tables 5.1 to 5.4). Most of the results are presented in groups according to their distance along a line drawn perpendicularly from a tangent at the post's circumference, in the direction of maximum slope (plate 2.8 and 2.9). The remaining results (Thursley Common - west) were from samples taken at distances drawn radially from the circumference (plate 2.9). The final column in the tables gives the mean value for each distance and these are the values which have been plotted at right angles to the post. The cross-sections give the general picture of the changing soil density on either side of the posts.

OBERON GLADE

distance(cm) from post	upslope									mean
41.0	15.6	15.9	21.7	15.0	18.6	16.8				17.3
33.0	14.3	14.9	16.5	16.8						15.6
23.0	16.2	14.6	12.7	15.1	12.4					14.2
17.0	12.2	12.7	13.2							12.7
10.0	13.0	10.7	11.7	12.0	11.6	9.6	10.1	7.2	9.4	9.2

Table 5.1

distance(cm) from post	downslope									mean
35.0	16.0	18.6	15.2	21.8	17.4	20.3	18.9	17.4		18.2
28.0	18.2	18.9	21.7	13.0	17.1	13.6	13.3			16.5
20.5	14.4	13.3	15.7	13.8	12.0	13.6	12.1			13.6
13.0	10.9	13.7	11.0	16.0	15.4	12.2				13.2
6.5	13.9	13.1	12.7	12.5	12.3	10.9	12.6	10.2	10.9	12.2

Table 5.2

THURSLEY COMMON

distance(cm) from post	west									mean
41 - 34	25.3	25.6	28.7	25.6	27.6	27.6				26.7
33 - 26	28.0	28.8	20.0	18.4	23.0	22.2	21.6	26.2		23.5
25 - 17	27.3	21.4	23.3	25.2	26.1	24.6	27.7	24.8	23.4	24.9
16 - 12	28.1	25.4	26.8	26.2	31.5	25.9	25.4	29.2		27.3
11 - 7	25.8	26.2	28.8	31.9	24.9	28.0	24.9			27.2
< 6	22.6	26.3	28.9	27.8	30.7	27.7	31.1	23.7		27.3

Table 5.3

distance(cm) from post	east								mean
44.0	22.5	23.6	23.8	28.7	28.3				25.4
36.0	24.4	23.6	22.6	27.1	24.7				24.5
29.5	22.3	24.4	22.2	23.7	20.8	22.2	25.4		23.0
20.0	24.9	28.4	28.3	30.2					27.9
14.5	23.6	26.5	22.5	23.2	25.0	24.3			24.2
6.0	24.0	29.9	27.6	21.9	23.3	17.6	19.7	23.6	23.5

Table 5.4

5.1 Plotting Mean Values at Right Angles to the Drift Direction

At Oberon Glade, both the up-slope and down-slope results show a definite trend of decreasing soil voidage towards the post (fig. 5.1). On the up-slope the values range from 17.3 percent at 41 centimetres away from the post to 9.2 percent adjacent to the post. On the down-slope side the values range from 18.2 percent at 35 centimetres from the post to 12.2 percent when adjacent to the post (table 5.1 and 5.2). The results from the flat site at Thursley Common do not show such a trend (fig. 5.2). On the east side the values range from 25.4 percent at 44 centimetres away from the post to 23.5 percent when six centimetres away. On the west side the values range from 26.7 percent at 41 centimtres away from the post to 27.3 percent adjacent with the post (table 5.3 and 5.4). See appendix H for a selection of the photographs.

i. Testing the significance of the difference.

The Kruskal-Wallis test, analysis of variance by ranking, was used, to test for the significance of the difference between plotted values within each site. The K-W test provides a non-parametric or distribution-free equivalent to the parametric F test for the Analysis of Variance (Silk, 1979, p.192). It is assumed that ordinal or ranked data are available in random sampling from three or more populations. When there are at least three groups, the null hypothesis holds that there is no difference between the three group distributions. If there are three or more groups ($k \geqslant 3$) with at least five observations in each then the value of H follows a χ^2 distribution with (k-1) degrees of freedom, where k is the number of groups. Each set of results was independently ranked assigning one

Mean percentage voidage results - Oberon Glade

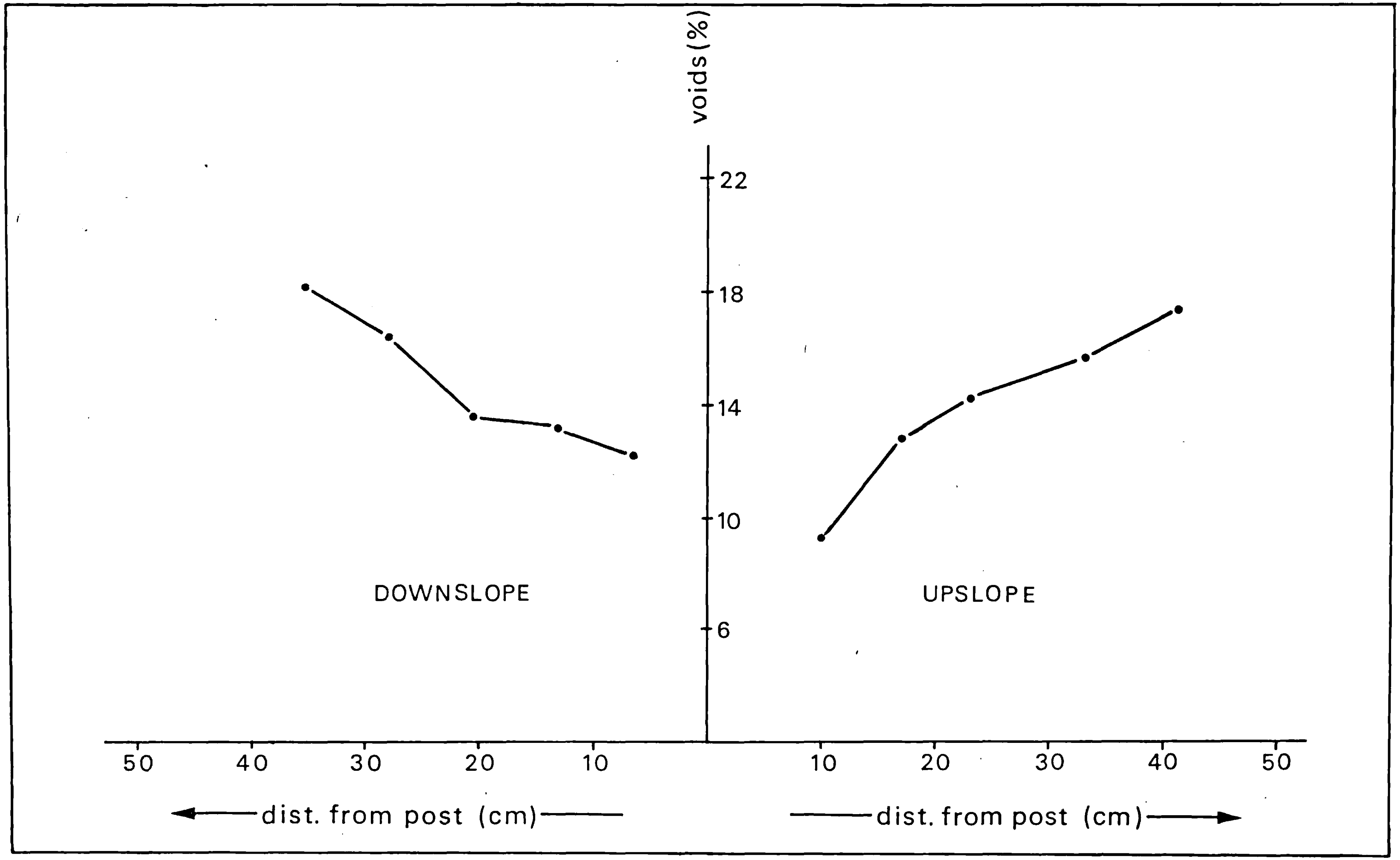


fig. 5.1

Mean percentage voidage results - Thursley Common

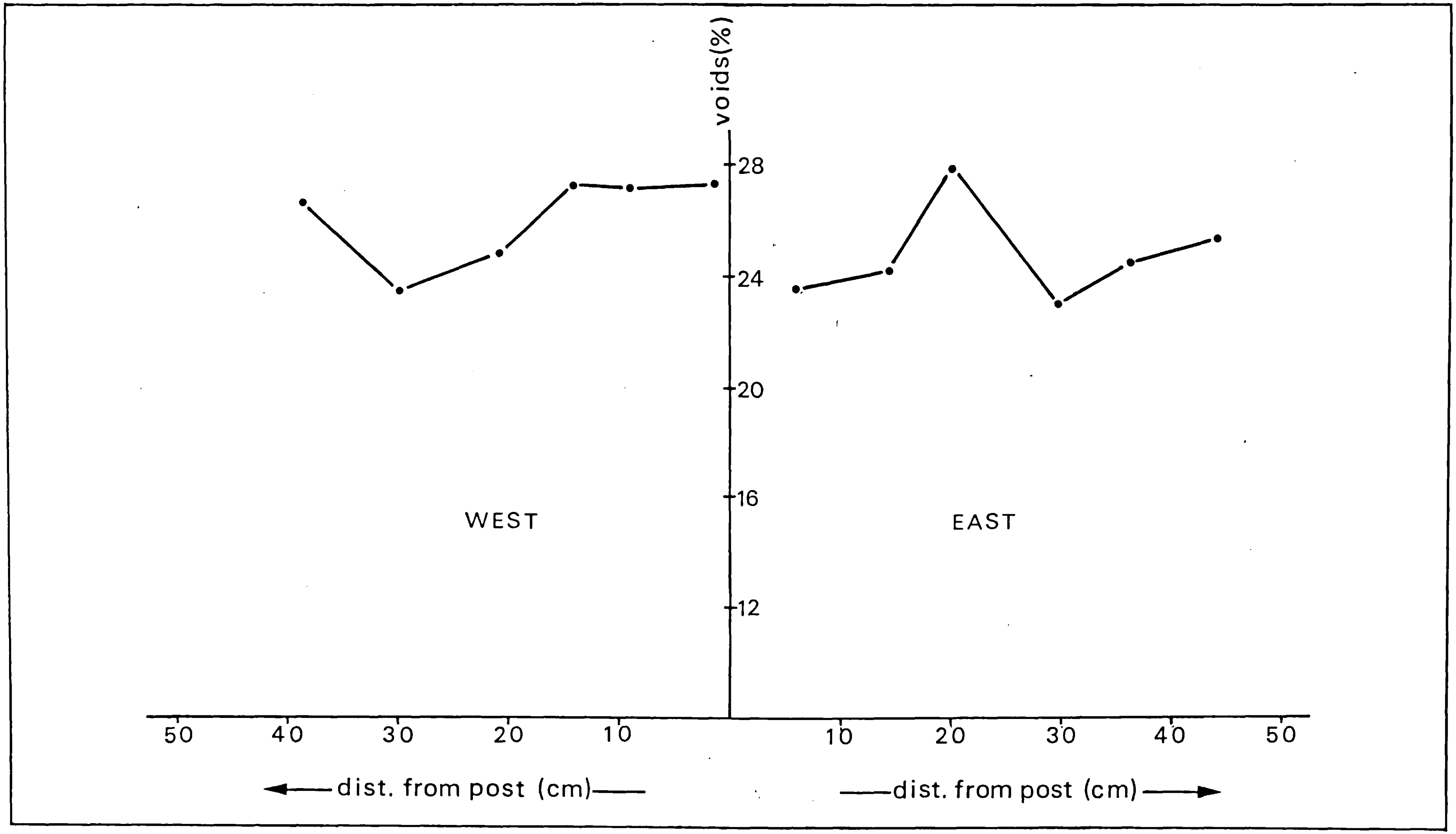


fig. 5.2

to the lowest value, two to the second lowest value and so on. Kruskal-Wallis H values were calculated and compared to critical H values (table 5.5).

Oberon Glade - the calculated H value for both up-slope and down-slope results is greater than the critical value at the 99 percent confidence level and the null hypothesis is rejected. Therefore, there is a highly significant difference between the five sets of up-slope results and between the five sets of down-slope results.

Thursley Common - the calculated H value for both the east and west side results is not greater than the critical value at the 95 percent confidence level and the null hypothesis is accepted. Therefore there is no significant difference between the six sets of results on the east side and between the six sets of results on the west side.

ii. Comparing plotted values with predicted curves.

Thursley Common was chosen as a control site (flat) because the theory predicts that if soil movement is random and diffusive in nature there should be no evidence of systematic patterning around an obstacle on flat land. Initial inspection of the Thursley Common results supports this argument. There was no systematic patterning found and therefore it was the intention to compare only the results from Oberon Glade with the predicted curves. The predictions from the theory are expressed in terms of concentration or density and to assist comparison the empirical values have been transformed by subtracting the voidage from unity and then expressing as a ratio of the background density level (table 5.6). The mean of the values

Sloping (OG)		Flat (TC)	
up slope	down slope	west	east
16.3	17.0	10.2	9.5
(9.49)	(9.49)	(11.07)	(11.07)

critical H value ($p = 0.05$) in brackets

Table 5.5

Kruskal-Wallis H values

furthest away from the post (55 centimetres), on the up-slope side, was taken as being the general background value.

up-slope			down-slope		
cm from post	% soil	density	cm from post	% soil	density
55	81.3	1.000			
41	82.7	1.017	35	81.8	1.006
33	84.4	1.038	28	83.5	1.027
23	85.8	1.055	20.5	86.4	1.063
17	87.3	1.074	13	86.8	1.068
10	90.8	1.117	6.5	87.8	1.080

Table 5.6

The equation used to calculate the predicted curves is outlined in appendix C. The curves show the concentration of particles around a cylindical obstacle for various values of U/D (down-slope drift coefficient divided by diffusion coefficient) with increasing distance away from an obstacle. It must be pointed out that the theory takes no account of the incompressibility of the particles and so although correct for heat conduction the predictions, with regard to particle density, become physically impossible above a certain point. Fig. 5.3 shows curves for values of U/D from 0.005 - 1.0 but values predicted above 0.02 are physically inapplicable. The soil density cannot increase by three or four times the original value. The results from up-slope of the post at Oberon Glade were found to lie in the region of 1.0 to 1.2 (table 5.6) and therefore it was necessary to expand the lower quarter of the graph to allow for a better comparison with the predicted results. The 0.003 and 0.002 curves were calculated and plotted together with the 0.005 curve at a larger scale (fig. 5.4). The curves show that the theory predicts an increase in the concentration of particles towards the

Predicted curves- up slope

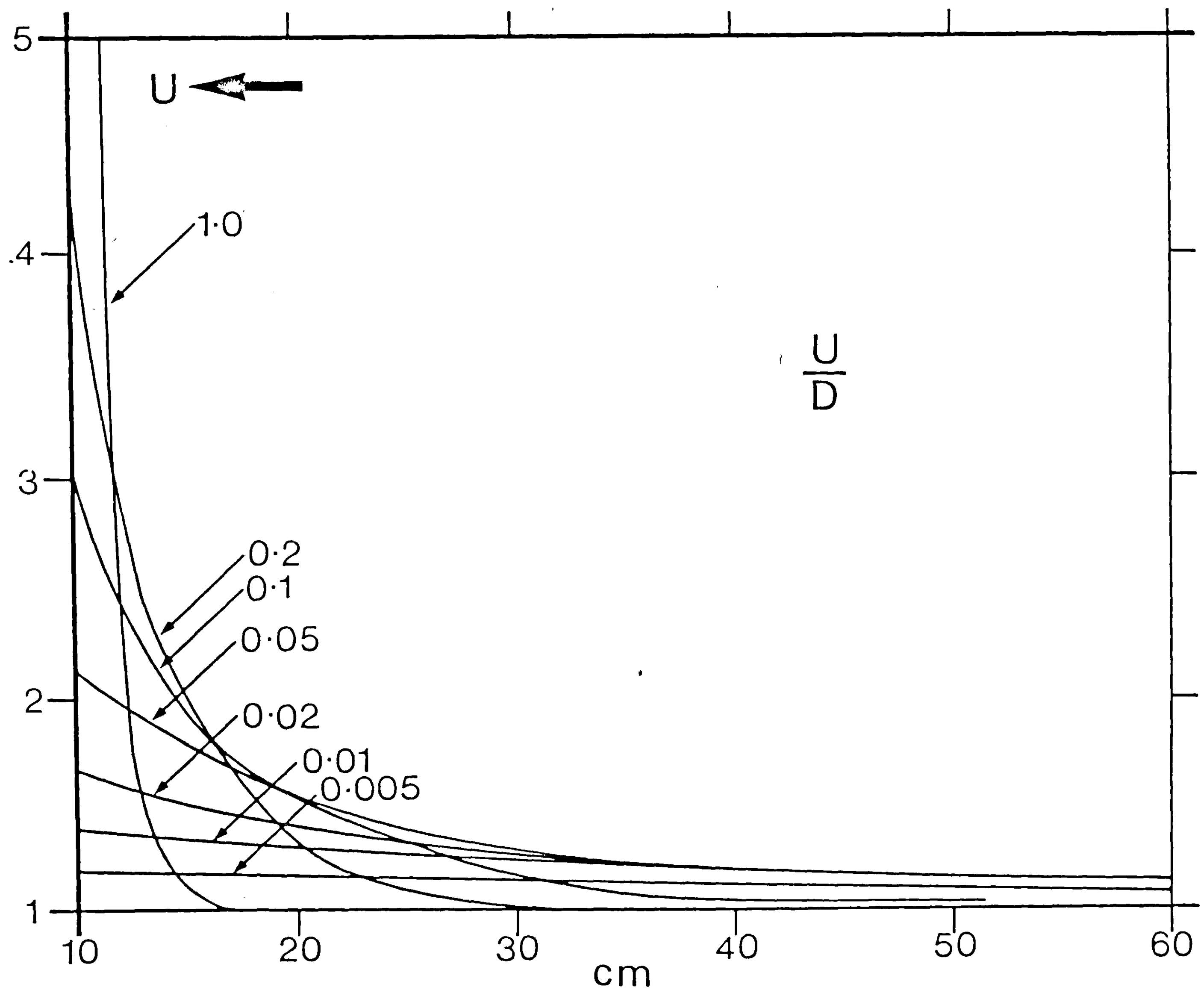


fig. 5.3

Predicted and empiral curves - up slope

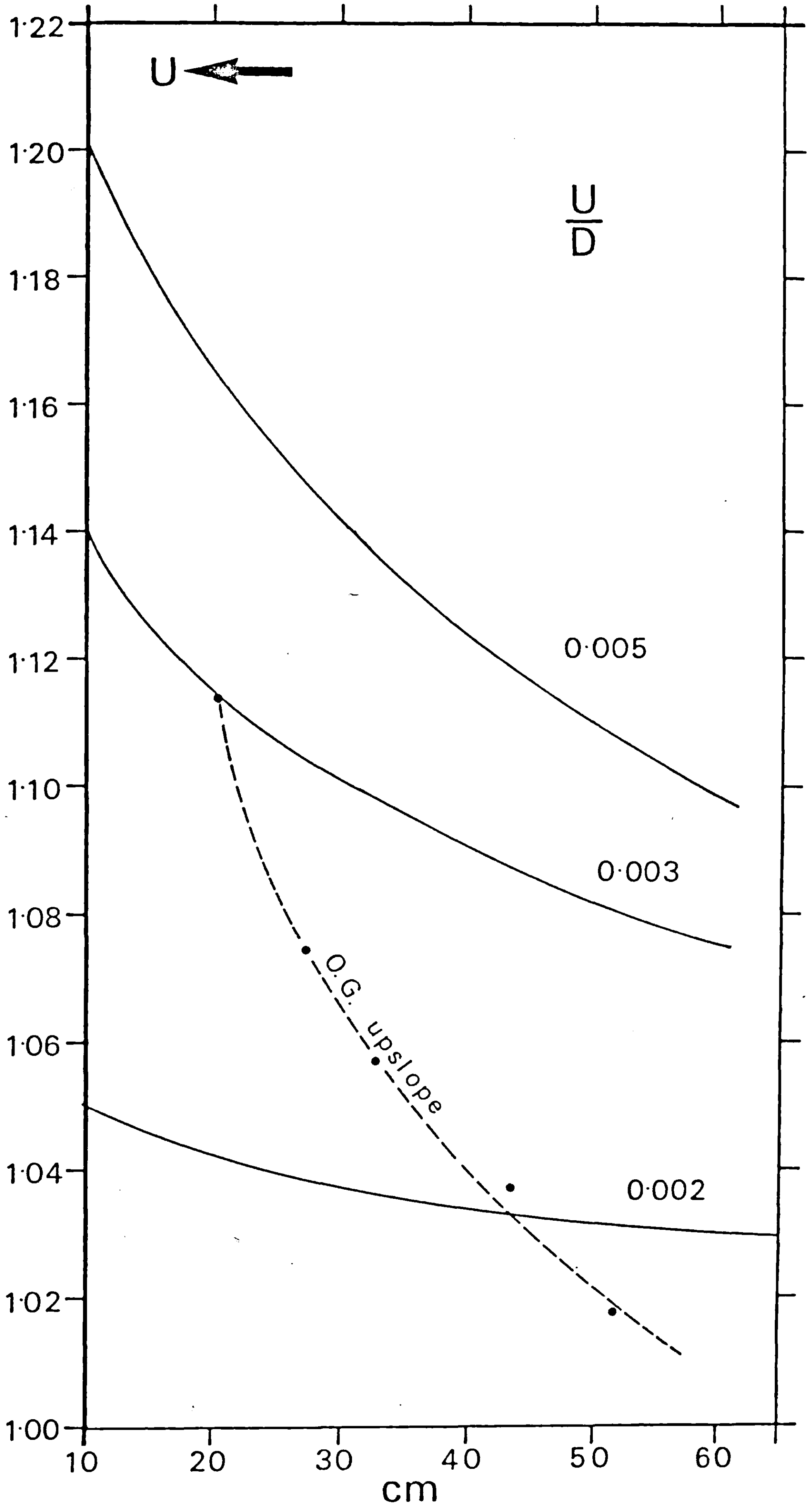


fig. 5.4

post (increase in soil density) on the up-slope side. The up-slope density values from Oberon Glade were plotted and it is found that the curve is qualitatively similar to the predicted ones, in being concave in nature and of similar absolute value, but has a far steeper gradient. The gradient of the curve is more akin to curves with larger U/D values.

Fig. 5.5 a shows the concentration of particles down-slope from a cylindical obstacle for various values of U/D with increasing distance away from an obstacle (radius of 10 centimetres). The results from down-slope of the post lie in the region less than 1.08 and therefore the 0.005, 0.01 and 0.02 curves were re-plotted with the empirical curve, at a larger scale, to allow for a better comparison to be made (fig. 5.5 b). The predicted curves trend upwards away from the obstacle's boundary and show that whereas the theory predicts low concentrations of soil particles towards the post (density values less than the background value) with a steady increase in the concentration of particles away from the post towards the general background level, the empirical curve for the down-slope, on the other hand, shows an decrease in the concentration of particles away from the post with the relatively higher density values nearest to the post. The trend of increasing soil density towards the post is similar but slightly less than that on the up-slope side but it is completely in the reverse direction to that predicted.

Predicted curves - down slope

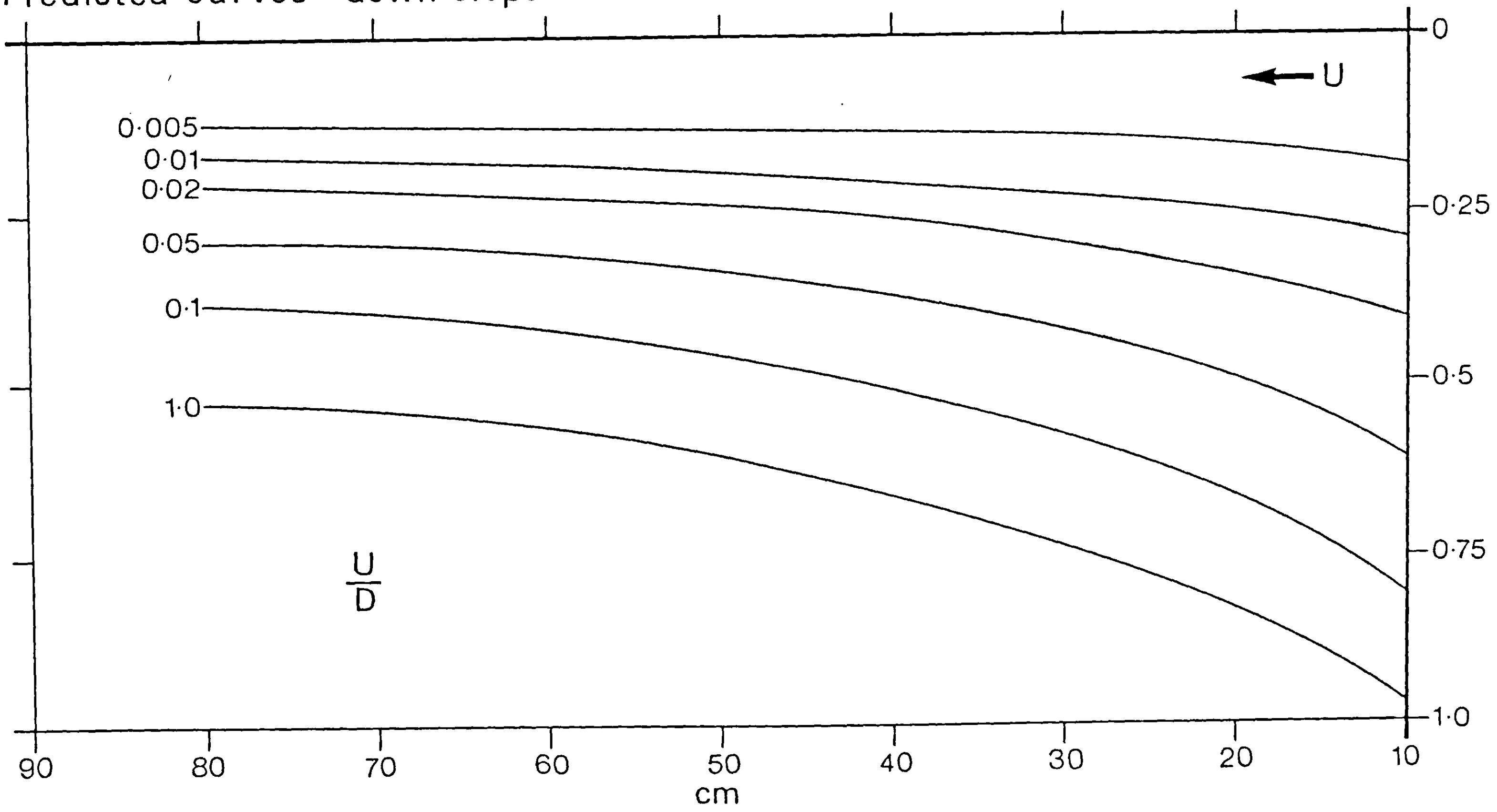


fig. 5.5 a

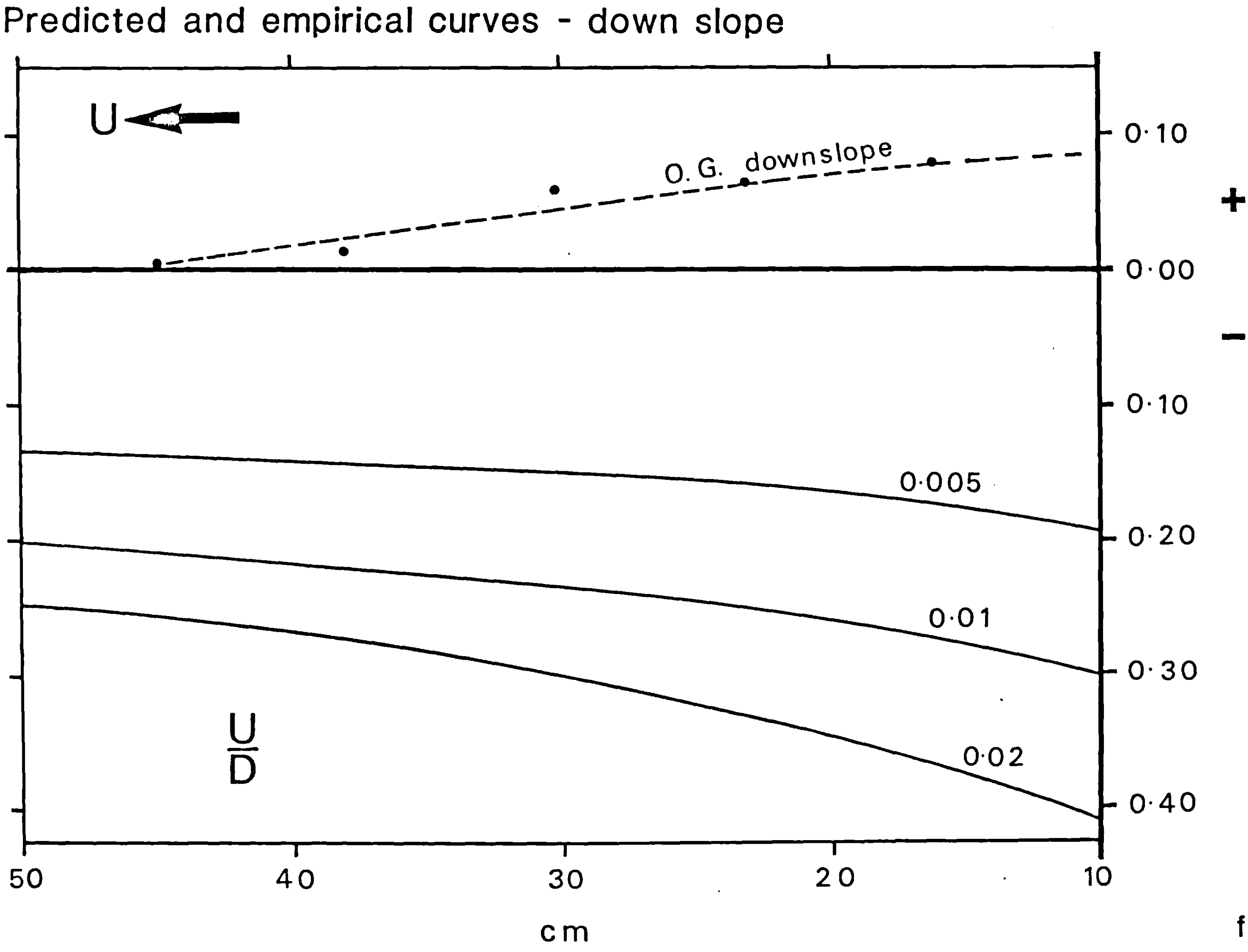
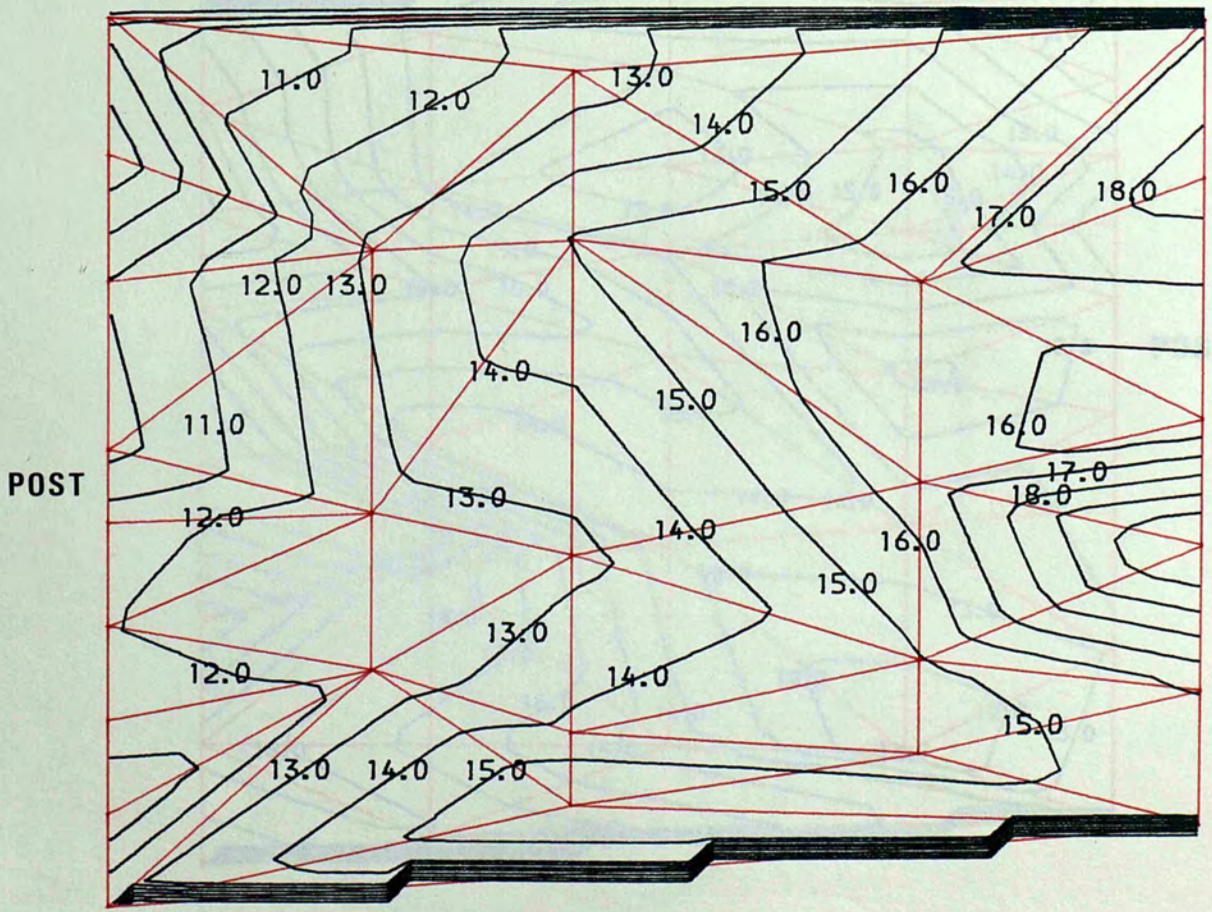

Predicted and empirical curves - down slope

fig. 5.5 b

5.2 Control Results

A number of thin sections were prepared from a control site. Samples were collected from a flat area of land, away from the vicinity of posts, at Thursley Common. The aim of the exercise was two fold. First, to check that trends are not detectable in areas away from the posts. Second, to obtain an estimate of the general undisturbed background pattern. Nine photographs were taken from four thin sections and treated as previously described. The values ranged from 14.1 percent up to 15.4 percent and there was no observable patterns in these voidage results. The Kruskal-Wallis test was used to assess the significance of the difference between the values from each of the thin sections (appendix B.3). The null hypothesis, that there is no significance difference between the sets of results, was accepted at the 95 percent confidence level. Therefore, the Kruskal-Wallis test shows that there is no significant difference between any of the results and that they are all drawn from the same population. The mean of the results, 14.7 percent, is taken as the background density level and it is lower than most of the values obtained from the two sites in the vicinity of the post. Soil structure is heterogenous in nature and therefore any investigation of this property has to make sure that the sampling strategy adopted is adequate enough to accurately quantify it. The data obtained from the control site has a small standard deviation and a statistical procedure did not show them to be drawn from different populations therefore the technique developed in the research is a suitable method for accurately estimating soil densities.

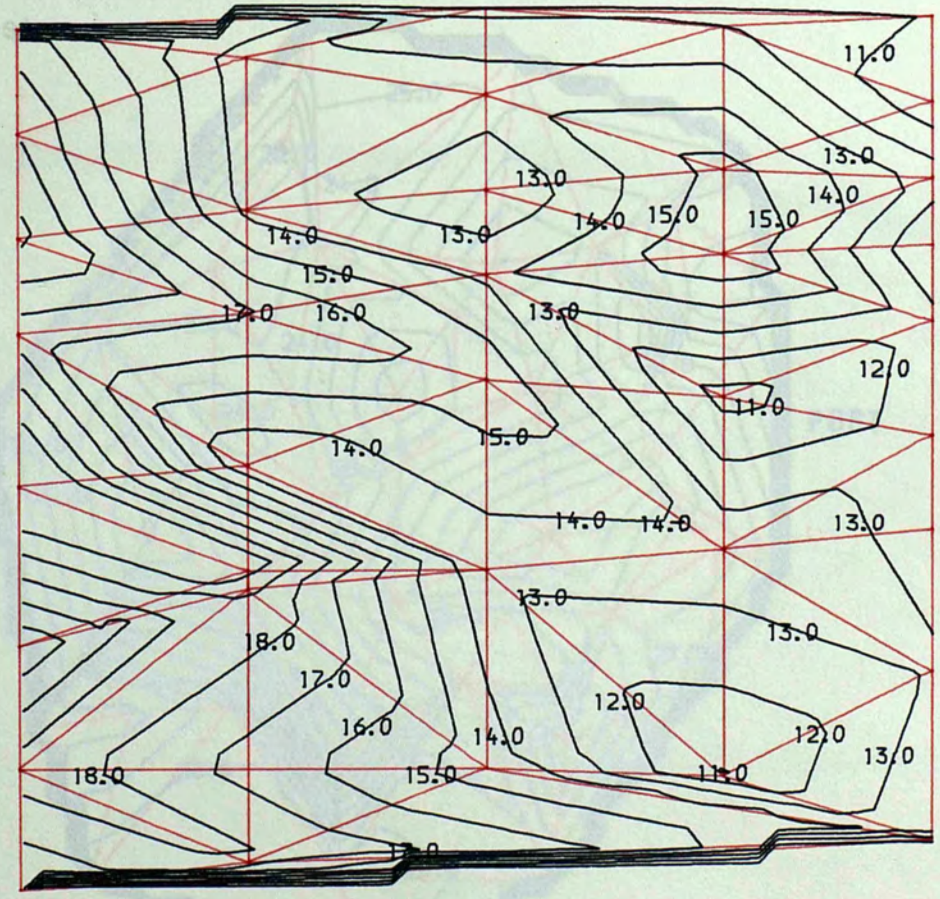
Oberon Glade - upslope



Graphics by DIMFILM

fig. 5.6 a

Oberon Glade - down slope



POST

Graphics by DIMFILM

fig. 5.6 b

Thursley Common - west

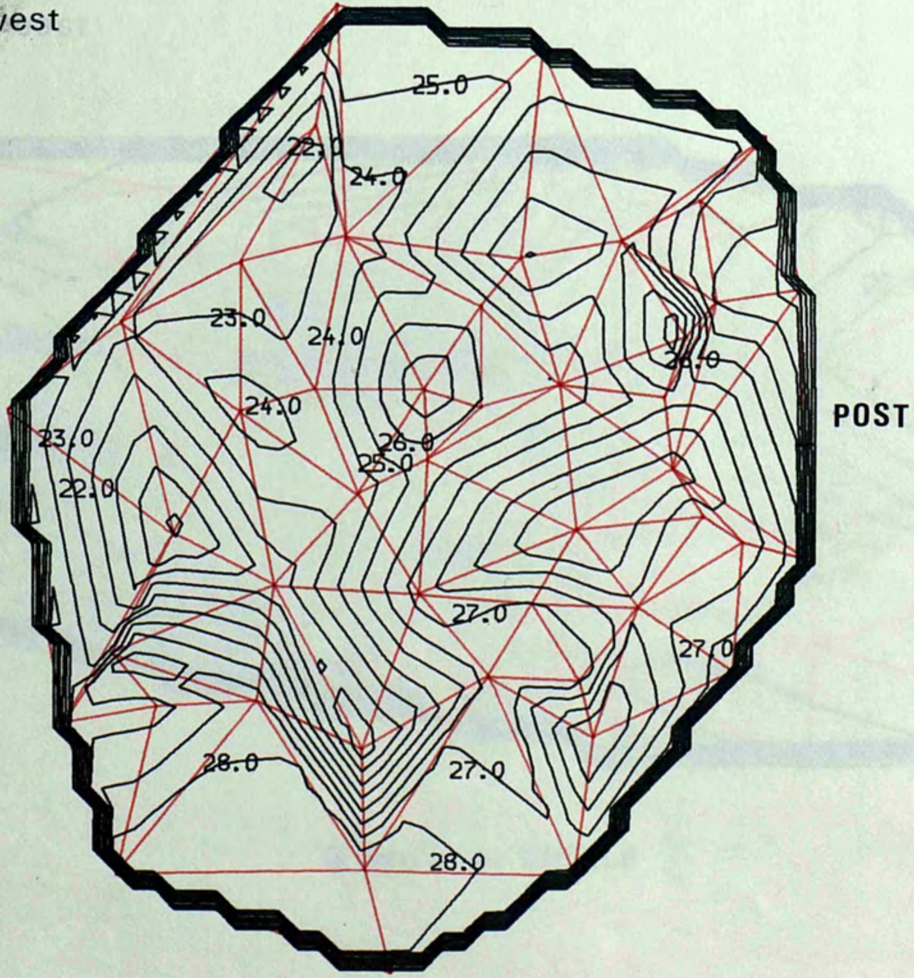


fig. 5.6 c

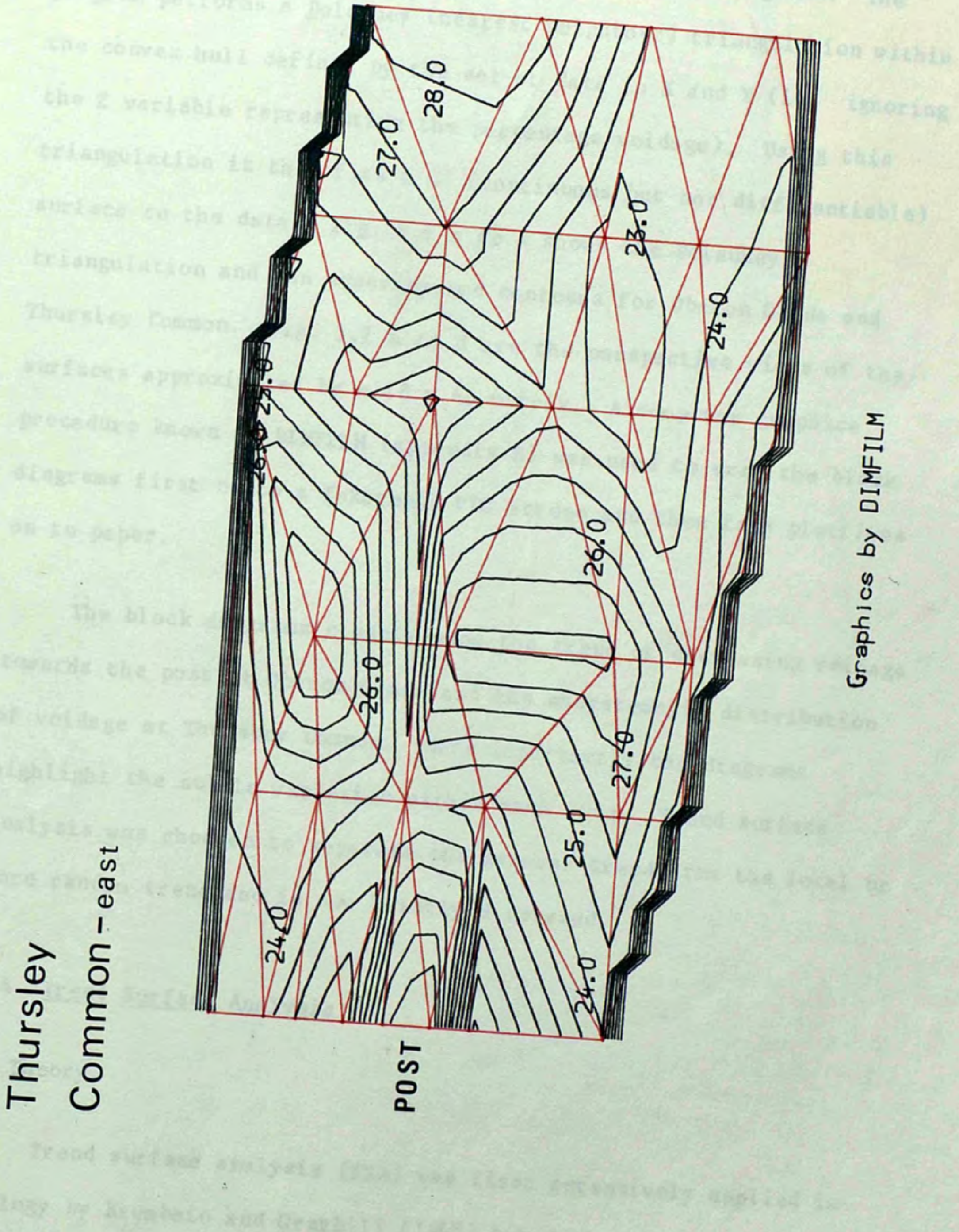

Thursley
Common - east
POST
24.0
26.0
26.0
28.0
25.0
27.0
28.0
26.0
27.0
25.0
24.0
23.0
24.0
24.0
Graphics by DIMFILM

fig. 5.6 d

5.3 Presentation of results in three dimensions

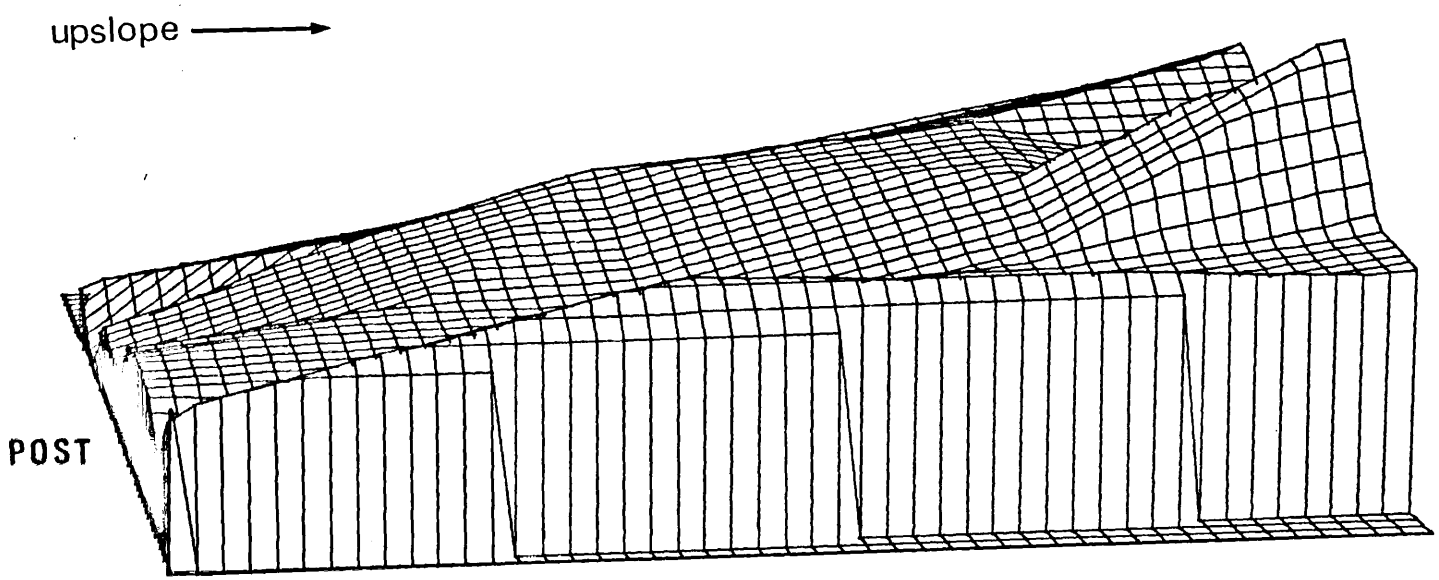
Further investigation of Culling's predicted pattern requires a more spatially directed study of the results. A computer program was used to plot the results in the form of block diagrams. The program performs a Delauney (nearest neighbour) triangulation within the convex hull defined by the set of data in X and Y (ie. ignoring the Z variable representing the percentage voidage). Using this triangulation it then fits a C′ (continuous but not differentiable) surface to the data. Fig. 5.6 a to d shows the Delauney triangulation and the superimposed contours for Oberon Glade and Thursley Common. Fig. 5.7 a to d are the perspective views of the surfaces approximated by a 48 x 48 matrix. A computer graphics procedure known as DIMFILM (appendix E) was used to draw the block diagrams first on to a Tektronik VDU screen and then from plotfiles on to paper.

The block diagrams clearly show the trend of decreasing voidage towards the post at Oberon Glade and the unsystematic distribution of voidage at Thursley Common. More importantly the diagrams highlight the subtle variation within each site. Trend surface analysis was choosen to separate the general trend from the local or more random trend and is now briefly discussed.

5.4 Trend Surface Analysis

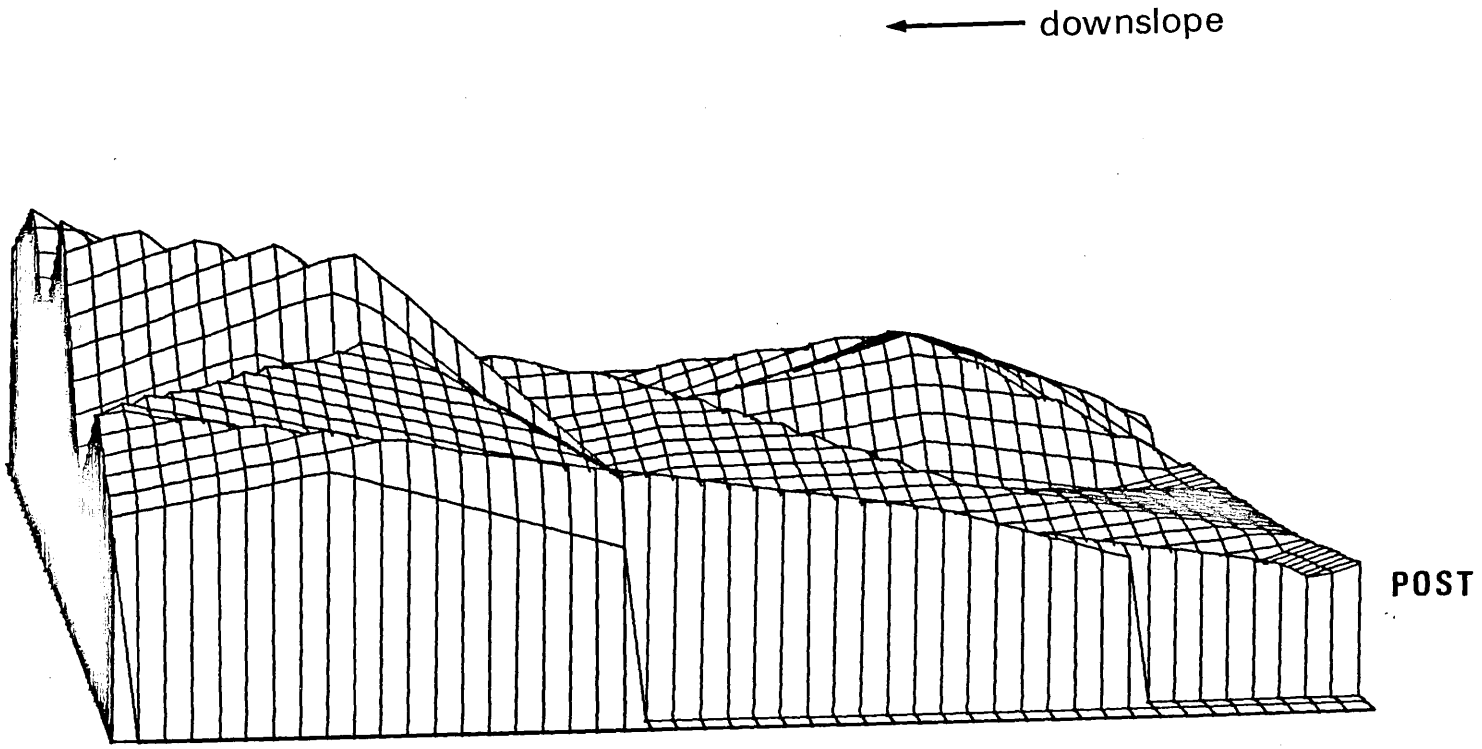
i. Theory.

Trend surface analysis (TSA) was first extensively applied in geology by Krumbein and Graybill (1965) but it has seen increasing use in geography following the work of Chorley and Haggett(1965).



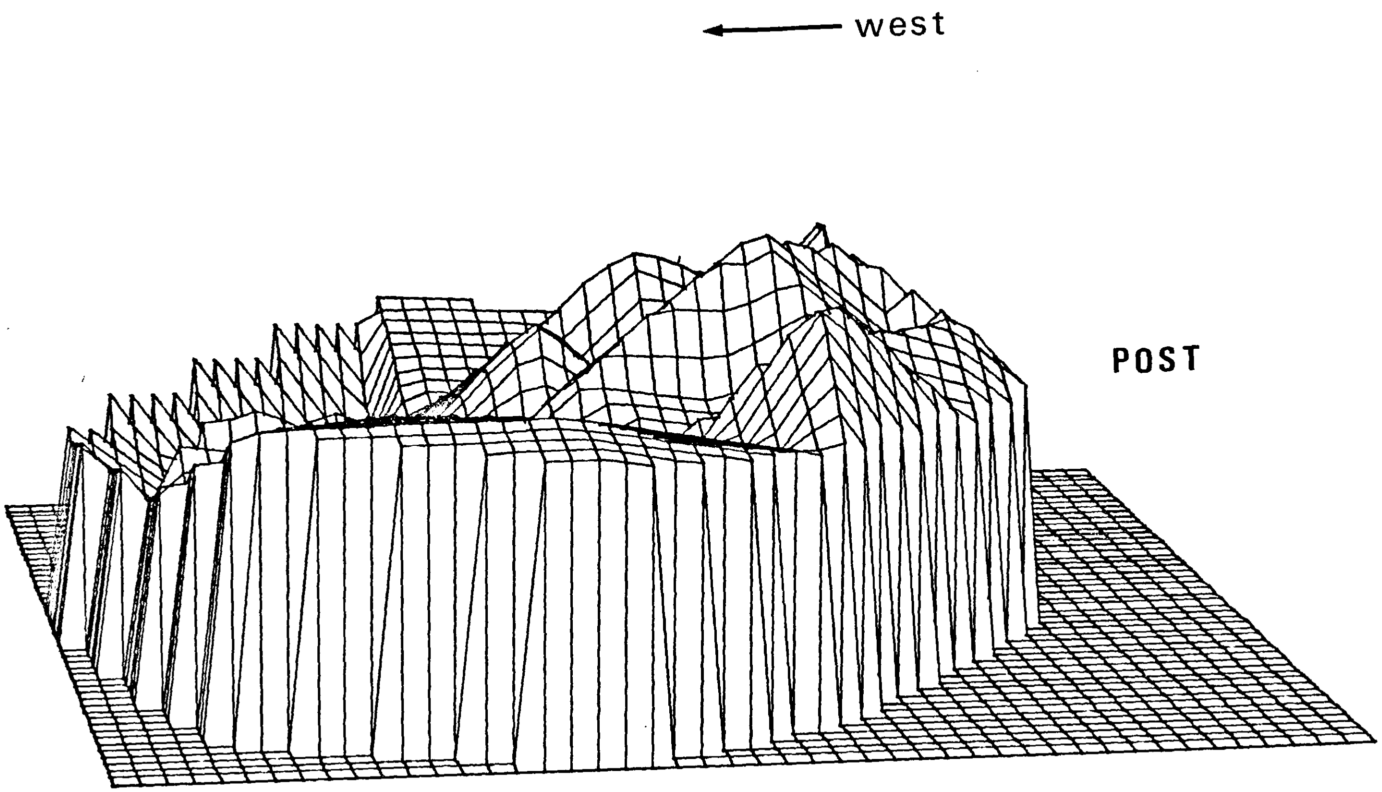
Oberon Glade

fig. 5.7 a



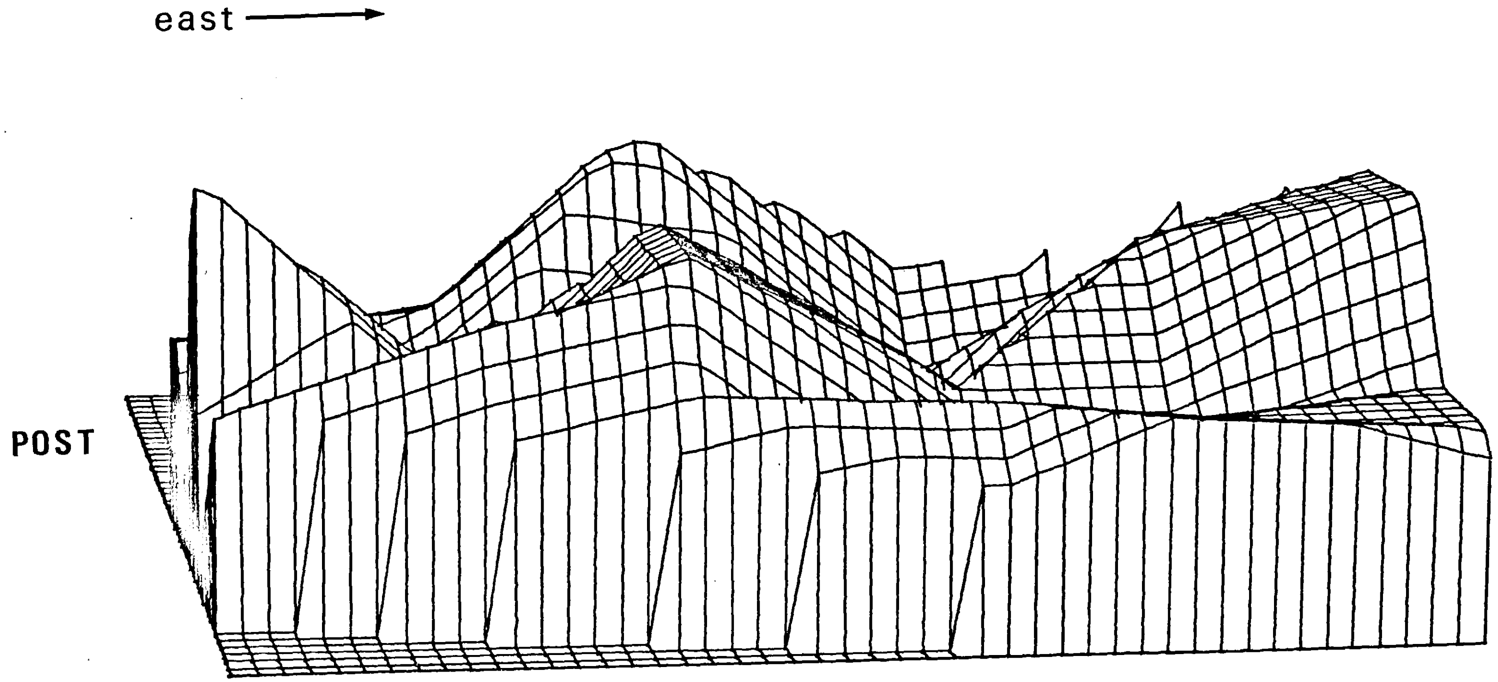
Oberon Glade

fig. 5.7 b



Thursley Common

fig. 5.7 c



Thursley Common

fig. 5.7 d

Formal TSA attempts to fit mathematically defined surfaces, of increasing complexity, to sets of points in three dimensions. The positions of the points are defined by their geographic co-ordinates (X,Y) and the value of the spatially distributed variable (Z). For example altitude (King, 1969; Lewin, 1969; Thornes and Jones, 1969); rainfall (Unwin, 1969) and median grain size (Chorley et al, 1966). Subjectively isolined ´observed value´ maps could be produced for this type of data but this method has several defects. It does not produce a mathematical statement of the relationships in space nor does it necessarily reveal the most significant properties of the data and it is open to the risk that random, local noise in the data will give misleading contours. TSA avoids most of these problems in providing clearly defined mathematical equations which represent generalized surfaces. It is a procedure by which each map observation is divided into two or more values; firstly, a trend value associated with large scale systematic changes which stretch from one edge of the map to the other and secondly, residual values associated with small scale fluctuations.

TSA is a regression technique in which we are dealing with planes instead of lines. Various surfaces can be fitted such as a first order linear surface, second order quadratic, third order cubic and so on,each one increasing in complexity. Two important variants of TSA exist, namely mathematical models based on trigonometric Fourier polynomials or power series polynomials. Both use the least squares method and are variants of the General Linear model. Fourier models are however most appropriate to periodic surfaces and aperiodic surfaces are more common in geographical data. Hence, the more general power series models, which are a special case of multiple regression, are widely used to analyse geographical data.

The computation of the first order surface is identical to that of multiple regression. The dependent variable (Z) is located in space by two ´independent´ co-ordinates (X,Y) and related as follows :

$$Z = a + b1\,X + b2\,Y$$

The next stage is the calculation of values for the parameters b1, b2 and a. There are three main ways :

1. Using short cut formulae - deviations from the mean
2. Solving normal simultaneous equations
3. Using a matrix algebra technique as illustrated in Krumbein and Graybill (1965) and now used in computer packages

Hand computation can be used with small data sets but is found to be totally impractical with large data sets and the calculation of higher order surfaces where additional quadratic, cubic, quartic terms are included in the above equation. It is now more common to use one of the available computer packages.

When the surface is computed it is necessary to assess the significance. A first impression of the usefulness is obtained by calculating the multiple correlation coefficient (R) between the variables. The square of this value gives the level of ´explanation´ achieved by the model. In TSA it is usually called the "percentage reduction sum of squares" and expressed as a percentage. It shows the percentage of the total variance in Z accounted for by the calculated functions of X and Y.

An improved spatial impression of the validity of the surface is obtained by plotting the predicted surface; that is, by substituting the co-ordinates of data points into the predicted equation and calculating Z at each point. Isolines drawn through these predictive values will be contours on the trend surface. A residual value is the difference between the observed value of Z and the calculated value of Z. If patterns in the residuals suggest that deviations from the trend surface model are not random, then it is necessary to either fit the next higher order surface to ´explain´ the deviations or to use a different variable.

F-tests can be used to test the overall significance of a trend equation, provided that the residuals do not contain systematic patterns. Commonly, however, F-tests are used as means of deciding what degree polynomial to fit. In which case they are used merely as indices to help decide when to stop without regard to any assumptions about the residuals which must be satisfied in a rigorous test of significance. The case is directly analogous to the use of F-tests in stepwise multiple regression to decide whether or not to introduce another variable into the equation.

ii. Limitations.

Davis (1973) says that at an absolute minimum the number of sample points must :

> "... exceed the number of coefficients in the polynomial equation or the results of the regression are invalid."

TSA assumes a continuous data set although the model uses sample points and it assumes that the same feature can take different values at every point between the sample points. This limits the use of TSA in Human Geography, nevertheless it has been applied to discrete data such as settlement patterns. The TSA map is a best-fit surface for a set points each of which ia an observation which might have been drawn from a population of values at that point. It is argued that taking a distant view will allow for discrete patterns to appear continuous. In theory it is necessary to have random samples but in practice this is often difficult to achieve. It is therefore suggested that provided the residuals are random then the test is valid.

The spacing of samples can have a serious effect on estimation of the scale of variability and on the form of the regression (Davis, 1973, p.350). Clustering of sample points has a deleterious effect on the trend. When areas of the map have little information on which to base the trend surface, higher order surfaces can be produced with erroneous steep gradients in those areas where there is little data to support the pattern. There is no apparent solution to this problem. Davis (1973) looked at the influence of clustering sample points on the trend surface. The experiments suggested :

> "that trend surface methods may be more robust against the effects of clustering than is commonly supposed."

The experimental tests used were essentially `noise-free' and Davis underlined the fact that more severe distortions were to be expected in the presence of local variation.

Finally, there will be a violation of the independence requirement of the General Linear Model if variables are not independent. Johnson (1980, p.89) pointed out that :

> "A small amount of collinearity is often tolerated in the regression equation....but accurate trend surface mapping requires uncorrelated co-ordinate sets."

If there is correlation between areas of the map, it is better to rotate the variables to remove the pattern and then re-calculate the surface. If the correlation was left in, there arises the probability of a higher level of explanation than was warranted. Again it is suggested that provided the residuals are uncorrelated then the independence rule is upheld.

iii. Symap.

Because of the large data sets involved in this research and the need to fit higher order surfaces it was decided to calculate and fit trend surfaces by using a computer program. Symap (Synagraphic Mapping) available on the Amdahl system at the University of London Computer Center is a program for producing maps on a line printer. Four basic maps may be generated : contour, conformant, proximal and trend surface. The trend surface map is derived by fitting a polynomial equation to the data points by a ′least squares′ method. Trend surface analysis assumes a planar grid of reference but a conical surface is expected from the prediction. There does not seem to be a procedure available to deal with this problem therefore it was decided to use the Symap program to perform trend surface analysis on the results in this research. Sample points were located by X and Y co-ordinates read from the initial scaled plan drawing of the sites. Linear, quadratic, cubic and quartic surfaces were fitted and the corresponding correlation and goodness of fit values are summarized in tables 5.7 to 5.10.

iv. Trend surface analysis results.

(a)Oberon Glade

Down-slope the correlation coefficients range from 0.76 to 0.87, explaining 58 percent and 76 percent respectively of the variation. Up-slope the correlation coefficients range from 0.85 to 0.91, explaining 73 percent and 81 percent respectively of the variation. Calculated F values show that all the fitted surfaces are significant (table 5.11). F values for the pure quadratic, cubic and quartic surfaces show that although each higher surface explains more of the variation there is no significant improvement on the linear surface. The linear surface is the best fit to the data (fig. 5.8 a and b).

(b)Thursley Common

On the east side the correlation coefficients range from 0.21 to 0.51, explaining 5 percent and 25 percent respectively of the variation. On the west side the correlation coefficients range from 0.48 to 0.71, explaining 23 percent and 51 percent respectively of the variation. Calculated F values show that surfaces fitted to the data from the west side are all significant but at a lower confidence level than the results from Oberon Glade. F values for the pure quadratic, cubic and quartic surfaces show that they do not significantly improve on the linear surface (table 5.11). The linear surface was the best fit to the data (fig. 5.8 c and d). Surfaces fitted to the data from the east side are not significant. The calculated F values were less than unity.

OBERON GLADE - up slope (n=27)

	Linear	Quadratic	Cubic	Quartic
variation explained	187.20	202.26	206.51	209.13
variation not explained	69.69	54.63	50.39	47.76
correlation coefficient	0.85	0.89	0.90	0.91
percentage reduction SS	73 %	79 %	80 %	81 %

Table 5.7

OBERON GLADE - down slope (n=37)

	Linear	Quadratic	Cubic	Quartic
variation explained	199.10	215.68	221.28	262.19
variation not explained	146.69	130.52	124.92	84.01
correlation coefficient	0.76	0.77	0.80	0.87
percentage reduction SS	58 %	62 %	64 %	76 %

Table 5.8

THURSLEY COMMON - west (n=46)

	Linear	Quadratic	Cubic	Quartic
variation explained	88.48	91.52	190.77	196.51
variation not explained	297.17	294.13	194.88	189.1
correlation coefficient	0.48	0.49	0.70	0.71
percentage reduction SS	23 %	24 %	49 %	51 %

Table 5.9

THURSLEY COMMON - east (n=35)

	Linear	Quadratic	Cubic	Quartic
variation explained	12.30	27.98	54.65	68.32
variation not explained	258.32	242.64	216.00	202.30
correlation coefficient	0.21	0.32	0.45	0.50
percentage reduction SS	5 %	10 %	20 %	25 %

Table 5.10

Significance of the Trend Surfaces (F-values)

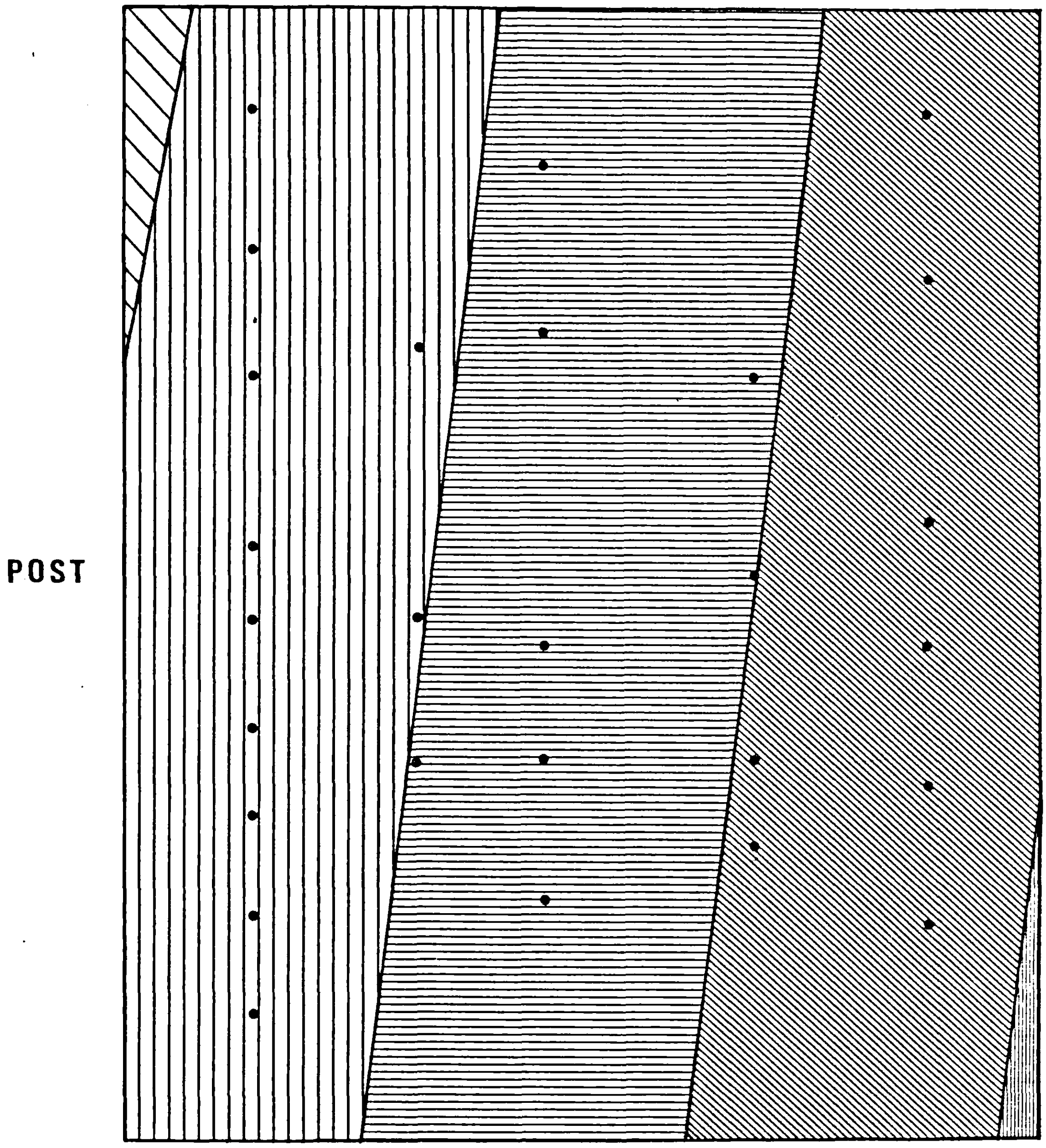
	OBERON GLADE		THURSLEY COMMON	
	up slope	down slope	west	east
linear	32.23 (3.40)	23.10 (3.28)	6.40 (3.20)	0.76
quadratic (pure)	1.93 (3.07)	1.28 (2.91)	0.13	0.67
cubic (pure)	0.15	0.13	2.04	0.70
quartic (pure)	0.05	0.76	0.07	0.48

Table 5.11

The values in the brackets are the critical F values at the 95 % significance level.

Linear Trend Surface

Oberon Glade - upslope



%

▧ 6·0 – 9·2

▥ 9·2 – 12·4

▤ 12·4 – 15·6

▩ 15·6 – 18·8

▦ 18·8 – 22·0

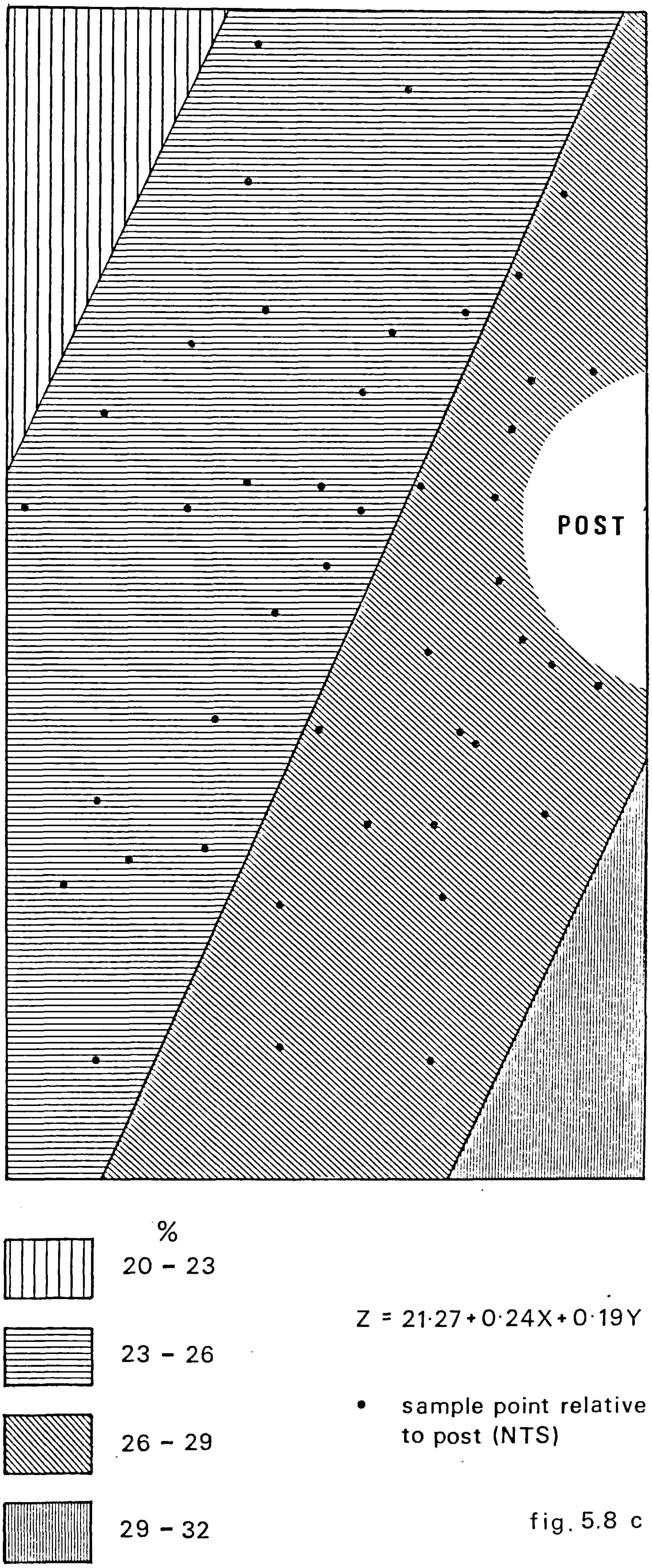
$Z = -3{\cdot}6 + 0{\cdot}65X + 0{\cdot}15Y$

● sample point relative to post (NTS)

fig. 5.8 a

Linear Trend Surface

Thursley Common – west

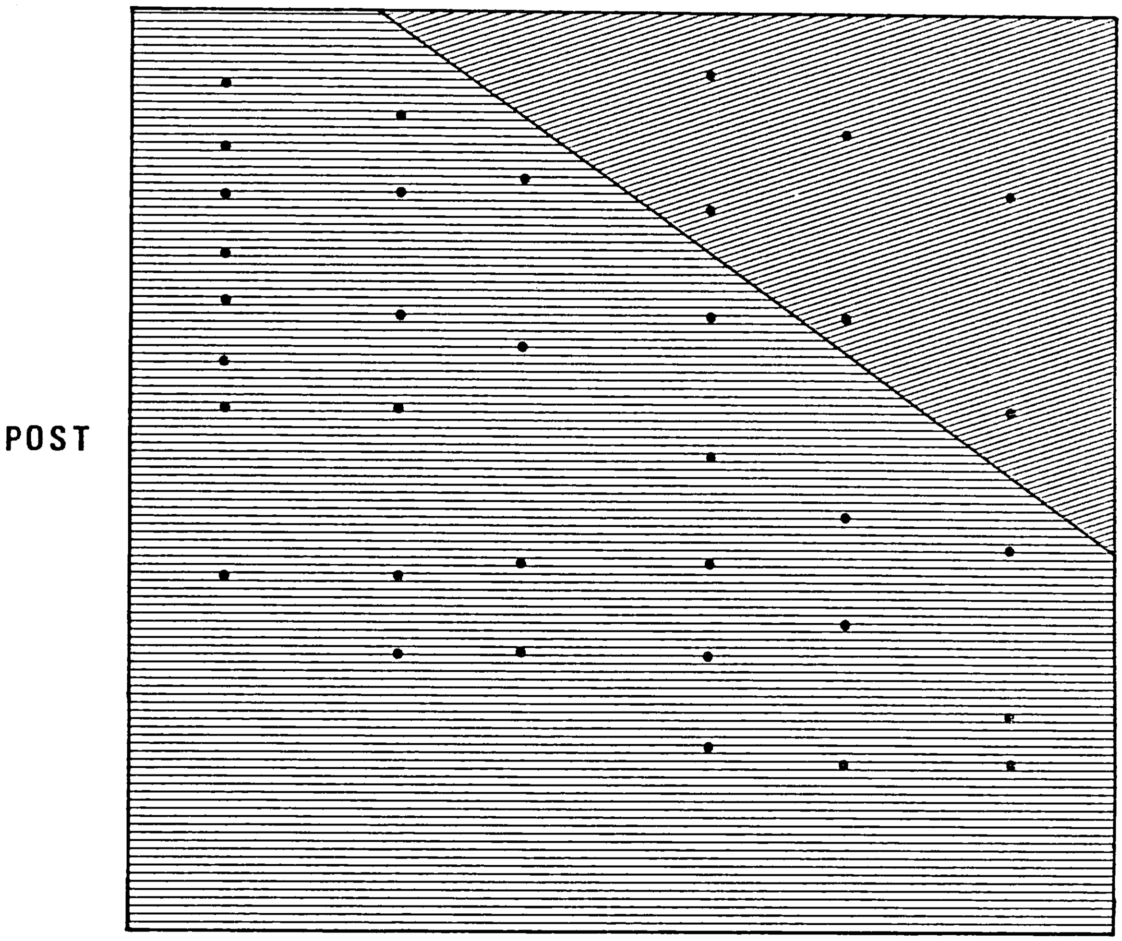


$Z = 21{\cdot}27 + 0{\cdot}24X + 0{\cdot}19Y$

fig. 5.8 c

Linear Trend Surface

Thursley Common - east



%

▤ 22 - 25

▨ 25 - 28

$Z = 23{\cdot}62 + 0{\cdot}11X - 0{\cdot}25Y$

● sample point relative to post (NTS)

fig. 5.8 d

5.5 Discussion of the Results

At Oberon Glade, on the up-slope side, the trend of decreasing voidage towards the post is to be expected with soil particles moving down the slope and building up in front of the obstacle. The curve plotting the change in density towards the post and the trend surface maps clearly show this but the gradient of the empirical curve is much steeper than the predicted curves for similar densities. This may be because the U/D values are much lower than expected and could be indicative of a high diffusion coefficient (D); that is, diffusive soil movement higher than predicted by at least one magnitude. The position of the empirical curve is sensitive to the background value. This was obtained from soil samples at least 60 centimetres away from the post on the up-slope side. The mean value (18.7 percent voids or a density of 81.3) was used but the data set has a standard deviation of 5.9. If the lower density value is taken (dividing throughout by a value equal to the mean + 1 s.d.) we find that the curve is now more attuned to the predicted values and cuts across the predicted curves at a much lower angle. But if the higher density value is taken (dividing throughout by a value equal to the mean - 1 s.d.) the predicted curves are intersected at even steeper angles (fig. 5.9).

On the down-slope side, the trend of increasing soil density towards the post is more difficult to explain. A definite pull away is predicted by the theory, with lower density values directly in front of the post and then increasing away towards the general background level of 17 to 18 percent. This phenomenon of an increase in the percentage of voids away from the post, or conversely increasing soil density towards the post, may indicate

Predicted and empirical curves

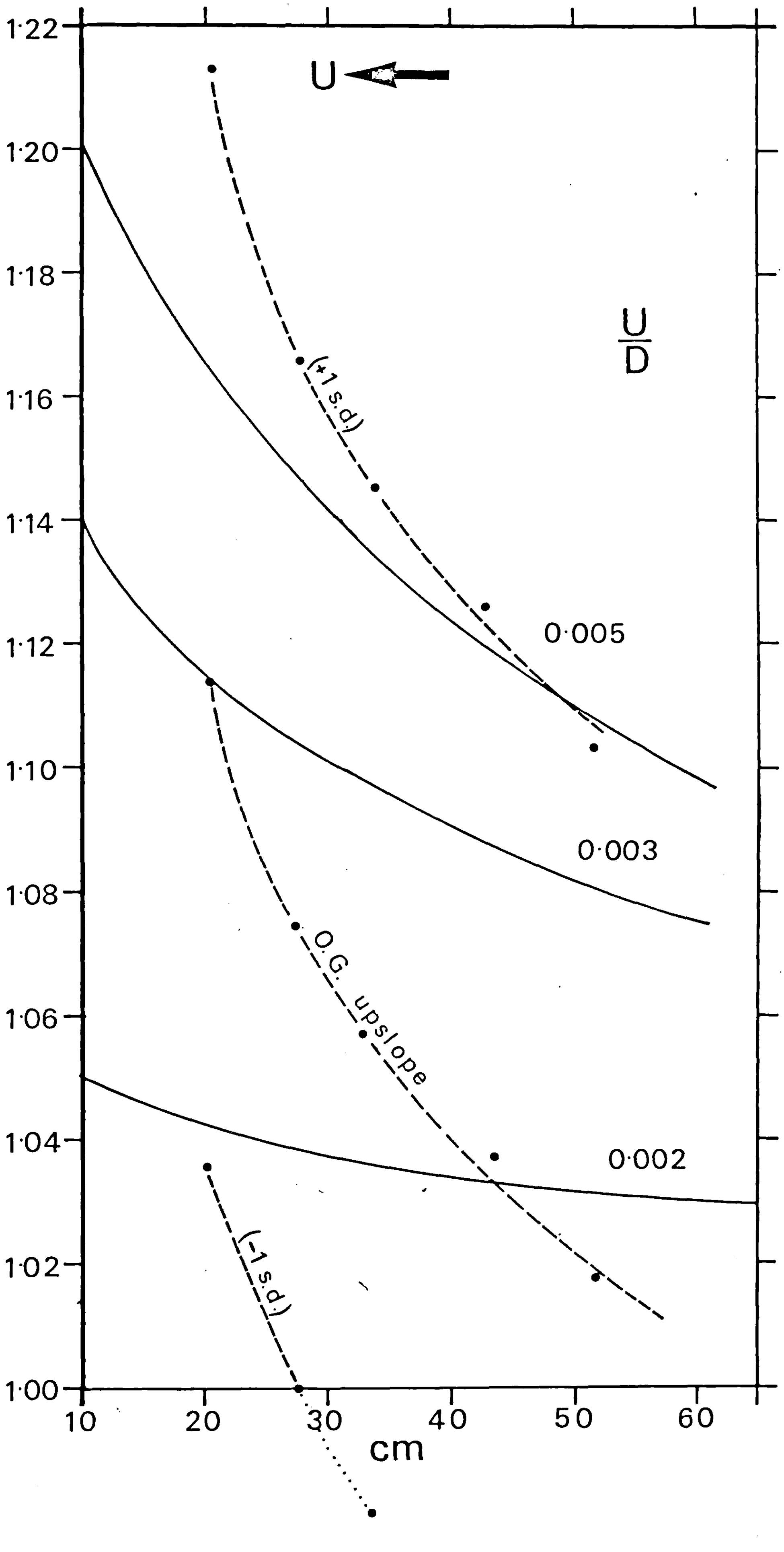


fig. 5.9

that there is increasing pressure towards the post on the down-slope side. This is not accounted for in the diffusion theory and it is a major finding of the research.

A possible explanation for the steepness of the empirical curve on the up-slope side and the increase in soil density towards the post on the down-slope side may be that the original disturbance and subsequent compaction of the soil, around the post, is still influencing the soil structure after 25 years later. This means that we are not dealing with a steady state system. The time needed to return to a steady state is variable and clearly depends on the degree of initial disturbance. We have here a paradox. If compaction has such a long lasting effect then the diffusion component must be weak indeed. On the other hand the absolute values for the empirical data, as mentioned above, indicate a strong diffusive element higher by at least one magnitude from expected values. A finding of a weak diffusion component has serious repercussions and implications for present day measuring techniques which automatically assume that any disturbance, arising from the introduction of various devices into the soil, is rapidly dissipated within a few years.

The soil density pattern being investigated around the obstacles in this research may be the result of a type of flow movement and not random, diffusive movement as predicted by Culling. If soil was flowing around obstacles such as posts there would still be an indicative pattern of soil density to be detected. In theory there would be higher pressure on the up-slope side, lower pressure on the sides and a definite rise in pressure on the down-slope side. This is a well known paradox (D'Alembert - see Birkhoff, 1950, p.10) from hydrodynamic theory of non-viscous fluids. Regarding its paradoxical nature which seems to go against all expectation of common sense, experimental values have shown that there is a rise in pressure behind circular, cylindrical obstacles (Goldstein, 1938). Nevertheless this theory and the experimental evidence are concerned with low viscosity, high velocity type flow and this does not seem to be applicable to the behaviour of a high viscosity medium such as the soil. No evidence of surface flow and scouring around the posts was observed at either sites. Therefore, there is little evidence from this research to suggest that the soil is moving by a laminar type flow, as for example in soliflucted flow.

Looking closely at the trend surface maps the decreasing voidage towards the post is the dominant feature up-slope and down slope. Most of the samples were taken perpendicular to a line drawn through the centre of the post in the direction of maximum slope. A significant amount of potential sampling area was destroyed during the removal of the soil using the trench method. This was especially so on the two sides of the posts. Hence, most of the results refer to a linear strip of land which is parallel to the downwards drift. If the results are considered with this in mind they do seem to fit the theory quite well. It is obvious that further work should adopt, whenever possible, the direct insertion method for collecting soil samples as used at Thursley Common on the west side of the post. This method significantly reduces the amount of potentially important soil that is lost due to sampling disturbance.

At Thursley Common, unlike the above Oberon Glade data, the results do not show obvious trends or patterns. This is to be expected on a flat site because there is no preferred direction to the soil movement (no drift component) and therefore there is an equal probability of soil moving in any direction around the post. There is no significant difference between the results on the east side or between the results on the west side and they bear no resemblence to the predicted curves for sloping sites. All this is consistent with the theory of random diffusive soil movement on a flat site. The apparent decrease in the voidage on the east side of the post could be due to residual soil compaction from when the post was installed in 1952/52. Again this suggests that the diffusion component is weak.

Trend surface analysis of the data reinforces some of the early findings. On the east side of the post the quartic surface produced looks nothing like the predicted pattern and it only accounts for 25 percent of the total variation. Looking at the four trend surface maps produced for the west side none seem to fit Culling´s pattern. The increase in soil voidage towards the post dominates the trend. A small hole, perhaps due to a small animal´s burrow, was noted near to the post when sampling. Larger voidage results in this area (the bottom SSE corner of the trend map) may be causing a false trend which really is not there. The surfaces account for very little of the variation, at the most 50 percent. Therefore the trend surface results do suggest that there is no patterning on either side of the post at the flat site. These findings from the Thursley Common data are consistent with Culling´s theory of diffusive soil movement.

VI Conclusions

Most of the past work dealing with soil creep can be categorised into two main groups. A minority have been concerned with the exact mechanism and theory of the process while the majority have dealt with field and laboratory measurement of the process. Both these approaches involve investigating soil movement over time and numerous problems and assumptions arise. These have been discussed in detail in the opening chapter of this thesis and catalogued in Culling (1981). This research by assuming a steady state condition, differs from earlier investigations in at least one important respect - the method involves just one set of observations, which may therefore be destructive. As far as is known, this is the first time such an approach has been used in field work to investigate soil creep. As pointed out by Culling (1983) the approach is designed to be complementary to existing measurement techniques. Furthermore a stochastic theory of soil creep was proposed in the 1960s (Culling, 1963; 1965) and the results presented in this thesis are the first field evidence relating specifically to that theory.

The first aim of the research was to develop fresh techniques for investigating random soil movement. As has been documented earlier in the thesis existing techniques were of insufficient accuracy and precision to arbitrate on the predictions of the theory. Various avenues were considered but it was decided to examine micro-changes in soil density from thin-sections. The thesis details the problems that arose and the manner in which they were overcome. The adopted procedure involved removing soil samples from the field site, impregnating them prior to thin-sectioning and the use of an automated procedure to quantify the soil void ratio.

Steady State Solution for the Diffusion Equation with Drift for the region outside a Telegraph Post

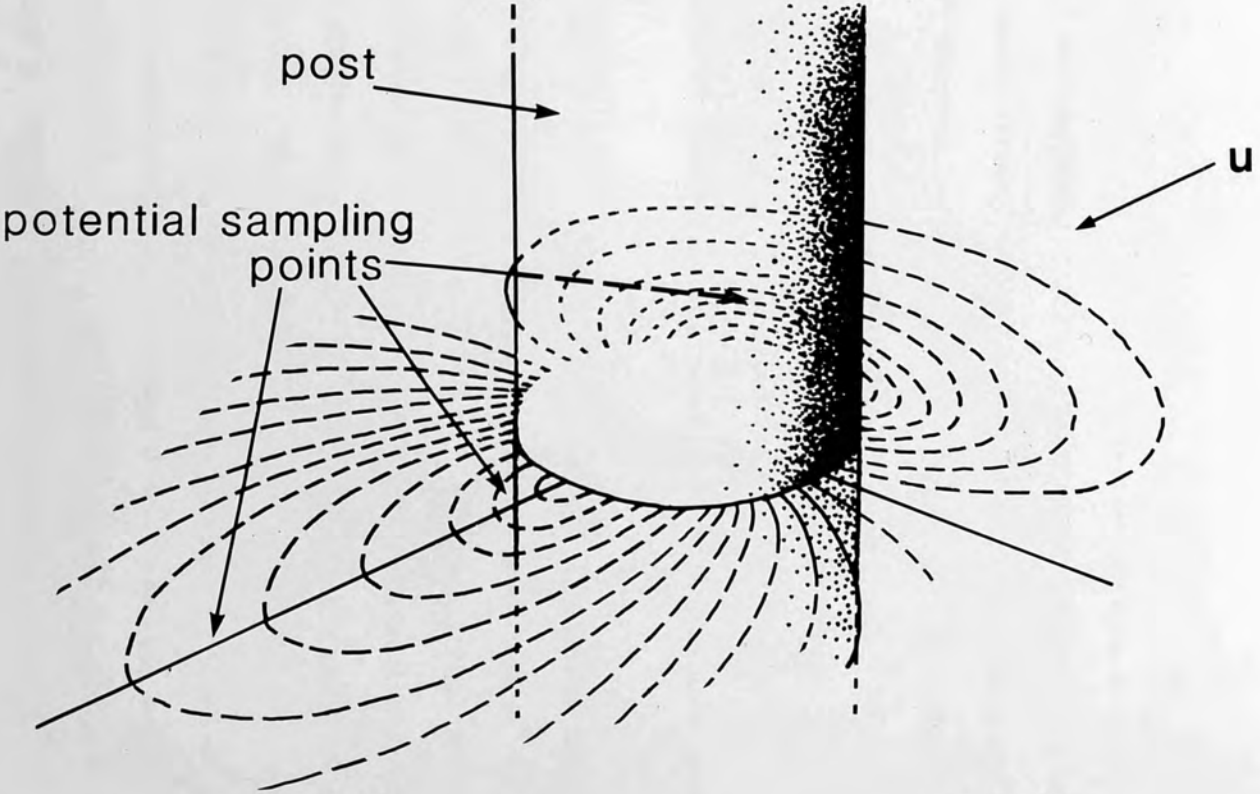


plate 6.1

The technique as adopted attained the requisite experimental criteria, it preserved soil structure and gave an unequivocal estimate of voidage so that the investigation was able to proceed at a higher level of precision (three decimal places) than is customary in geomorphology.

Although developed specifically for the problem at hand, the technique does have wide potential use in other soil studies both in the short term - density changes upon vegetal growth, application of fertiliser, micro-climatic change, changes in soil drainage and moisture - and in the long term - secular changes in density and structure subsequent to vegetal change, climatic change, the progress of weathering in a variety of climatic regimes, the investigation of palaeosols, the analysis of archaeological sites.

The use of image analysis has become increasingly prominent in the quantification of soil structure over the last decade. The technique used here employs considerable refinements over customary techniques, using dyes, phase contrast and ultra-violet photographic methods to enhance the image of the soil property in question (in this case voids). The possibility of variable response to the image analyser means that the technique is not limited to an all or nothing, 0-1, measurement. If constituents of the soil can be characterised by a fairly well defined grey level then repetition of the procedure at varying cut-off points gives the potential for the analysis of soil composition and structure to a finer degree than with existing techniques.

Having developed the method of estimating voidage to the prescribed precision and accuracy the second aim of the research

- the field verification of a stochastic theory of soil creep (Culling, 1963) could be set in motion.

Soil is a particulate array and any bulk movement will include a random component. In addition there may be a preferred direction to the movement of the particles, induced by external forces which are facilitated by the intrinsic random displacement of each particle. The problem is how large both relatively and absolutely are the random (diffusion) and the preferred (drift) values. Thus the major assumptions are:

1. Soil particles moving in a random, diffusive manner.
2. A superimposed down-slope drift component present (sloping site)
3. With time a steady state will exist with an indicative density pattern around a circular, cylindrical obstacle as shown in plate 6.1 (see also fig. 1.4)

The main problem here is the discovery of suitable sites. The more general and fundamental a scientific theory the more difficult it becomes to find crucial test situations particularly, as in this research, where it is necessary to make the experiments. The criteria have already been detailed (Ch. 2) to ensure that the influence of redundant variables and extraneous disturbances are kept to a minimum while providing for a dateable obstacle of simple symmetry to allow for analytical prediction and of a size to give on the one hand measureable density variations, but on the other hand not of a size to build up a counterslope so altering the conditions of the problem and inducing non-linearity.

After considerable research two main sites were chosen to test the theory, one sloping and the other flat. In the presence of a surface gradient, on the up-slope side of the post, the pattern found is qualitatively as predicted and supports the theory but on the down-slope side the results are the complete opposite to those predicted. Furthermore the empirical up-slope curve of voidage presents a paradoxical situation. The gradient of the curve as a whole is steeper than expected for the appropriate values for the ratio U/D while the values for U/D itself are much lower than expected when using the customary wisdom relating to rates of soil creep. Thus on the one hand the gradient implies a weak effect while on the other the value itself implies a strong diffusion coefficient.

If the diffusion coefficient is weak as is partially suggested then the possibility arises of residual compaction or other disturbance to the soil still detectable after twenty years. This has bearing on all existing methods of estimating soil creep.

On the down-slope side the data indicates an increase in soil denisty and this may suggest an increase in pressure behind the post. This is not accounted for in the diffusion theory and if substantiated by further work is a major finding of the research. Although residual compaction, from the time of insertion, could also be a causal factor. On the level site there is no evidence of a density pattern around the post and this is in accordance with the theory and mitigates against the survival of any compaction.

Therefore it can be claimed that some of the research evidence is inconclusive. This can be attributed to two main factors.
The initial difficulty in finding suitable sites and secondly the results are somewhat ambiguous but provide a paradox that invites

resolution. There are three main areas for further investigation arising from this research.

1. Improvement of the technique. This research has found that the critical region for investigating the predicted pattern is within an area no more than 50 centimetres away from the post. Future work, along these lines, should limit itself to this region and develop the technique using tubes, inserted directly down into the soil surface, instead of using Kubiena tins. There is a need for more density values from the sides of posts. Eventually it should be possible to use the data to estimate the rate of soil movement over a fixed period of time. One of the major findings of the research was the increasing soil density towards the post on the down-slope side. Further investigation of soil on the down-slope side of posts is necessary to establish whether or not the increasing trend is unique to this research site or actually is of general occurence. It is not accounted for in the diffusion theory or indeed any other theory of soil creep and a thorough enquiry into this finding would improve our understanding of the exact nature of soil movement.

2. Resolution of the paradox. A comparison with the empirical up-slope curve and the predicted curves suggests that the diffusion component of the soil movement is relatively weak. At the same time the small U/D values imply that the diffusion component is larger than expected by at least one magnitude. It is important that this paradox is resolved in any future work as it is a crucial step towards attaining a better estimate of the magnitude of the diffusion coefficient.

3. Extension to include other techniques. A more efficient way to extract data from the thin sections should be sought and the use of X-rays could prove to be a most promising avenue in further investigations. An X-ray technique has been used in the late 1960's (Greacen, Farrell and Forrest, 1967) to measure the distribution of density on a semi-microscopic scale around a penetrometer hole, in order to test a theoretical model of the penetration mechanism. X-rays have not been used in this investigation but they are recognised as having great potential in future studies involving quantification of soil structural properties from thin sections.

A.1 OBERON GLADE -UPSLOPE

no. of slide	distance from post(cm)	depth(mm) from surface	% voidage									mean
6	41	80	18.2	14.2	18.1	28.3	14.7	10.6	10.9	14.5	10.5	15.6
7	41	70	13.8	17.0	16.7	15.9	19.7	18.1	14.1	14.7	13.5	15.9
8	41	40	18.3	19.3	22.1	22.3	28.3	27.3	20.1	19.8	17.7	21.7
9	41	50	16.2	17.4	18.3	13.3	15.7	13.1	11.4	16.0	12.3	15.0
10	41	130	12.4	16.3	23.2	25.7	18.3	18.2	15.0	20.5	17.6	18.6
11	41	70	23.7	16.5	15.8	13.9	19.9	19.0	14.9	13.6	13.9	16.8
12	33	50	7.0	13.4	13.2	21.5	25.9	16.0	10.0	10.4	11.4	14.3
13	33	60	11.1	19.0	14.0	7.6	23.8	14.0	14.8	16.4	13.3	14.9
15	33	50	19.9	10.9	12.0	18.6	16.5	17.5	20.4	15.8	17.3	16.5
16	33	80	25.8	11.3	13.4	16.8	14.3	21.5	16.1	12.8	19.5	16.8
17	23	110	12.0	15.4	12.9	17.2	17.8	22.3	17.3	14.7	16.1	16.2
18	23	60	9.5	16.3	19.9	18.4	14.6	14.5	12.5	11.4	14.1	14.6
19	23	65	13.2	12.7	9.0	20.2	8.0	12.9	13.8	11.9	12.4	12.7
20	23	65	destroyed									—
21	23	45	19.3	26.1	16.0	18.0	11.0	8.5	13.2	13.2	10.2	15.1
22	23	50	10.6	9.4	9.8	11.1	15.0	15.9	11.3	13.5	15.3	12.4
23	17	55	6.7	28.4	6.7	6.2	8.0	13.4	14.5	11.9	14.3	12.2
24	17	40	12.5	8.5	12.5	11.2	10.3	19.0	16.9	11.1	12.6	12.7
25	17	50	18.5	9.9	18.6	10.1	16.2	10.4	15.2	12.6	6.9	13.2
26	10	30	13.1	17.0	16.3	13.1	18.2	9.4	13.5	7.8	8.3	13.0
28	10	15	14.1	9.5	14.7	6.6	9.1	8.1	14.7	13.3	6.5	10.7
29	10	45	11.2	18.5	17.4	11.4	10.7	11.4	8.2	8.3	8.3	11.7
30	10	40	8.6	13.9	9.6	14.9	10.0	13.5	16.4	13.4	8.0	12.0
31	10	60	11.7	14.2	16.7	8.1	15.7	11.8	9.3	9.5	7.5	11.6
32	10	30	7.2	13.9	12.5	10.6	15.5	8.7	5.8	6.3	6.1	9.6
33	10	55	10.9	11.4	13.2	8.8	7.8	12.6	8.3	10.3	7.2	10.1
34	10	50	6.7	5.8	3.9	8.4	8.6	6.5	6.3	9.1	9.1	7.2
35	10	50	9.3	13.3	14.9	7.1	7.6	7.9	10.9	6.5	7.1	9.4

A.2 OBERON GLADE - DOWNSLOPE

no. of slide	distance from post(cm)	depth(mm) from surface	% voidage									mean
1	35	35	19.7	18.0	18.9	14.4	18.3	19.7	9.7	13.3	12.2	16.0
2	35	75	32.6	27.4	27.7	11.6	10.3	13.8	10.8	17.7	15.5	18.6
3	35	85	20.5	23.2	24.4	9.7	8.3	7.0	11.4	21.4	11.4	15.2
4	35	60	31.3	28.2	29.3	19.7	16.1	19.0	15.2	19.0	18.8	21.8
5	35	40	17.3	16.2	26.4	9.5	24.4	12.4	17.1	17.6	15.8	17.4
6	35	55	24.8	20.7	30.4	15.6	15.6	27.2	18.6	10.5	19.4	20.3
7	35	35	25.8	27.2	24.2	17.0	13.1	21.2	9.8	13.1	18.4	18.9
8	35	30	23.9	22.2	20.0	14.0	19.2	20.2	10.4	11.9	14.8	17.4
9	28	55	24.8	24.2	25.4	20.3	15.3	15.5	16.4	12.8	8.9	18.2
10	28	15	23.4	20.3	25.2	16.1	13.3	15.2	18.2	18.5	20.2	18.9
11	28	35	23.4	23.6	27.4	21.8	24.5	25.7	18.3	15.5	15.1	21.7
12	28	10	16.6	21.9	16.0	6.0	13.2	13.3	9.1	8.6	12.2	13.0
13	28	25	28.5	26.8	25.1	7.9	6.3	6.5	15.4	16.8	20.6	17.1
14	28	30	28.0	23.7	11.7	11.2	5.8	7.4	14.9	10.6	8.9	13.6
15	28	60	20.9	19.8	13.7	8.7	15.0	6.9	12.5	10.3	11.7	13.3
16	20.5	35	19.9	17.2	16.1	7.8	10.4	10.6	13.5	17.5	16.8	14.4
17	20.5	30	15.1	23.2	28.1	8.1	7.1	6.4	14.0	5.1	12.3	13.3
18	20.5	45	20.6	19.4	19.7	13.0	9.6	9.4	18.7	13.0	18.0	15.7
19	20.5	30	23.1	15.8	13.4	5.9	9.6	6.2	15.5	11.1	23.3	13.8
20	20.5	30	24.0	19.4	16.1	7.3	4.9	3.6	10.2	12.9	9.7	12.0
21	20.5	20	15.9	25.0	27.7	7.0	5.7	4.6	13.0	10.9	12.7	13.6
22	20.5	40	18.7	12.4	19.2	6.5	9.3	5.2	15.6	15.8	6.2	12.1
23	13	30	destroyed									—
24	13	30	19.7	19.3	16.5	9.0	3.5	7.1	6.9	6.6	9.6	10.9
25	13	30	18.7	27.1	21.1	9.0	5.0	6.1	15.3	10.3	10.6	13.7
26	13	50	19.7	16.9	14.8	7.5	6.2	7.0	10.5	9.0	7.3	11.0
27	13	40	13.0	27.9	26.6	12.5	15.6	14.5	12.3	11.0	11.0	16.0
28	13	50	21.7	18.8	25.3	15.5	17.0	15.5	11.3	6.2	7.2	15.4
29	13	40	22.6	13.8	20.4	10.8	7.5	8.4	13.1	6.6	6.4	12.2
30	6.5	75	17.4	16.7	22.1	10.1	8.7	15.2	9.3	14.7	11.3	13.9
31	6.5	50	18.4	19.0	13.8	6.7	8.3	13.0	11.9	13.9	12.9	13.1
32	6.5	75	20.6	27.3	10.2	6.9	6.5	12.9	4.0	9.5	16.3	12.7
33	6.5	50	22.0	20.2	17.6	5.1	9.7	3.8	9.2	11.1	13.8	12.5
34	6.5	30	18.5	11.5	28.0	6.3	7.2	5.3	10.7	11.8	11.3	12.3
35	6.5	60	26.0	14.0	8.5	5.0	13.3	5.2	5.5	11.2	9.2	10.9
36	6.5	50	26.9	16.8	6.7	9.0	8.1	10.6	10.2	13.3	11.8	12.6
37	6.5	75	20.5	10.2	7.7	10.1	12.2	6.2	7.1	8.7	9.5	10.2
38	6.5	55	13.7	11.4	13.2	7.5	14.8	9.6	11.9	9.3	7.0	10.9

A.3 THURSLEY COMMON - WEST

no. of slide	distance from post(cm)	depth(mm) from surface	%voidage									mean
1	38.5	2.5	21.4	47.6	37.3	23.3	19.2	19.1	20.6	20.3	18.5	25.3
2	38.5	2.5	23.4	31.6	34.4	20.5	16.2	24.1	30.3	24.2	25.7	25.6
3	41	2.5	28.9	49.8	47.6	18.5	28.3	21.8	23.2	27.5	24.1	30.0
4	32.8	2.5	18.6	38.4	35.2	42.4	23.7	25.6	23.0	26.4	18.4	28.0
5	32	2.5	30.0	41.0	43.1	20.9	24.3	21.2	24.2	32.4	22.4	28.8
6	34	2.5	31.8	28.1	44.0	24.9	26.8	25.5	15.2	15.5	18.3	25.6
7	35.2	2.5	51.1	32.3	42.0	26.1	22.0	19.4	22.6	14.8	18.5	27.6
8	23.2	2.5	35.8	27.4	40.7	20.8	23.0	23.1	28.9	29.6	16.0	27.3
9	26.0	2.5	17.8	25.9	17.3	23.3	19.5	17.2	14.9	30.1	14.0	20.0
10	39	2.5	21.1	36.7	29.0	26.5	34.6	28.2	35.2	25.5	11.5	27.6
11	25.5	2.5	35.6	29.4	20.6	18.4	20.0	19.9	17.3	13.0	18.1	21.4
12	30.5	2.5	25.2	19.4	17.1	16.1	16.9	19.1	24.2	12.4	15.5	18.4
13	32.8	2.5	27.9	39.1	33.4	20.2	15.8	12.7	15.4	20.1	22.5	23.0
14	27.2	2.5	30.8	16.4	44.3	23.4	17.7	14.7	20.2	13.3	18.5	22.2
15	22	2.5	28.2	25.1	26.7	25.1	22.1	18.7	23.7	11.0	20.6	23.3
16	26	2.5	24.9	25.3	17.3	24.6	16.6	18.6	22.0	25.9	18.9	21.6
17	29.3	2.5	26.3	34.7	37.6	18.8	24.2	24.4	21.8	25.7	22.6	26.2
18	19.8	2.5	25.3	22.3	37.3	37.8	18.9	27.1	19.0	17.0	22.5	25.2
20	9.5	2.5	38.6	42.5	19.9	21.2	18.2	24.6	27.0	19.3	20.8	25.8
21	1.5	2.5	33.3	22.0	18.0	21.9	15.1	23.0	25.7	22.8	21.3	22.6
22	17.6	2.5	27.6	25.1	44.3	32.4	21.9	26.3	18.3	18.6	20.1	26.1
23	25.5	2.5	38.3	25.2	13.5	25.7	23.9	23.3	26.2	23.8	21.4	24.6
24	18.4	2.5	27.2	23.4	34.9	32.1	35.1	22.0	19.3	30.9	24.6	27.7
25	21.2	2.5	30.0	23.6	24.7	19.9	24.6	23.3	26.5	20.6	30.3	24.8
26	21.5	2.5	24.3	23.5	24.8	18.1	23.6	27.0	32.7	14.7	21.9	23.4
27	16	2.5	34.0	30.5	35.0	33.5	18.1	33.8	20.9	26.1	20.8	28.1
28	16	2.5	31.8	15.3	34.6	20.2	32.3	22.2	29.7	24.4	17.8	25.4
29	13	2.5	23.7	24.6	27.3	35.7	36.7	27.3	22.4	20.0	23.9	26.8
30	14	2.5	35.7	33.6	14.7	30.2	33.5	21.4	20.6	17.0	28.7	26.2
31	13.5	2.5	33.5	26.1	36.8	36.9	27.4	44.3	19.7	32.3	26.5	31.5
32	9.5	2.5	20.2	33.6	19.0	26.8	30.9	28.3	24.0	27.5	25.1	26.2
33	2.5	2.5	32.8	30.9	22.1	27.8	31.2	22.9	21.3	22.0	25.6	26.3
34	8.8	2.5	17.9	29.2	31.5	35.6	40.7	30.1	28.5	23.0	23.6	28.8
35	2.5	2.5	19.0	37.9	28.1	37.0	45.1	27.5	22.7	22.8	20.6	28.9
36	8.8	2.5	41.9	46.5	26.8	22.5	42.6	35.3	22.1	22.2	26.9	31.9
37	12.8	2.5	41.8	34.8	24.9	18.1	27.5	21.0	18.1	24.1	23.0	25.9
38	14	2.5	38.3	19.5	36.4	27.3	30.2	16.7	19.8	17.1	23.8	25.5
39	2.5	2.5	33.3	22.9	20.2	44.0	32.4	21.9	29.0	20.2	26.6	27.8
40	2.5	2.5	19.3	25.1	42.4	33.6	37.1	19.4	29.4	20.7	49.7	30.7
41	2.5	2.5	32.9	34.4	18.1	31.1	15.2	28.7	32.3	28.6	28.0	27.7
42	8.5	2.5	38.5	32.3	19.7	32.1	27.1	18.3	18.1	26.2	11.8	24.9
43	12.8	2.5	31.1	28.4	26.6	30.7	41.8	34.6	23.0	15.6	30.9	29.2
44	8	2.5	44.1	28.8	24.1	36.0	31.0	23.1	18.3	21.8	25.0	28.0
45	8	2.5	24.7	23.6	23.0	29.4	28.5	30.1	18.7	25.0	21.2	24.9
46	2.5	2.5	37.0	48.3	37.4	34.0	27.7	38.0	18.4	18.5	20.3	31.1
47	2.5	2.5	27.3	22.2	32.6	24.3	24.5	26.8	15.1	23.2	17.4	23.7

A.4 THURSLEY COMMON - EAST

no. of slide	distance from post(cm)	depth(mm) from surface	% voidage									mean
7	44	64	24.4	21.2	18.0	27.4	13.6	25.3	28.9	23.1	20.2	22.5
8	44	72	25.2	22.3	30.0	21.1	18.3	23.9	34.1	20.1	17.2	23.6
9	44	96	28.6	35.4	19.6	32.7	18.1	12.7	27.0	24.0	16.0	23.8
10	44	40	27.0	22.8	28.3	29.2	35.4	33.1	29.9	25.6	26.9	28.7
11	44	40	20.7	22.6	30.1	20.9	32.3	42.6	23.3	28.3	34.2	28.3
12	36	80	26.2	38.3	22.7	23.3	18.4	25.8	24.3	18.8	22.0	24.4
13	36	80	20.8	27.6	22.7	13.6	26.2	23.7	27.6	27.3	23.3	23.6
14	36	104	28.1	22.9	39.7	18.5	17.2	25.3	21.4	15.7	14.5	22.6
15	36	40	35.7	36.5	41.3	21.0	26.4	18.7	21.7	21.8	21.2	27.1
16	36	40	33.2	26.2	25.5	28.5	29.9	23.3	15.5	22.3	17.7	24.7
17	29.5	64	25.5	33.4	26.0	23.9	9.5	18.6	27.9	20.9	15.5	22.3
18	29.5	88	30.3	24.8	36.8	21.9	21.7	22.1	15.0	24.7	22.2	24.4
19	29.5	48	21.7	27.5	27.1	19.1	27.7	22.9	20.6	14.1	18.7	22.2
20	29.5	152	25.3	21.4	29.9	22.9	17.5	25.2	34.4	13.2	23.1	23.7
21	29.5	64	18.4	24.1	32.0	16.7	20.6	22.5	18.3	16.4	18.2	20.8
22	29.5	56	21.9	23.3	26.5	15.3	29.2	24.3	18.5	21.6	19.0	22.2
23	29.5	56	17.1	28.7	20.7	28.8	23.3	25.3	22.9	28.8	33.3	25.4
24	20	88	22.7	31.6	21.1	17.6	30.9	31.5	16.8	25.1	18.9	24.9
25	20	72	24.9	25.5	31.7	26.4	39.5	33.6	23.8	31.8	18.3	28.4
26	20	48	20.6	30.8	36.0	33.6	30.5	35.6	18.1	28.7	20.6	28.3
27	20	48	36.0	31.9	28.1	27.1	30.1	27.3	30.8	27.2	32.9	30.2
28	14.5	72	30.0	20.5	28.3	19.8	37.2	30.8	19.4	16.3	10.3	23.6
29	14.5	72	28.5	26.7	25.7	28.6	39.5	24.1	17.5	23.4	24.6	26.5
30	14.5	72	destroyed									--
31	14.5	32	20.5	28.1	26.1	26.9	21.8	20.1	18.2	16.3	24.3	22.5
32	14.5	40	14.6	29.2	14.7	40.3	20.4	18.3	25.5	17.4	28.1	23.2
33	14.5	48	26.6	39.4	25.7	20.9	25.7	23.4	25.4	21.0	17.2	25.0
34	14.5	48	17.5	34.2	29.2	27.1	31.9	21.7	15.6	23.2	18.5	24.3
35	6	48	20.1	27.6	11.8	21.5	28.0	36.3	19.4	14.6	36.7	24.0
36	6	48	30.7	35.6	36.6	31.0	39.7	33.8	20.7	25.1	15.5	29.9
37	6	48	34.9	31.8	26.8	26.6	38.1	33.8	22.5	18.8	15.5	27.6
38	6	48	26.5	20.3	24.0	24.9	25.4	18.8	17.9	23.4	15.6	21.9
39	6	48	22.4	22.5	19.1	36.6	25.5	22.4	13.9	17.3	30.3	23.3
40	6	112	17.4	23.1	16.3	20.8	21.5	11.8	17.7	15.3	14.4	17.6
41	6	112	15.3	23.5	24.7	23.0	18.7	22.4	18.5	12.6	18.3	19.7
42	6	112	16.0	17.5	22.4	9.2	33.5	33.6	36.9	23.4	20.1	23.6

Appendix B - calculations

B.1 To Determine Sample Size

No. of slide	depth	no. of negatives	% voidage			
TC right 27	48mm	36	37.2	39.9	35.9	37.1
			38.2	34.2	41.0	40.1
			41.8	39.9	37.6	37.3
			34.2	53.7	53.7	46.0
			42.7	38.4	37.0	41.9
			44.2	33.4	50.1	38.1
			36.9	33.6	45.4	42.6
			44.6	41.9	45.0	38.5
			36.2	46.4	40.7	39.0

To estimate required sample size :-

$$\text{sample size } (n) = \left[\frac{t_{n-1;\, \alpha/2} \times s}{e} \right]^2$$

where N (no. of observations in pilot study) = 36
$\bar{X}$ (mean of the observations) = 40.67
s (standard deviation of observations) = 5.00
e (maximum tolerable sampling error) = 4.07
t (student t value) = 2.00

$$n = \left[\frac{2.00 \times 5.00}{4.07} \right]^2 = 6.04$$

n = 6, df = 5, now t = 2.57

$$n = \left[\frac{2.57 \times 5.00}{4.07} \right]^2 = 9.97$$

n = 10, df = 9, now t = 2.26

$$n = \left[\frac{2.26 \times 5.00}{4.07} \right]^2 = 7.71$$

n = 8, df = 7, now t = 2.37

$$n = \left[\frac{2.37 \times 5.00}{4.07} \right]^2 = 8.48$$

n = 9, df = 8, now t = 2.31

$$n = \left[\frac{2.31 \times 5.00}{4.07} \right]^2 = 8.05$$

The required sample size is therefore between eight to nine. It was to take nine photographs of each thin section.

B.2 Validation of Digitized Results

	digitized (Y)	point counts (X)
1	18.0	18.1
2	7.0	10.2
3	18.2	19.6
4	6.5	9.8
5	18.6	19.6
6	21.2	21.1
7	14.8	13.2
8	16.4	14.2
9	13.3	14.2
10	28.3	26.5
11	6.2	8.0
12	9.7	10.3
13	13.3	14.2
14	10.6	11.7
15	9.6	8.8
16	10.2	9.8
17	20.4	20.1
18	15.7	15.2
19	34.7	34.3
20	35.2	34.8
21	21.8	19.6
22	19.2	21.1
23	19.1	20.1
24	16.2	15.2
25	26.5	26.5
26	23.6	24.0
27	25.0	25.0
28	17.2	16.7
29	32.7	32.4
30	18.9	18.6
31	30.3	30.9
32	22.4	20.1
33	13.6	13.2
34	24.3	24.5
35	18.6	19.1
36	17.3	18.1
37	23.3	24.5
38	22.3	20.6
39	12.2	12.3
40	18.8	18.1
41	7.3	6.9

To calculate the degree of correlation (r) between X and Y :

$$r = \frac{N\sum XY - (\sum X).(\sum Y)}{\sqrt{[N\sum X^2 - (\sum X)^2] . [N\sum Y^2 - (\sum Y)^2]}}$$

where $\sum X = 761.20$ $\quad \sum Y = 758.30$ $\quad \sum XY = 16153.65$

$\sum X^2 = 16144.80$ $\quad \sum Y^2 = 16234.71$ $\quad N = 41.00$

$$r = \frac{(41 \times 16153.65) - (761.20 \times 758.30)}{\sqrt{(41 \times 16144.80 - 761.20^2) \times (41 \times 16234.71 - 758.30^2)}}$$

$$r = 0.98$$

testing the significance of r using :

$$t = r\sqrt{\frac{N - 2}{(1 - r^2)}}$$

$$t = 30.76$$

df = N-2, two-tailed test at the 99.9% level, critical t value = 3.55. The calculated value (30.76) is far greater than the critical value (3.55). Therefore, it can be said that the positive correlation between the digitized and point count results is highly significant and there is no significant difference between the methods.

B.3 % Voidage Results from Four Control Sections

All four samples were taken at a constant depth of 30 millimetres, at least 15 centimetres apart and on a flat site away from the influence of posts. Using a Kruskal-Wallis (analysis of variance by ranking) to see :

Ho : all the median scores are equal
H1 : at least two of the median scores are unequal

The observations are ranked by assigning rank 1 to the lowest, rank 2 to the next lowest and so on.

%	R	%	R	%	R	%	R
14.2	18.5	9.1	2	12.6	9	12.9	11.5
17.5	3	22.3	3	16.1	26	15.9	25
11.2	22	22.4	36	17.9	32	12.1	7
15.2	13	11.3	4	12.2	8	17.3	29
14.9	30	11.8	5.5	13.7	14.5	14.5	21
14.8	24	14.2	18.5	18.3	34	14.3	20
11.8	5.5	13.8	16	17.9	32	8.9	1
13.2	23	16.3	27	16.6	28	14.0	17
13.7	14.5	12.9	11.5	12.8	10	17.9	32
$\bar{X}=14.1$	153.5	$\bar{X}=14.9$	155.5	$\bar{X}=15.4$	193.5	$\bar{X}=14.2$	163.5

$$H = \frac{12}{N\,(N+1)} \cdot \left[\sum \frac{Ri^2}{n\,i} \right] - 3\,(N+1)$$

$$H = \frac{12}{36 \times 37} \times \left(\frac{153.5^2 + 155.5^2 + 193.5^2 + 163.5^2}{9} \right) - (3 \times 37)$$

$$H = 1.03$$

df = (4-1) = 3, one-tailed test at the 95% level, H values follow the χ^2 distribution when there is more than three categories to compare and at least five observations within each category. Critical H value is 7.8.
The calculated H value (1.03) is less than the critical H value. Therefore, Ho can be accepted, that is all the median scores above are equal and there is no significant difference between the samples.

Appendix C - Continuous source solutions

The following equation is an expression of the steady state distribution of concentration of material about a cylindical barrier (Culling, 1983, p.215) : -

$$v = V_0 + V_0 \frac{U}{D} \cos\theta \, e^{-\frac{U_r}{2D}\cos\theta} \times$$

$$\times \sum_{0}^{\infty} \epsilon_n \frac{I_n\left(\frac{U_a}{2D}\right) K_n\left(\frac{U_r}{2D}\right) \cos n\theta}{\left[\frac{U}{4D} K_{n+1}\left(\frac{U_a}{2D}\right) - h K_n\left(\frac{U_a}{2D}\right) - \frac{U}{4D} K_{n-1}\left(\frac{U_a}{2D}\right)\right]}$$

Where, ϵ_o = 1, $\epsilon_n = 2,\ n > 1$
h = (U / 2D)cos θ
V_o = initial concentration (r = a)
U = uniform drift velocity in the direction of the negative x - axis (down slope)
D = diffusion constant
a = radius of circular boundary
r = distance from the circular boundary

The full derivation of this can be found in Culling (1983, appendix 1). He also points out that the equation is not as complicated as it looks. It is of Fourier - Bessel form : -

$$v = \sum a_n K_n \left(\frac{Ur}{2D}\right) \cos n\theta$$

and strongly convergent, being dominated by the first term. The modified K-type Bessel functions are strongly "concave-to-the-sky" and are radially disposed about the circle of the barrier.

Appendix D - Grain size analysis

Method

1 Weigh 20 g. air dry soil into 1000 ml. beaker. Add 100 ml. of 6 % H_2O_2. Steambath for 45 mins.
2 Add 150 ml. tap water and boil for 5 min.
3 Add 25 ml. 2N HCl and make up to 250 ml. with tap water. Boil for 5 min. stirring regularly.
4 Add de-ionized water to 1000 ml. Leave to stand over night.
5 Syphon to 2 cm. depth.
6 Adjust solution to pH 4.0 wth known volume of Na_2CO_3 .
7 Add 25 ml. dispersant ($(NaPO_3)_6$ and Na_2CO_3). Add de-ionized water to 400 ml.
8 Bring to the boil, stirring regularly, for 5 min. Place beaker immediately into cold water.
9 Transfer solution to 1 litre cylinder (with stopper) and make up to 1000 ml. Shake the cylinder for 60 seconds then pipette 20 ml. samples into pre-weighed 50 ml. flasks as follows :

< 50 μm	20 cm. depth	1 min 28 secs
< 22 μm	..	7 min 10 secs
< 8 μm	..	52 min
< 4 μm	..	3 hrs 32 min
< 2 μm	..	14 hrs 19 min 48 sec

The > 53 μm fraction of sand is collected by washing residue through a 53 μm mesh sieve, then dry and weigh. The 20 ml. samples are dried in the flasks and re-weighed. Care must be taken to subtract the weight due to the dispersant and Na_2CO_3 .

Results

The U.S.D.A. triangle was used to classify the results on their textural characteristics. They were as follows :

	Thursley Common	Oberon Glade
Sand > 53 μm	94.4 %	50.3 %
Silt 53 μm - 2 μm	1.1 %	39.6 %
Clay < 2 μm	1.9 %	9.0 %
	(SAND)	(SANDY LOAM)

Appendix - E

Copyright: The copyright for the various items of software resides in

John Gilbert (ULCC) (DIMFILM).
Adrian Clarke (QEC) (VAX DIMFILM implementation, DISPLOT)
Philip Taylor (Bedford) (SURFIT, PLOT3D, OVERLAY)

References:

DIMFILM: A general-purpose graphics library, written by John Gilbert at the University of London Computer Centre. The VAX implementation was performed by Nigel Arnot and Adrian Clarke of Queen Elizabeth College. The VAX implementation includes 3-dimensional surface drawing routines, SRFACE and SURFACE, based on routines written by . . .

```
C SPECIALIST                  THOMAS WRIGHT, NCAR,
C                             BOULDER, COLORADO  80303
C
C LANGUAGE                    FORTRAN
C
C HISTORY                     REPLACES K.S.+G. ALGORITHM CALLED SOLIDS AT
C                             NCAR.  WRITTEN DECEMBER 1971, STANDARDIZED
C                             JANUARY 1973.
C                             PREPARED FOR SIGGRAPH, AUGUST 1976.
C
C ALGORITHM                   HIGHEST SO FAR IS VISIBLE FROM ABOVE.  (SEE
C                             REFERENCE.)
C
C REFERENCE                   WRIGHT, T.J., A TWO SPACE SOLUTION TO THE
C                             HIDDEN LINE PROBLEM FOR PLOTTING A FUNCTION
C                             OF TWO VARIABLES.  IEEE TRANS. COMP.,
C                             PP 28-33, JANUARY 1973.
```

Appendix - F

Computer Program used to Analyse the Black and White Photographs

```
{ FPL Library - available functions:  HELP, START, RANGE, AREA

  genealogy:
        EHISTC, xx.11.83.     SOILAC, 7.3.84.      SOILAD, 6.6.84. }

HELP:   WRITE
        "(' Calling routines: HELP, START, RANGE, FRAME, VIEW, AREA ')"
        RETURN;

VIEW:   DO IN:= 0 OD RETURN;

INPUT:  IN:=0; WHILE IN>15 DO SKIP OD RETURN;

RANGE:  WRITE "(' Borders - Left, Right ? ',$)"; READ LEFT, RIGHT;
        WRITE "(' Borders - Top, Bottom ? ',$)"; READ TOP, BOTTOM;
        WRITE LEFT, RIGHT, TOP, BOTTOM;
        XMIN:= LEFT; XMAX:= 127-RIGHT;
        YMIN:= TOP;  YMAX:= 127-BOTTOM;
FRAME:  [[ IF X<XMIN ! X>XMAX !Y<YMIN ! Y>YMAX THEN PO:= 0 FI ]]  RETURN;

AREA:   WRITE "(' AREA THRESHOLD ?',$)";  READ AREATH;
        AA:= 0; AB:= 0; AC:= 0;
        [[ IF PO>AREATH   THEN AA:= AA+1 FI;
           IF PO>AREATH-4 THEN AB:= AB+1 FI;
           IF PO>AREATH+4 THEN AC:= AC+1 FI ]];
        ATOT:= (XMAX-XMIN+1)*(YMAX-YMIN+1);
        ATMOD:= (ATOT + 25)/50; CORR:= ATMOD/2;
        AAP:= AA*2/ATMOD; AAD:= AAP*ATMOD; AAQ:= ((AA*2-AAD)*10+CORR)/ATMOD;
        ABP:= AB*2/ATMOD; ABD:= ABP*ATMOD; ABQ:= ((AB*2-ABD)*10+CORR)/ATMOD;
        ACP:= AC*2/ATMOD; ACD:= ACP*ATMOD; ACQ:= ((AC*2-ACD)*10+CORR)/ATMOD;
        WRITE "(' AREA = ', 4I5)", ATOT, AC, AA, AB;
        WRITE "(' Percentages = ',$)";
        WRITE "(' ', I5, '.',$)", ACP;   WRITE "(' ', I1, '%',$)", ACQ;
        WRITE "(' ', I5, '.',$)", AAP;   WRITE "(' ', I1, '%',$)", AAQ;
        WRITE "(' ', I5, '.',$)", ABP;   WRITE "(' ', I1, '%',$)", ABQ;
        WRITE "('     (error ~0.1%) ')";
        WRITE "(' Which Picture ? ')"
        RETURN;

PICTUR: PO RETURN;  { to use on any other picture change here
        ^^                                                       }

START:  @INPUT;
        RGB256[2]:=0; RGB256:=^100000!255;
        OUT:=0; NTH:=100;
        [[ RGB256[1]:=Y*256!X; RGB256:=PO ]];
        [[ FOR YY FROM 130 TO 136 DO FOR XX FROM 0 TO 255 DO
           RGB256[1]:=YY*256!XX; RGB256:=XX OD OD; EXIT ]];
        @GO; WRITE  "(' Initial threshold = ',I3)", TH;
        DO
           SET:=TRUE;
           IF JSTICK#48 THEN
              D:= IF   ~JSTICK&48  THEN  20  ELSE  4  FI;  { step size }
              IF  JSTICK&1  THEN  NTH:= TH+D; @GO  FI;      { increase }
              IF  JSTICK&2  THEN  NTH:= TH-D; @GO  FI;      { decrease }
              IF  JSTICK&64  THEN                          { print value }
                                 WRITE  "(' Threshold = ',I3)", TH;
                                 WHILE JSTICK#48 DO SKIP OD
              FI
           FI
        OD  RETURN;

GO:     [[ VVV:=255;
           TO 2 DO FOR YY FROM 138 TO 148 DO
           RGB256[1]:=YY*256!TH; RGB256:=VVV OD;
           RGB256[1]:=139*256!TH-1; RGB256:=VVV; RGB256[1]:=139*256!TH+1;
           RGB256:=VVV; RGB256[1]:=140*256!TH-2; RGB256:=VVV;
           RGB256[1]:=140*256!TH+2; RGB256:=VVV;
           MDC512[1]:=TH+TH+TH+TH;
           FOR I FROM 0 TO 90 DO MDC512[2]:=I; MDC512:=255-VVV OD;
           VVV:=0; TH:=NTH OD;
           EXIT ]];
        [[ RGB256[1]:=Y*256!X!128; RGB256:=(PO>TH)&255 ]]
        RETURN;

7Z:     [[ QO:=PO > TH ]]
        RETURN;
```

by Dr. E.R. Davies

Appendix G - Addresses

1. Crystic resin (17449)
Catalyst Q (17447)
Accelerator (17448)

B & K Resins,
Unit 2,
Ashgrove Estate,
Ashgrove Road,
Bromley. Kent. BR1 4TH.

Tel no : 01-464 7734/5

2. Uvitex OB
(fluorescent dye)

Dyestuffs & Chemical Division,
CIBA-GEIGY (ADP) Company,
Clayton,
Manchester. M11 4AR.

Tel no : 061-223 1341

3. Epofix

Vickers Instruments,
Haxby Road,
York. YO3 7DS.

Tel no : 0904 24112

4. Xlon boxes (XT1783)
100 x 100 x 65 mm

Scientific Supplies Co. Ltd.,
Scientific House,
Vine Hl.,
London. EC1.

Tel no : 01-278 8241

5. Vinyl aerosol spray

Fisons Scientific Apparatus,
Loughborough,
Leics.

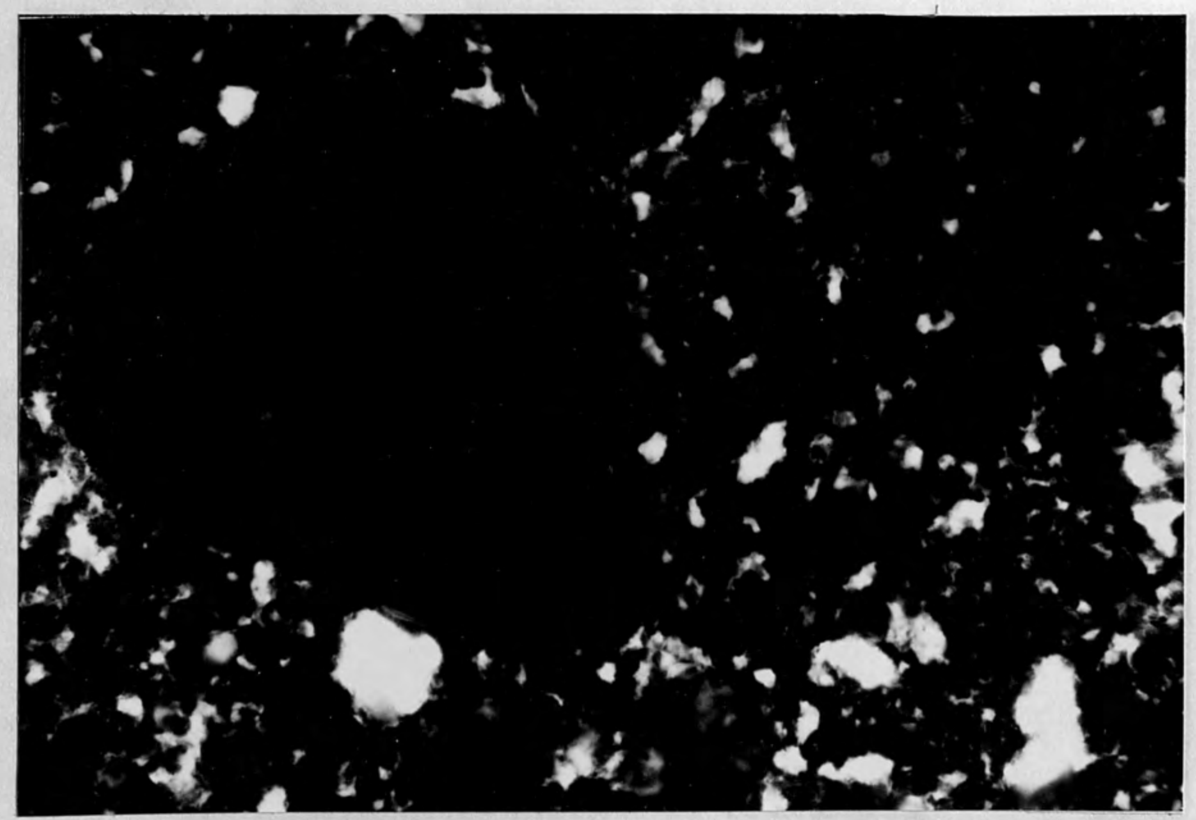
Appendix H - black and white photographs

Oberon Glade - up slope 6.5 percent voids (x320)

plate 5.1 a

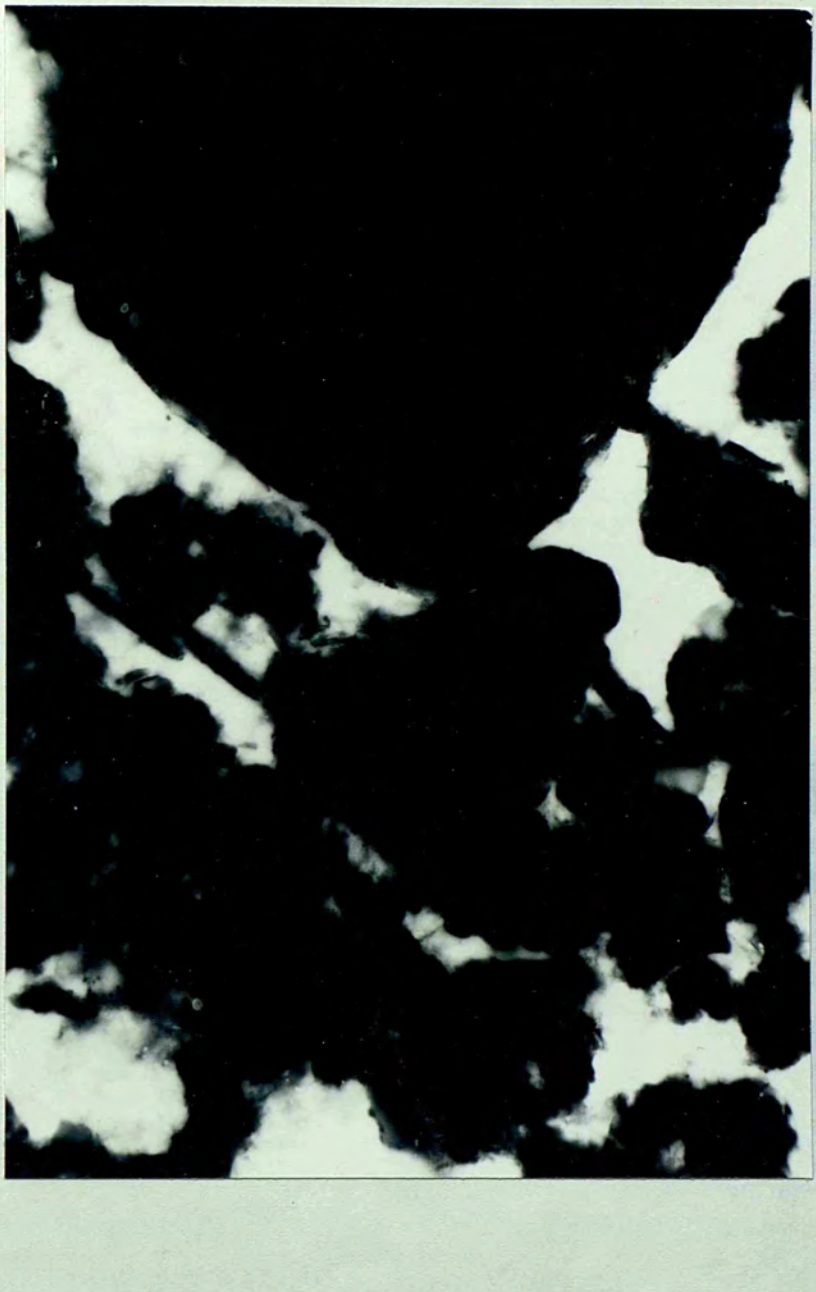
Oberon Glade - up slope 18.2 percent voids (x320)

plate 5.1 b



Oberon Glade - down slope 7.0 percent voids (x320)

plate 5. 2 a



Oberon Glade - down slope 18.6 percent voids (x320)

plate 5.2 b

Thursley Common - west 20.6 percent voids (x320)

plate 5.3 a

Thursley Common - west 21.5 percent voids (x320)

plate 5.3 b

Thursley Common - east 14.5 percent voids (x320)

plate 5.4 a

Thursley Common - east 28.1 percent voids (x320)

plate 5.4 b

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