THE EFFECT OF AGRICULTURAL IMPLEMENTS AND TRAFFIC ON SOIL BULK DENSITY USING GAMMA-RAY TECHNIQUES

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NOTES

Note (1) Units of measurement

An attempt has been made throughout the thesis to restrict the use of units to the metric system. However where reference is made to certain specific measurements in civil engineering and agriculture, British units have been retained for clarity. This follows a policy advocated by Koehler and Moodie (1967) who contend that ".... there are still many circumstances where metric units are not suitable for field research ....". Unit symbols correspond to BS 1991: Part 1: 1967 except that 'in.' has been used for inch(es) in conformity with the policy of the Journal of Soil Science.

Note (2) Computer programmes

During the course of this project the author prepared the following programmes in Atlas Autocode for computational and statistical operations.

IAE 001/0003	Analysis of variance of randomised complete block experiment with assessment of within-plot sampling error
IAE 001/0005	Computation of dry bulk density from gamma-ray transmission data with correction for non-standard geometry and provision for tabular and two dimensional coordinate output
IAE 001/0015	Computation of soil moisture content
IAE 001/0018	Computation of confidence limits for linear regression
IAE 001/0026	Computation of liquid and plastic limits, Proctor maximum density and optimum moisture content, particle density, sedimentation and sieving results for standard soil tests with provision for automatic allocation to U.S.D.A. textural class
IAE 001/0027	Computation of Bartlett's test for homogeneous variances with unequal degrees of freedom

Additional programmes for trend surface and multiple regression analyses were obtained respectively from Dr. P. McL. Duff, Geology Department, University of Edinburgh, and Mr. R. Day, E.R.C.C., and I am grateful for their assistance.

PART A REVIEW OF LITERATURE

CHAPTER 1

INTRODUCTION

1.1 The evolution of tillage equipment and usage

Traditional methods of crop production in all parts of the world include some form of soil tillage prior to planting. In its simplest and earliest form tillage consisted merely of dragging a roughly shaped tine-like implement through the soil which was loosened to a very limited degree and depth. Reade (1872) considered that "..civilisation commenced in the application of mechanics to the cultivation of the fields..". During the gradual evolution of agriculture, there has been a steady development of more specialised tillage equipment so that the farmer today has a wide range available, permitting him to perform at will almost any treatment to the soil which he considers necessary. With improved traction and auxiliary rotary and hydraulic power, the modern tractor is capable of drawing implements through soil which previously would have been considered unworkable. Tillage operations can therefore be varied very widely, both in the type of equipment and the time and manner of use.

1.2 The lack of quantitative criteria for optimum soil physical conditions

Unfortunately our knowledge of the required physical properties of the soil for different crops has not kept pace with the modern engineering achievements in tractor and implement design. There has been little attempt to define the desired physical properties which tillage should produce in the soil, certainly nothing comparable to the application of scientific methods for assessing the fertiliser requirements of soils. Jacks (1966) analysed the output of research papers in the field of soil science and noted that only 12-15% of the total were concerned with studies of physical properties. There are certain reasons for this retarded development in an important part of agricultural soil science. One is the difficulty of measuring soil physical properties in an undisturbed state. For example core sampling is tedious, destructive and impossible in stony or loose soils. Work on the physical properties of the clay-with-flints soil at Rothamsted started with considerable enthusiasm in the mid 19th Century but appears to have been abandoned later (Hall, 1905) due in some degree to the high stone content which amounted to approximately 20% $^w/w$ of the 0-9 in. depth in the classical fields. Within recent years certain non-destructive methods have become available but very little use has yet been made of these for studying soils in situ in the field. A second difficulty is that responses to physical management of the soil occur over short as well as long time scales. For example, the loosening action of a cultivation may be almost immediately modified or even nullified by heavy rain whereas the compactive effects produced below a plough share may be measurable only after many seasons. It has therefore not been possible to define experimental treatments and results with the same exactness as used in studying the chemical aspects of soil fertility.

1.3 Modern developments in tillage systems

The development of modern motive and tillage equipment represents a break from the traditional tillage systems inherited, in an almost unchanged condition, from the days of horse-drawn equipment. The obvious benefits from the use of tractors lead to a proliferation of wheeled traffic in the field for an ever increasing number of operations. The early suspicion of some farmers that tractors would harm the soil was considered laughable by those unfamiliar with the sensitivity of soils to damage from compaction. Careful observers such as Scott (1908) were concerned even with the compaction resulting from the treading of horses. As the weight and use of tractors has increased it has become increasingly apparent that serious physical deterioration of the soil <u>can</u> result from the mishandling of modern equipment.

The processes of physical deterioration are complex, showing different effects for different soils and crops and are often associated with changes in the soil organic matter status. Although there is little scientific understanding of these effects various attempts have been made to introduce improvements in the design and use of machinery. Of these the most important are tillage below plough depth, reduction in loading pressure beneath tractor wheels, reduction in wheel slip and the reduction of tillage operations through the use of herbicides. Tillage below plough depth is used to a variable degree with unpredictable results. The Potato Marketing Board, Anon. (1965a), showed that the proportion of the main crop potato acreage which was subsoiled was 22% in East Anglia, 16% in the East Midlands and virtually nil throughout the remainder of England and Scotland. It is often difficult to demonstrate an economic crop response to subsoiling and it is rarely possible to predict the effectiveness of the operation from observation of soil properties.

The use of track-laying tractors greatly decreases loading pressures and, in spite of extra capital and maintenance expenses, their use is considered justified in certain areas but in Britain generally only 4-5% of all tractors are tracked, Anon. (1965b). The use of multiple wheel, cage wheel and tool carrier systems would also result in useful reductions in loading pressures but their use is negligible to date. Considerable soil deterioration and power wasteage results from wheel slip if the traction requirement is too great for the available bearing capacity. This difficulty can be partly overcome through the use of implements designed to use rotary, hydraulic or vibrational energy direct from the tractor.

The use of herbicides has lead to progressive reduction in the frequency and depth of tillage. This development, loosely known under the term "Minimum tillage" offers the most drastic revision of tillage techniques. However, our limited knowledge of critical soil physical conditions at the moment precludes the prediction of the likelihood of the success of this system for different crops and soils. Of particular concern in this connection is the trend shown in Fig. 1.1 towards heavier harvesting equipment for cereals, potatoes and other root crops. Some of these harvesters may weigh as much as 5 tons and if used under unfavourable soil conditions could cause compactive damage incompatible with a minimum tillage system.

1.4 Economic aspects of tillage research

Kuipers (1963) presented a diagrammatical representation of the way in which tillage operations influence both the costs and the returns of farm cropping and hence have a double effect on profitability (Fig. 1.2). He points out that ".. if a farmer succeeds in saving an expensive chemical weed spray by effective cheap tillage operation, it is more realistic to say that the objective of the tillage operation was to decrease the production costs than that it was meant to increase crop yield".

Under the very rapidly changing situation concerning the design of motive units and implements and developments of herbicide usage, it is essential that a rational assessment based on scientific principles should

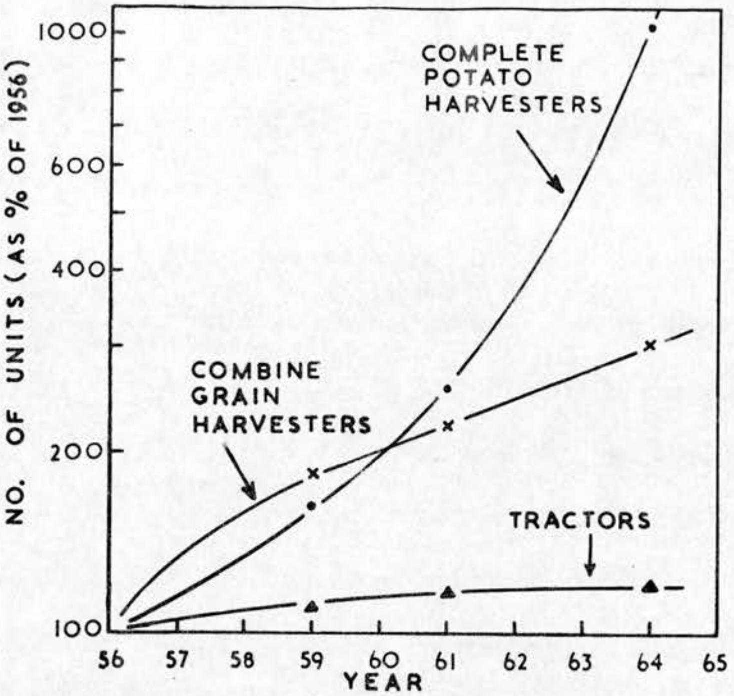

Fig. 1.1 Relative changes in number of complete potato harvesters, combine grain harvesters and tractors in Scotland during period 1956 to 1964 (Data abstracted from Anon., 1958 , 1962, 1964, 1966)

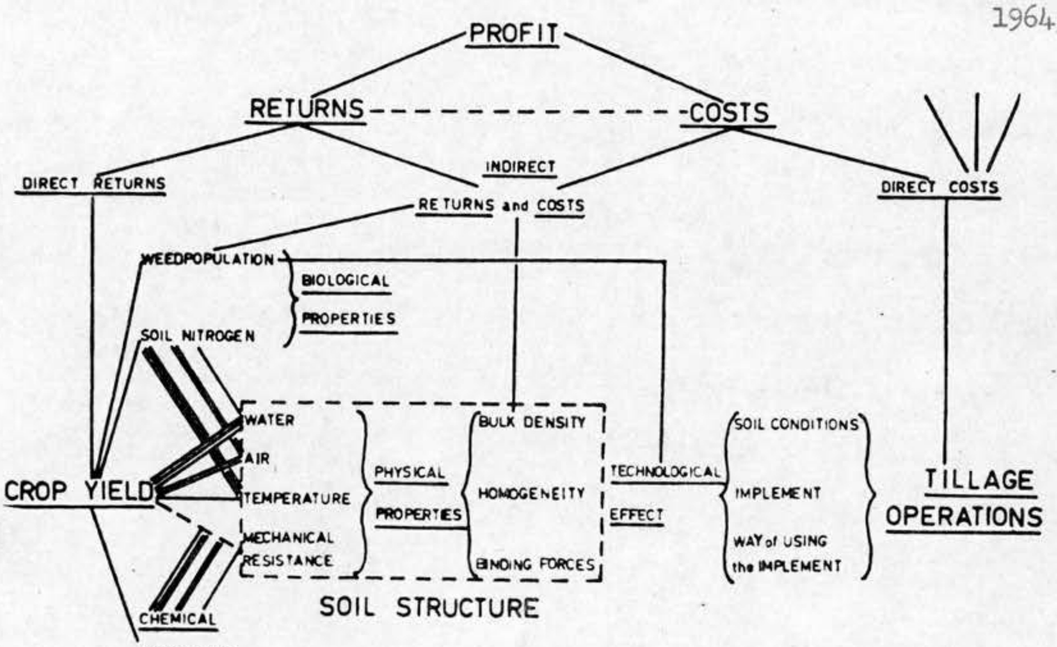

Fig. 1.2 Economic and "technological" aspects of tillage according to Kuipers (1963)

be made of all types of tillage operations in order to establish criteria and performance standards. In particular the long term effects must be considered since sustained productivity must be maintained in view of the capital investment in every acre of agricultural soil. The contribution of faulty tillage in long-term fertility degradation has not received much attention in this country. In U.S.A., Traboic _et al._ (1959) considered that "the mechanical consolidation of tillable soils has reduced crop yields and in extreme cases forced removal of the land from agricultural production".

1.5 The status of tillage research as a science

The new developments, referred to in section 1.3, have stimulated a growing awareness that lack of tillage research is limiting the application of the new systems and equipment which have become available in recent years. The awakening of interest is typified by the holding of the first International Conference on the Objectives of Soil Tillage in 1963 but the scale of the conference was very limited, only eleven papers being presented in a two-day period. However, it seemed to justify a more intensive effort to expand and co-ordinate research in this field. Blake (1963) particularly stressed that tillage studies must take account of all those operations which exert mechanical forces on the soil, traffic as well as tillage _per se_.

The proceedings of a subsequent conference in 1965* on 'Characterisation Problems in Soil Tillage' illustrate the progress made in the application of improved techniques. However among the 16 research papers presented by European and American specialists there was none from Britain. In contrast the advanced state of tillage research in the Scandinavian countries

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* Published in Grundförbättring 19: 1-227, 1966.

was shown by the statements of Njøs (1966) and Heinonen (1966) that the number of tillage experiments per year were 50 and 100 in Norway and Sweden respectively.

That tillage research is full of difficulties and delays is illustrated by the research of the National Tillage Laboratory, Alabama, which, under the directorship of Dr. M. L. Nichols, had already established nine 20 ft x 250 ft soil tanks in 1935. Twenty-two years later Nichols (1957) wrote "Unfortunately, we have not gone far enough with these studies to give the farmer or the machine designer specific instructions or to set further limitations for avoidance of compaction on the various soils under various conditions". These comments make an interesting comparison with those of Small (1784) "Let the husbandman once be agreed as to the state in which the ground should be left by the plough". Since then, although we may have acquired a large amount of information, agreement has not yet been reached and in the words of Harris _et al._ (1964) we have not "produced an adequate agricultural mechanics" with which to tackle the problem.

The most promising development in tillage research today appears to be the application of non-destructive testing methods in soil tanks and in the field and the more rigorous application of current techniques developed for the study of soil behaviour in the fields of civil engineering and off-the-road locomotion. The subject of soil bulk density measurement in tillage experiments was chosen for this study as it appeared that improvements in technique could yield results leading to an immediate and important contribution to the solution of several practical and theoretical problems. The review of literature which follows has been prepared in order to assess to what extent and by what mechanisms is bulk density a critical property of agricultural soils, the degree to which changes in bulk density occur in the tillage cycle and the methods by which bulk density may be measured.

CHAPTER 2

SOIL BULK DENSITY AND THE ROOT ENVIRONMENT

2.1 The limited usefulness of yield as an assessment of tillage effects

Nearly all tillage research, until very recently, has involved the use of crop yield as the main assessment of tillage effects. Even recently Barker (1963) and, to a lesser extent Van Doren (1965), employed this traditional approach. However Collis-George and Davey (1960) expressed dissatisfaction with field trials, stating "The interpretation of many field trials involving biological parameters would appear, after a century, to have come to a stalemate for lack of recorded "control" or environmental data". Byers and Webber (1957) and Russell (1950) claimed that much of the previous work on tillage was of extremely limited application both to practical farming and the scientific assessment of tillage practices. Pizer (1961) was unable to "relate the results of experiments in this country (Britain) on deep ploughing, subsoiling and other cultivations to soil structure, because information on soil profile conditions and changes in soil structure following treatment are largely missing from the accounts".

The reasons for the weakness of the traditional type of tillage experiment are numerous. The efficiency and effect of a tillage operation cannot be assessed merely by the statement that a specified tillage tool was used. The yield of crops is strongly influenced by the climate (above and below ground) during the growing season and the incidence of weeds, pathogens and insects, all of which may show marked interactions with the method of tillage. Economic considerations may justify a reduced yield if profitability can be sufficiently increased by a change in tillage practice. Understanding of the mechanisms by which tillage practices affect crop growth and yield will be successful only if soil physical properties of direct and proven relevance are measured before and after tillage operations under specified and reproducible conditions.

Frese (1963) stressed the weakness of tillage studies which do not take account of soil physical factors of direct relevance to plant growth. Kuipers (1963) suggested the term "technological effect" to indicate the overall effect of tillage on yield. This term covers changes in (a) weed population, (b) direct mechanical action on the crop and (c) soil physical conditions.

2.2 The plants' physical requirements of the soil

One of the first re-appraisals of traditional tillage/yield experimentation was made by Fountaine (1959) and this has served as a guide for much later work. He stressed the need to measure the effects of tillage methods in terms of four physical properties which he considered had 'direct' influence on plant growth, namely soil water, soil air, soil temperature and soil strength. Although his ideas were generally supported there were, and to some extent still are, certain serious experimental difficulties in measuring these properties on a suitably intensive scale in field experiments. The four 'direct' properties are generally considered to relate to the soil as a whole but in practice 'distribution' or 'intensity' factors in the profile may be important. For instance, studies on physical conditions affecting the germinating seed must take into account soil-seed contact characteristics rather than merely the bulk soil properties. Similarly the presence of secondary aggregates of high bulk density and strength (clods) may have important local influence on crop response which would be obscured if only bulk soil properties were measured.

Measurements of such properties as bulk density and aggregate-size distribution, which are of 'indirect' influence on plant growth, have often continued to be made owing to relative ease of their determination. Bulk density is of particular significance because it is strongly related to soil strength, aeration, water retention and hydraulic conductivity. Therefore the accurate determination of the distribution of bulk density within the tilled and sub-tilled layers at intervals throughout the cycle of ploughing, cultivation, sowing, crop growth and harvest would represent an important advance. However this has rarely, if ever, been satisfactorily achieved because of the limitations of traditional methods. For a given soil/climate association tillage practices may not introduce important variation in all the 'direct' properties. For conditions in S.E. Scotland variations of soil temperature and water status resulting from tillage operations have not been considered in detail although tillage workers elsewhere, particularly in the more arid parts of North America have established the relevance of these properties in tillage studies, Larson (1963).

2.3 Soil bulk density around the seed

Under certain conditions the normal planting technique does not produce sufficient contact between the soil and seed. Reduced or delayed emergence can result. This effect is most prevalent in areas in which soils are comparatively dry at and following the time of seeding. There may then be a considerable impedance to liquid flow of water between the soil and the seed. In this case compactive treatments are usually applied immediately after planting. Stout et al. (1961) examined the effect of different surface pressures on the emergence of several crops. The position of application of the pressure is important since surface crusts may result from compaction on the surface and emergence will not be improved. Compaction immediately at seed level tends to be more effective especially with large seeds.

Larson (1963) pointed out that the measurement of bulk-density changes resulting from compactive loading at or following seeding was particularly difficult owing to "the short horizontal distances over which the effect takes place". This is a situation for which the gamma-ray transmission method for the measurement of soil density (see Chapter 6) has outstanding advantages. An extremely striking example of the benefits of post-planting compaction was given by Dasberg et al. (1966) for grain sorghum grown on a clay loam with restricted moisture supply in Israel. Seedling emergence was increased tenfold by a heavy compaction treatment with a grain yield increase of 50%. Determination of bulk density, air permeability and penetrometer resistance were made and differences between a variety of compaction treatments were found to a depth of 6 in. Johnson and Henry (1964) reviewed work on the relation between press wheel performance, soil conditions and maize emergence.

Under certain conditions very considerable surface pressures may be required. Peterson (1960) found that after planting maize compaction caused by the front wheels of the tractor alone was not sufficient to give rapid germination. Normal press wheels were also inadequate. Fountaine and Payne (1952) noticed improved germination of grain in the tractor wheel tracks on chalk soils. However, on many soils the reverse is often noticed. The effect of post-planting compaction is unlikely to have any deleterious effect unless moisture contents are high. If the moisture content is sufficiently low the compaction will extend to only shallow depths and can be confined laterally to a narrow band on either side of the planting row for row crops.

2.4 The effect of compaction/density/porosity relationships on root development and yield.

For maximum growth and yield the root system should develop rapidly and intensively into as large a soil volume as is consistent with the characteristics of the crop. Root growth may be restricted by a number of interacting physical properties of which mechanical impedance and deficient aeration are the most important in this region. Detailed reviews of research in this field have been prepared by Lutz (1952), Rosenberg (1964) and Eavis (1965).

In many tillage and compaction experiments there has been a failure to record the basic physical parameters influencing the mechanical processes involved. The interpretation of results is difficult because of failure to pay due attention also to the differences between soils resulting from inherent variation in texture and structure and the differences between plant species due to variation in rooting habit, morphology and physiology.

(a) <u>The significance of soil differences</u> The importance of soil differences in relating bulk density to root growth was established in the classical work of Veihmeyer and Hendrickson (1948) and confirmed by Trouse and Humbert (1961). For hydromorphic humic latosol, root development of sugar cane was restricted at a bulk density as low as 1.1 g cm^{-3} whereas for grey hydromorphic clay, root penetration continued up to a bulk density of 1.75 g cm^{-3}. Bateman (1963) pointed out that, when considering plant responses to compaction, bulk density values should be reported for the same moisture content owing to the effect of different swelling and shrinkage characteristics. Rosenberg and Willits (1962) used three contrasting soils each compacted to five levels of bulk density with barley, beans and wheat as indicators and found that the plant responses to a given change of density depend on the interactions between the changes in porosity characteristics, hydraulic conductivity, oxygen-diffusion rate and available water capacity. Barley growth in a dry spring on sand increased with an increase of bulk density, attributable to improved water holding capacity. Oxygen-diffusion rate appeared to be the property most sensitive to compaction in a silty-loam whereas hydraulic conductivity was the most sensitive property for loamy sand and sand.

Håkansson (1966) showed that the drop in barley yield following similar surface compaction treatment varied from 2% for muck soil to 67% for a loam. A clay of bad structure showed a yield depression of 29% compared with 11% for a well structured clay. The response of Loblolly pine seedlings to different compaction treatments was studied by Foil and Ralston (1967) for three soils. Kneading compaction decreased bulk density when compared with static pressure application but seedling survival decreased markedly, indicating the significance of a puddling action not directly related to bulk-density change. Apart from this effect, root length for all soils showed a negative correlation with bulk density although the bulk densities were not as high as those reported elsewhere as being the cause of restricted root penetration. Differences in soil characteristics are probably responsible for many anomalies which occur in the literature. For instance compaction increased the yield of cotton according to Hubbell and Staten (1951) but the reverse effect was reported by Randolph <u>et al</u>. (1940). Interpretation of early work is frequently not possible owing to restricted analytical data.

(b) Differences between crops Considerable differences have been established in the ability of crops to withstand the deleterious effects of soil compaction. The reasons for this have not been fully investigated but are probably related to the known differences of root distribution, morphology and physiology in crop plants together with the different management techniques associated with their production.

The particular sensitivity of potatoes to soil physical conditions was shown by a prolonged series of experiments by Bushnell (1953). Pot experiments indicated that soil tamping was just as harmful as water-logging in decreasing yields. On a silt loam, poor yields were obtained if the total porosity was less than 49% but large yield responses resulted from an increase of total porosity of only 1 - 2%. Adams <u>et al.</u> (1960) studied the effect of compaction resulting from a pressure of about 150 lb in.$^{-2}$ applied on the surface and on the plough furrow bottom of a silty-clay loam and a silt loam. Very considerable and highly significant reductions in yield of potatoes and sugar beet were obtained. The mean depth of potato tuber development was approximately one in. less on the surface compacted soil and tuber specific gravity was reduced from 1.070 to 1.063 (highly significant). Changes in bulk density as a result of the compaction were small (1.02 increased to 1.17 g cm^{-3}) but a far more striking change of porosity at 60 cm H_2O suction occurred (14.9 to $8.4^{V}/V\%$). The authors considered that this was the dominant cause of the yield reductions. Compaction below the ploughed layer had an important effect on reducing yields either with or without surface packing. The variation in plant sensitivity to compactive changes was demonstrated convincingly. Yield depressions of 54%, 13%, 13% and 7.5% were obtained for potatoes, sugar beet, wheat and maize respectively, in response to a common compactive treatment. The sensitivity of sugar beet to compaction was demonstrated by Baver and Farnsworth (1940), Smith and Cook (1946) and Blake <u>et al.</u> (1960).

Rosenberg and Willits (1962) made a detailed study of the effect of compaction on the growth and yield of cereals and beans for three contrasting soils. For cereals negative correlation between yield and bulk density was recorded except for a sand for which the correlation was positive. Yield correlation coefficients were in general as high with bulk density as with the more 'direct' factors such as oxygen-diffusion rate, hydraulic conductivity and available water capacity. However bean yields were not significantly affected by the compaction treatments but a highly significant positive correlation was obtained between bulk density and "concentration of maturity" of the bean crop on silty loam soil. A detailed study of the effect of compaction of a clay soil on the growth of maize was reported by Phillips and Kirkham (1962). Reductions of stand, yield, height, mineral content, root weight and delayed development were recorded as compaction increased. Flocker et al. (1958a) established differences between the sensitivity of cover crop species to compactive increases of density from 1.22 g cm^{-3} to 1.58 g cm^{-3}.

Tomatoes have been the test crop for a number of compaction experiments. Bateman (1963) reported that the minimum tolerance for air voids is 30% for tomatoes but 8% for root crops. However the work of Flocker et al. (1960) showed no yield differences for tomatoes grown on soil compacted to different degrees in the previous autumn although root growth below 18 in. was affected by compaction. The fairly vigorous and extensive rooting system of the tomato was thought to account for its insensitivity to compaction in contrast to the potato which suffered a ware yield reduction of more than 50% for the compaction treatment. Work with tomatoes by Flocker and Menary (1960) was notable for the pronounced parabolic yield response to bulk density variation. This was probably related to the sandy soil used, for which water holding capacity would be restricted at low bulk densities. Optimum yields were obtained at a bulk density of 1.3 g cm^{-3}. Parabolic yield relationships with bulk density were also established by Revut <u>et al.</u> (1962). For a sandy loam maximum yields were obtained when the bulk density of the ploughed layer was 1.2 and 1.6 g cm^{-3} for oats and maize (green) respectively.

2.5 <u>Mechanical impedance</u>

Although root behaviour in synthetic media is now partially understood, the role of traffic and tillage in the development of zones within field soils sufficiently compact to reduce or inhibit root growth has not been fully established. Indeed Hawkins (1960) considered that although an increase of density results from the passage of tractors, "... it has reached a level far below what is accepted as too dense for plant roots to penetrate ...". There is some evidence that this represents a too optimistic viewpoint. De Roo (1960), working with coarse to medium textured soils in Connecticut, found considerable evidence for restriction to root growth by plough pans. The effect was entirely overcome by deep tillage. The bulk density of the impeding layer was 1.60 g cm^{-3} and the non-capillary porosity was 8%. Root restriction was attributed to mechanical impedence since oxygen supply was not limiting growth. Jamison <u>et al.</u> (1952) found that deep tillage caused marked responses in root development and yield if a plough pan was present but no effect if the pan was absent.

Rosenberg (1964) in a comprehensive review stated "It is becoming increasingly evident particularly on soils of medium and coarse texture, that compaction effects on plant growth need not necessarily involve impeded aeration". The sensitivity of mechanical impedance tests to changes due to compaction was shown by the work of Bateman (1963). For one silty-clay loam the change from minimum to maximum compaction increased the bulk density by 26%, decreased available air voids by 62% and increased mechanical impedance by 90%.

Studies of mechanical impedance of roots have developed with the aid of simplified media. The effect of rigidity of packing of soil particles and pore size was investigated by Aubertin and Kardos (1965 a, b) using glass beads of known diameters with and without external pressure. For rigid systems any reduction of pore diameter below approximately 412 µm resulted in reduced maize root penetration. No penetration occurred at pore diameters less than 138 µm. In non-rigid systems, pore size had no influence on root penetration. The specific effect of pore size in rigid systems was also investigated by Wiersum (1957) using sintered glass discs. The cohesional strength of glass bead-water mixtures was investigated by Vomocil and Waldron (1962). Lotspeich (1964) used compacted mixtures of kaolinite and glass beads. The strength was found to be related to the number of contact points. However these effects relate to the bulk strength of the material rather than the impedance to an object as small as a root tip.

Waxes of differing rigidity were used by Taylor and Gardner (1960) to simulate hardpans. Penetration depended upon the rigidity of the wax, the plant species and the density of the overlying soil.

Attempts to establish relationships between penetrometer measurements and root growth have been reviewed by Vomocil (1957). Phillips and Kirkham (1962) showed that maize-root growth decreased continuously with increasing bulk density and needle-penetrometer values. Taylor and Burnett (1964) expressed soil strength in terms of resistance to penetrometer movement. A strength greater than 30 bar was sufficient to restrict all root penetration. Field experiments were conducted in which compaction and tillage treatments had a marked influence on root development on a fine sandy loam. The reason for the restricted root development following compaction could not be associated with deficient aeration as even at a bulk density of 1.88 g cm^{-3} the air filled porosity was 15% whereas soil strength was found to be about 25-30 bar. It was concluded that "... it is soil strength, and no other physical factor of the soil, that controls growth of roots through moist soil". This generalisation cannot be accepted since there is plenty of evidence that aeration may be severely deficient in certain compacted soils.

Eavis (1965) used a penetrometer constructed to be the same physical shape as the root tips of pea seedlings. The penetrometer was driven at a constant speed by a triaxial test machine. The values for stress on the cross section of the penetrometer were 5 to 9 times as great as that on the root. This could not be explained by the difference in rate of penetration. Root tip movement cannot be treated as a mechanical phenomenon analogous to a penetrometer although close negative correlations however were established between impedance and root length. Henry and McKibbon (1967) reported penetrometer resistance values of 22 and 66 lb $in.^{-2}$ for cultivated and uncultivated soil at the end of the growing season of maize.

Field compaction and subsoiling tests by Taylor et al. (1962) showed such deterioration in plant growth that plants died unless planted over a line of subsoiler passage. The growth restriction was not considered to be due to insufficient aeration since the air-filled porosity at field capacity was 15% and root growth impedance was more severe at low moisture contents than at high values. Also there were very short boundaries between well-rooted zones and root-free zones. Penetrometer and vane shear results were more satisfactory indications of rooting ability than were bulk density results.

Garner and Bowen (1963) measured the forces exerted by emerging cotton seedlings and attempted to apply the Bekker sinkage theory to the action of root penetration and the Mohr theory of plastic failure. Application of theories developed for bulk soil behaviour to the penetration of roots is clearly fraught with difficulties because of the breakdown of dimensional similitude.

2.6 Aeration

Deficient aeration as a cause of infertility was demonstrated by Bushnell (1953) who investigated the cause of declining potato yields in Ohio in a long series of experiments. Applications of manure and the ploughing-under of green manure crops were not effective in maintaining good yields whereas ploughing under a sod prior to potatoes was effective. The reduction in organic matter and structural instability resulting from repetetive cropping apparently produced conditions in which aeration became a limiting factor to potato yield. Tile drains laid underneath planting rows gave considerable increases of yield (24%), especially if the tile was perforated. He considered a number of methods for improving the porosity including subsoiling, manuring and the incorporation of chopped straw. The latter was the only treatment which produced a yield response, due it is suggested, to the intimate mixing of the straw with the soil. The benefits of preceding potatoes by a sod crop was attributed to the high total porosity values found subsequently.

Aeration in soils can be expressed by the air-filled porosity, soil-air composition and oxygen-diffusion rate. Air filled porosity has been used widely on account of its simplicity of determination. Critical values have been reported by Baver and Farnsworth (1940), 10% for sugarbeet yield; Adams et al. (1960), 9% for potato yield; Bateman (1963), 10% for maize yield and Gradwell (1965), 7-8% for ryegrass root growth. Njøs and Nordby (1966) used air-filled porosity as an indication of compaction in an experiment comparing different levels of tractor traffic in a potato crop. Decreases of yield were associated with reduction in air-filled porosity following inter-row wheel traffic.

Bateman (1963) considered that comparisons of the effect of machinery on soil properties could best be made on the basis of air-filled porosity at field capacity since a 62% change in this property occurred from minimum to maximum compaction treatment whereas bulk density changed by only 26%. However the air-filled porosity is not necessarily a satisfactory indication of aeration status because of the significance of the thickness of water films in controlling the oxygen-diffusion rate to roots. The diffusion rate of oxygen through water is 10^{-4} of that through air. It has become usual to express air-filled porosity values at a specific soil-water suction, for instance 60 or 100 cm water.

The methods used for soil air composition studies have been reviewed by Van Bavel (1965). Soil air composition has not received much attention as a determinant in tillage research in the field but forced circulation of gas mixtures has been widely used for laboratory experiments involving controlled aeration treatment for root penetration studies. Results have generally shown that root growth is strongly dependent on oxygen concentration below a certain level. Eavis (1965), for instance, found that for pea seedlings the critical level was 16% oxygen with a decrease of root growth as oxygen concentration was reduced below this level.

Kuipers (1961a) has suggested the use of water content at pF 2 as a characteristic indicator of aeration conditions in tillage research. He showed that it was not necessary to use undisturbed core samples for this test provided that aggregates smaller than 2 or 3 mm are not formed during preparation of the sub-sample. This method does not appear to have been widely adopted in spite of its simplicity.

Previously mentioned methods for aeration assessment give only an indication of static properties whereas soil-air oxygen is in a state of dynamic equilibrium between the rate of absorption by plant roots and soil organisms and the rate of supply by diffusion into the soil. Using the 2000 l respirometers described by Fountaine and Brown (1959), Brown _et al._ (1965) investigated the difference in oxygen consumption in different soil and crop systems. Disturbance of a soil resulted in a considerable increase in its oxygen consumption. They found that surface crusts or caps were unlikely to be an effective barrier to gas movement except when saturated with water for an appreciable time.

The use of the platinum microelectrode for the polarographic determination of the oxygen status of the soil atmosphere is widely accepted and is reviewed by Menzel (1965). The method has been used by Gradwell (1965) who examined the restriction of growth and activity of barley roots during wet winter conditions in New Zealand. He compared the results of core sampling for the measurement of density and porosity with the platinum microelectrode method for oxygen-diffusion rate. He concluded that for wet soils of low strength, yield showed a closer correlation with oxygen diffusion rate than with soil moisture content or bulk density. The presence of a considerable number of blank-ended air-filled pores resulted in a less useful assessment of aeration status from air-filled porosity than with the platinum microelectrode.

Rosenberg and Willits (1962) measured oxygen diffusion rates in compacted silty loam soil by the platinum microelectrode method and showed that very large changes were obtained with relatively small changes in bulk density. For bulk densities of 1.07, 1.21 and 1.35 g cm^{-3} oxygen diffusion rates were 44.6, 14.9 and 9.6 g x 10^{-8} cm^{-2} min^{-1} respectively. Rickman et al.(1965) attempted to distinguish between oxygen deficiency and mechanical impedance effects in compacted soils. The oxygen-diffusion rate in compacted silt loam (+ Krilium) was below the critical value of 20 g x 10^{-8} cm^{-2} min^{-1} for good growth of tomatoes.

It may be concluded that aeration deficiency may occur in compacted soils particularly during periods of wet weather. Aeration problems may be particularly relevant where minimum tillage is practiced on soils with restricted internal drainage.

2.7 Moisture status and hydraulic conductivity

Compactive and disruptive change in soil may have marked effects on the moisture status of arable soils. These effects may occur in two ways. Firstly as a result of changes in the air/soil interface giving rise to differences in rainfall acceptance and evaporation rates and secondly as a result of changes in the internal soil properties particularly water retention and conductivity characteristics. The former type of effect is not generally important in humid temperate regions but the latter effect may be very important although it has received little practical attention. A theoretical treatment of the subject has been given by Arndt and Rose (1966c).

(a) Water retention Changes in bulk density were shown to have a considerable influence on water retention characteristics at low suctions by Taylor and Box (1961), Box and Taylor (1962) and Hill and Sumner (1967). The former workers found that a change in bulk density from 1.1 to 1.4 g cm^{-3} for a silt loam, which may readily occur in both directions during a yearly cycle for an arable soil, was accompanied by a change of matric suction from approximately 260 mb to 150 mb at a moisture content of 23%. Hill and Sumner (1967) showed that the effect of compaction on water retention varied widely between different soils. An increase in water retention (% $^{w}/w$) with increasing bulk density was found for all soils at low suctions but at high suctions water retention was unaffected by increasing bulk density in sands, increased considerably in clay and decreased in sandy loams and sandy-clay loams. Czeratzki (1966) reports that the loosening resulting from subsoiling of clay soils caused an increase of water retention at 100 cm water suction whereas the opposite effect occurred in sandy soils. Rosenberg and Willits (1962) found a 48% increase of available water capacity as a result of compacting a sandy soil.

(b) Effect on hydraulic conductivity Hydraulic conductivity of soils is primarily influenced by the large pores which are particularly susceptible to reduction during compaction. Striking examples of the effect of compaction on the hydraulic conductivity of soils are given by Taylor and Henderson (1959) who found a tenfold decrease of hydraulic conductivity for a bulk-density increase from 1.2 to 1.4 g cm^{-3}. This effect has been observed under field conditions by Nichols (1957). Pizer (1961) noticed the failure of undersown crops in a wet summer on chalky boulder clay which was attributed to the presence of a plough pan which had reduced permeability. Rickman et al. (1965) demonstrated the presence of a perched water table above compacted layers in pot tests.

Hawkins and Brown (1963) presented evidence of the increase of run-off of irrigation water on soil over which tractor wheels had passed in the plough-furrow bottom. Distinct differences were shown when wheel passage occurred in every furrow compared with alternate furrows.

2.8 Interaction effects

It has been shown in Sections 2.4.2, 2.4.3 and 2.4.4. that the compaction of soil may be sufficiently severe to restrict root growth as a result of mechanical impedance, deficient aeration or restricted permeability to water (high water content and low water suction). In recent years several workers have demonstrated that these factors show marked interactions. Taylor and Gardner (1963) found that the root penetration of cotton in fine sandy loam showed highly significant negative correlations with both density and soil moisture suction and also a marked degree of interaction. At a density of 1.65 g cm^{-3} penetration was 80% at a suction of 0.20 bar but only 20% when the suction was raised to 0.66 bar. This effect was confirmed by Eavis (1965) using pea roots and a mechanical method for assessing impedance and it is supported by workers using normal bulk soil-strength measurements in relation to moisture content. Håkansson (1966) obtained marked interaction, as measured in barley yield, between bulk density and moisture regime in field-tillage experiments in conditions corresponding to wet, normal and dry spring weather.

Interactions between the effects of oxygen status and mechanical impedance on root growth have also been found to be striking. This has been established for a glass-bead medium by Aubertin and Kardos (1965b) and for soil by Tackett and Pearson (1964). The last named workers found that cotton root penetration at a density of 1.3 g cm^{-3} continued normally unless the oxygen gas concentration fell to below 5%. At densities above 1.5 g cm^{-3} penetration was strongly dependent on oxygen concentration whereas at a bulk density of 1.9 g cm^{-3} root penetration was zero at all oxygen levels. Eavis (1965) also used soil but measured impedance mechanically. Significant interactions between mechanical impedance and oxygen concentration were found for root length, fresh root weight and root volume. His study appears to be the first in which a wide range of mechanical impedance, aeration and moisture status treatments have all been studied in single factorial designs.

2.9 The special significance of clods*

2.9.1 The diluent effect of clods

The importance of the structure of clods as indicated by bulk density, porosity or strength has not been sufficiently investigated. Keen (1942) pointed out the limitations of tillage experiments in which only clod-size distribution is measured. Bushnell (1953) measured the total porosity of clods which were examined to see whether potato-root penetration had occurred. 47% total porosity appeared to be the minimum for potato root penetration. Fountaine and Payne (1952) mention that the severely compacted soil portions which are formed between the lugs of tractors wheels and tracks might be the source of clods which could have a 'diluent' effect and so reduce the effective soil volume. The roots of different crop plants were found to have markedly differing ability to penetrate clods. Mustard roots would not penetrate clods if the total porosity was less than 39% whereas the finer graminaceous roots of wheat penetrated into clods unless the total porosity was less than 30%.

The presence of large quantities of clods depresses the yield of potatoes. Flocker et al. (1960) reported yield reductions of more than 50% for potatoes

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* A clod has been defined by the Soil Science Society of America (1965) as "A compact, coherent mass of soil ranging in size from 5 or 10 mm to as much as 8 or 10 in.; produced artificially, usually by the activity of man by ploughing, digging, etc., especially when these operations are performed on soils that are either too wet or too dry for normal tillage operations."

grown in cloddy soils following pre-ploughing compaction when compared with uncompacted soil while Timm and Flocker (1966) showed that angular tuber development occurred in cloddy soil, the tubers conforming to the shape of the adjacent clods.

Flocker _et al._ (1960) showed that for Yolo fine sandy loam, clods following light, moderate and severe compaction gave approximately 10-15% higher bulk density values than the whole soil. The shear strength of clods from compacted soil was nearly double that of clods from lightly compacted soil. Work on the effect of clods on soil nutrient status has been reported by Coulter (1965) and Cornforth (1965). The former found that root penetration into large clods was restricted and this effect was the apparent explanation of the relationship between aggregate size and uptake of P and NO_3 reported by the latter worker. Water-soluble nutrients such as NO_3 will remain relatively unaffected in availability in the presence of clods whereas nutrients whose uptake depends on intimate soil-root contact will be reduced in availability where clods are present.

2.9.2 Clods as a problem at potato harvest

Clods of high density may have sufficient strength to withstand the impact loading which they incur in a potato digger and elevator. Because of damage to the crop it is not practical to increase the agitation to a level such that all clods can be eliminated. The presence of clods is particularly undesirable because the handling and separation rate of potatoes is reduced, and some potato separator mechanisms do not function satisfactorily in the presence of clods. Robertson (1960a, 1960b) showed that the elimination of inter-row cultivation through the use of herbicides could result in a lower clod content in the ridge, earlier maturation and no loss of yield (higher yield occurred in one year). Green (1965) states that the separation of clods is the greatest single problem in the harvest of potatoes. Traditionally autumn ploughing was considered to be the essential means of ensuring a low incidence of clods but improvements in or elimination of post-planting cultivations result in a striking reduction in the incidence of clods at harvest.

2.10 Weather conditions in relation to soil physical properties

2.10.1 Frost action

The influence of frost on soils is complex, depending on the degree of exposure, the surface roughness, the moisture content and the pattern of freezing-thawing cycles. Keen (1942) mentions the attention given at Rothamsted in the period 1926-1928 to the influence of frost conditions on the size distribution of aggregates after subsequent tillage operations. After frost-free winters even rotary cultivation was ineffective at producing the desired comminution. The action of freezing and thawing on secondary aggregate fracture is influenced by the moisture content. Bisal and Nielsen (1964) showed that freeze-drying resulted in much finer comminution of aggregates than if the drying occurred after thawing. When there is little or no snow cover it is possible that exposed layers and clods will be freeze-dried. Cooper (1960-61) has suggested that compaction problems are likely to be more serious in areas where deep freezing and thawing effects do not occur. However the significance of frost action in modifying compaction effects has not been fully explored.

De Boodt et al. (1952) studied the effect of autumn and spring ploughing on soil physical properties. A higher air permeability was observed for autumn-ploughed soil. Slater and Hopp (1951) found that for eastern U.S.A.

soils a severe winter (mean air temperature November - March 37°F) with much freezing and thawing can cause a deterioration of soil structure on clean-tilled land. They noticed a "slumping" of soil with a decrease of macropores. As a result they do not recommend autumn ploughing for that area. Interesting changes in soil physical properties were reported by Flocker _et al._ (1960) for the relatively mild winter conditions in Central Valley, California, using Yolo fine sandy loam previously compacted to different degrees. Bulk density increased (1.25 to 1.33 g cm^{-3}) for the non-compacted plots and fell (1.63 to 1.47 g cm^{-3}) for compacted plots. Although the effects resulting from the previous compaction treatment were greatly reduced they were not eliminated. The exact mechanisms for overall winter weathering treatments of this type are not readily examined in the field owing to the interaction of freezing/thawing cycles with melting/drying cycles.

The theories of Jung (1931) appear to be of interest since the interactions between thermal and moisture content cycles were considered. Detailed attention was given to the rate of freezing. Four types of frost action were postulated namely aggregation, disaggregation (physico-mechanical effects), coagulation and dispersion (colloid effects). Slow freezing gave rise to large ice crystals and pressure aggregation whereas rapid freezing gave rise to small crystals and disaggregation on thawing.

Cowell (1957) measured the cohesion of clods at intervals during a comparitively mild Northumberland winter. Striking reductions of cohesion occurred during frost periods. Land ploughed in autumn showed a much greater break-down of clods than spring ploughed land. This effect was attributed to extra exposure to frost action but attempts to exploit the effect further by ridging land during the winter were not successful.

Njøs (1966) confirms that, for Norwegian conditions, "The variation in aggregate-size distribution brought about by cultivation implements is usually much less than the change produced by the yearly variation in climatic conditions, especially the frost action". Similarly Czeratzki (1966) reports differences in pore volume in spring within the range 42-52% depending on different winter weather conditions. This range is such that the desirable secondary tillage treatment may be loosening in some years and compaction in others.

2.10.2 Rain action

Rain, particularly that falling in winter when precipitation generally exceeds evapotranspiration, can cause a considerable modification of soil physical properties. Cole (1939) in California found that the changes in size distribution of secondary aggregates caused by the action of winter rain may be as great as that resulting from tillage practices while Pizer (1961) in S.E. England considers that "the most damaging structural change is slaking of the soil by water". De Roo (1960) found that deep tillage in the autumn has a variable effect on soil physical properties depending on the settling effect of winter rains which resulted in zones of secondary compaction later demonstrated by root examination. Bushnell (1953) also drew attention to the action of rain in slaking and compacting surface soils especially those which had previously been in a loose friable condition. In many of his field experiments testing soil physical conditions on potatoes, physical treatment differences were frequently eliminated by periods of heavy rain. Quantitative measurements of the degree of slumping caused by winter and spring rain were given by Kuipers and Van Ouwerkerk (1963) based on results obtained with a surface-relief meter while Millington (1961) showed that soil bulk density during the life of a cereal crop was strongly related to the amount of rain falling in the month after sowing. The incidence of rain is likely to be an important variable modifying the results of differing tillage treatments and necessitating seasonal replication of field experiments.

2.11 Influence of crop management practices

Crop management and rotation practices have a considerable influence on tillage frequency and soil physical properties. Certain crops require less tillage and traffic than others while perennial crops such as grass permit a continuous period of growth, death and regeneration of roots and the build-up of stable organic matter proceeds without interruption through tillage. The benefits of grass leys in improving and maintaining soil structure have been widely recognised. For conditions in Iowa, Browning (1950) considered that most soils require as many years of meadow or pasture crops as tilled crops in the rotation for the maintenance of soil structure. Rotations lacking in grass result in severe surface capping in that area. For British conditions Crompton (1958) suggested that "... a grass break is the only practical method of maintaining and restoring soil structure on the average farm" and "... on difficult soils they (leys) may need to be used with the welfare of the soil foremost in mind, rather than the crop or stock". It is surprising that these authoritive statements should have been made such a comparitively short time ago since economic conditions today frequently result in the almost complete elimination of grass in the rotation of many arable farms. The full implication of this development is not yet clear. There is already evidence however that the swing from mixed cropping to continuous cereal growing may result in soil deterioration. At a recent farming conference Rowsell (1967) considered that this "system of monoculture ... is leaving our land worse than at any other time in its history". Evidence for this view is largely subjective and the deterioration is likely to be a syndrome in which tillage-sensitive physical properties of the soil are probably involved together with nutrition and disease factors.

The influence of incorporated plant residues on physical properties of the soil has not received adequate attention. It has particular relevance in respect to minimum cultivation methods. Jamison (1960) studied the effect of a layer of shredded corn on downward water flow and a pronounced impedance was found. Air contents at subcritical levels were found for 10 hours after wetting soils without a layer of residues while for soil with buried residues these conditions persisted for 50 hours.

Byers and Webber (1957) presented data on the seasonal variation of bulk density for two soil types and nine cultivation treatments. During a four-year experiment a highly significant decrease of bulk density occurred. No explanation was given other than the suggestion that this was part of a long-term change of properties related to cropping practice. Very marked differences in soil properties were established between different crops due to differing amount of inter-row cultivation. Timm and Flocker (1963), working on Yolo sandy loam, found that compaction several months previous to planting of potatoes had a highly deleterious effect on emergence. This affect was apparently due to aeration deficiency and high soil temperatures and possibly high soil moisture content following irrigation.

For row-planted crops different tillage treatment may be applied along the row from that between the rows. For several crops such as potatoes this has long been an established practice. Larson (1963) reviewed the development of management practices for the row and inter-row zones for the maize crop. He points out that the inter-row zone can be so managed to give the maximum possible intake of water particularly in spring when the soil is bare and when precipitation rates can be high. Peterson (1960) pointed out the benefits of wheel-track planting of maize. Compaction along the plant row provided suitable soil-seed contact while the inter-row zone is a suitably loose root-bed. The use of beds for potato production was considered by Green (1963) and it seems likely that developments of this type will become increasingly popular, particularly when they lead to the more efficient use of machinery.

CHAPTER 3

DISRUPTIVE EFFECTS OF IMPLEMENTS

3.1 Disruptive processes

In spite of the fact that soil disruption is the most important aspect of tillage, there has been very little work on the processes by which the effect is achieved. There is no established nomenclature, many terms being accepted from practical farming usage without a clear definition for use in a research context, for instance 'soil breakdown' as used by Hawkins (1960).

In this review 'disruption' is used to cover the processes of soil loosening, comminution, inversion and mixing. These processes are difficult to define explicitly and generally impossible to separate experimentally. Studies of the processes have generally fallen into two groups, morphological and mechanical.

3.1.1 Morphological approach

(a) Loosening and comminution Loosening is accompanied by a decrease of bulk density due to the separation of soil structural units which were previously in closer association while comminution is a process in which discrete soil structural units (peds, clods or massive layers) are divided into more numerous portions of smaller size. Under certain conditions comminution can result in an increase of bulk density.

Keen (1942) stressed the importance of natural lines of weakness in soil in affecting the way in which it breaks under the action of cultivation machinery. The work of Brewer (1964) and Mitchell (1956) has lead to a greatly increased interest in the importance of fabric characteristics on the resistance of the soil to disruption. Optical examination reveals a complex arrangement of particle orientation in natural soils and it is largely the difficulty of reproducing the same orientation patterns which account for the discrepancy of properties between undisturbed soils and those which have been disturbed or remoulded.

The distinction between soil loosening and comminution was recognised by Joffe (1946) with particular reference to the action of rotary tillage implements which he says "pulverise" the soil "but do not loosen it". The latter process is "a natural cleavage along the surface of structural units" which "increases the non-capillary pore space and facilitates aeration and movement of water". The comminution resulting from rotary tillage may decrease non-capillary pore space. These observations appear to be at variance with those of Keen (1933) who studied the size distribution of aggregates following rotary cultivation and found that it did "not produce a much finer tilth than other implements, as is commonly supposed" but it gave a much looser tilth.

One of the most comprehensive studies on this subject was undertaken by Luttrell _et al_. (1964) who measured a wide range of physical characteristics following ploughing with a variable number of disking operations. Characteristics which were strongly influenced by treatment were bulk density, surface roughness coefficient and mean weight diameter of aggregates (clods). Ploughing markedly decreased bulk density and subsequent tillage increased it again, but not to the same extent as occurred during winter exposure. Soil type had a pronounced effect on the degree of bulk density changes. Although ploughing had a marked effect on comminution, disking surprisingly did not in general significantly decrease clod size and in one experiment a larger mean weight diameter was found for ploughing plus disking than for ploughing alone. Feuerlein (1966) determined the loosening effect of ploughing with a surface relief meter and expressed the result as a % increase of volume of the disturbed ploughed layer. The loosening effect was much greater for a general-purpose plough body than for a short digger body.

(b) Soil inversion Although inversion does not always occur during tillage processes it has been considered a fundamental part of mouldboard ploughing and some other operations. Hawkins (1960) considered that the weed control ability of the mouldboard plough is the "main reason why it is almost universally used in the temperate climate of Europe". In addition the effective burial of plant residues can be an extremely important factor in disease and insect-pest control particularly in certain tropical crops such as tobacco and cotton. The burial of a "damaged" topsoil was considered to be an important feature of ploughing by Hawkins and Brown (1963) for the re-establishment of suitable conditions for a seedbed particularly after the severe loading of wet soils which frequently occurs during the harvesting of root crops in late autumn. Feuerlein (1966) discussed the importance of the inversion pattern in ploughing and describes the use of an inversion-angle meter for stiff furrow slices and the displacement of markers in crumbling slices. Inversion through 135° is considered correct for a crumbled furrow after stubble whereas 140° is recommended for grassland.

(c) Soil Mixing This process is distinct from inversion although it frequently occurs at the same time. It has important agronomic significance in the incorporation of fertilizers and mixing of soil layers of differing properties. Steenberg and Njøs (1964) compared the inversion and mixing action of a rotary cultivator and a mouldboard plough using a radioactive tracer applied to the soil surface. Very marked differencies were observed. Rotary cultivation gave the highest concentration in the surface layers whereas with the mouldboard plough the highest concentration was at the base of the furrow. Similar results were obtained by Hulburt and Menzel (1953).

Hawkins (1960) pointed out that tines and subsoiling equipment, if used frequently, may cause appreciable mixing due to the passage of soil up the leading face of an inclined tool. The degree of mixing in normal ploughing is very slight except at high speeds, Feuerlein (1966). Very detailed studies of soil mixing and inversion patterns with different types of ploughs were reported by Pronin (1965) particular attention being given to the changing of plough depth in different years with a view to promoting maximum mixing action within the plough depth.

(d) Surface roughness The passage of implements through soil invariably causes a change of surface roughness. The surface roughness of the soil is an important characteristic which affects the exposure to weathering and frost action due to the change of surface area, the pattern of lodgement of snow and hence exposure to frost and the storage of rain in depressions. Peterson (1960) found that under conditions of low rainfall wheel tracks cause increased surface water storage during wheel track planting of maize. On the other hand the rough loose soil between the rows permitted rapid drying out of the surface soil which is important in restricting weed growth. Holmes et al. (1960) showed the importance of soil-surface roughness in the movement of water vapour from the soil to the atmosphere. Surface roughness affects infiltration characteristics and resistance to lateral flow of water, particularly important in surface irrigation and erosion problems. Chepil (1960) drew attention to the particular significance of surface roughness in the susceptibility to "blowing". Excessive roughness may lead to leaching of soil-applied residual herbicides into the root zone and displacement due to crumbling from potato ridges into furrow bottoms, Evans (1966).

Until very recently practically no quantitative roughness measurements were made and the subject was unmentioned in a recent comprehensive textbook on physical analysis of soils, Black (1965). A number of soil surface roughness measurement techniques have been developed and were described by De Boodt _et al._ (1967) and Allmaras _et al._ (1966). Results obtained in tillage experiments were given by Mannering _et al._ (1966). They showed that the surface-roughness index, defined according to Burwell _et al._ (1963), was greater for minimum secondary tillage (0.65 in.) than for conventional tillage (0.41 in.). This lead to greater infiltration (37% increase on 3 year average) for the minimum cultivation plots. After 5.2 in. of simulated rain the roughness indices were 0.39 and 0.22 in. for the minimum and conventional treatments.

Kuipers _et al._ (1966) reported that surface roughness was strongly influenced by clay content, slaking by rain, different seasons, speed of ploughing and type of mouldboard. The significance of surface characteristics in ploughing was also described by Feuerlein (1966). For over-winter weathering the tops of the ridges should have a cross section of isosceles triangles. This was considered particularly important in silty soils subject to excessive slumping under the influence of rain and snow. The change in shape of the plough ridges under the influence of frost was measured.

(e) _Soil surface elevation change_ Early workers appreciated that considerable changes of surface elevation accompany certain tillage operations. For instance Bushnell (1953) reported that subsoiling under each ploughing furrow caused a surface elevation rise of 3 - 4 in. Subsequent heavy rain caused slumping and a return to a surface level approximately similar to the original. Nichols <u>et al</u>. (1955) measured surface elevation before and after subsoiling as an indication of disruptive efficiency, while Wilton (1964) found differences in surface elevation between four tillage systems. Ploughing and rotary cultivation lead to greater loosening and lifting of the soil than a rigid-tine cultivation and disk harrows. Observations were closely dependent on the depth of working which tended to be confounded with the tool used. Considerable carryover effects were noticed, for instance the use of a deep beet plough for harvesting operations obscured the effects of different cultivation methods applied to a subsequent barley crop. Håkansson (1966) found that sinkage of the soil surface after seedbed preparation continued slowly until harvest time.

The measurement of surface relief before and after tillage in conjunction with bulk density determinations before tillage provides a convenient method for assessing porosity and bulk density of tilled soils, which is otherwise difficult. This technique was used by Kuipers and Van Ouwerkerk (1963), Luttrell <u>et al</u>. (1964), Van Doren (1965) and Burwell <u>et al</u>. (1963). The last-named were able to demonstrate significant differences in the total porosity following different tillage treatments. From an initial porosity of 53% for the 0-6 in. layer, conventional seedbed cultivation gave 66% porosity compared with 83% for wheel track planting in which disking and harrowing did not occur. However Kuipers <u>et al</u>. (1966) pointed out that a 1% volume change in a 20 cm layer of disturbed soil is equivalent to an elevation change of only 2 mm and they recommended the use of at least 400 surface level readings in order to assess porosity changes accurately with the reference datum established to an accuracy of 1 mm. The method was not considered satisfactory for operations in which the depth of the disturbed layer was less than about 20 cm.

Allmaras et al. (1966) reported studies on the effects on porosity and roughness of zero ploughing in comparison with various ploughing and cultivation treatments. Under friable conditions disking and harrowing decreased porosity but the opposite effect was obtained when the soil was in the plastic range of consistency. Later work by Allmaras et al. (1967) showed that the moisture content and initial porosity were the only factors which consistently affected the total porosity increase and random roughness resulting from ploughing. Clay, silt or carbon contents were not effective in explaining this variation.

3.1.2 Mechanical studies

Nichols (1929) was one of the first to study the mechanics of the disruptive processes involved in ploughing. Using a glass-fronted tank he observed transverse shearing action of the mouldboard which was contrary to the then current theory of longitudinal shearing. The mechanics of soil fracture under stress have been investigated by McMurdie (1965) as part of the general phenomenon of soil behaviour known as yield, which may occur as a compactive response to stress or, under different conditions, as slip or fracture. The two processes are essentially the breakage of cohesive bonding between particles and the overcoming of internal friction. The rate of strain is likely to be particularly important during fracture-yield processes.

There is no adequate mechanics for describing the disruptive action of tillage tools. Vanden Berg and Reaves (1966) have suggested an empirical relation such that both the forces on the tillage tool and the final state of the soil are expressed qualitatively by

$$S_f = f(S_i, T_m, T_s,)$$

where S_i is the initial soil condition, S_f is the final soil condition, T_m is the manner of tool movement, and T_s is the shape of the tool. However there is no satisfactory technique for expressing these variables in quantitative terms.

3.2 Energy requirements for soil disruption

The objective of tillage is to achieve a stated disruption objective with the minimum cost. It is therefore important to know the energy requirements and the efficiency achieved for different soil-equipment associations. Cooper *et al.* (1963) reported detailed studies on the energy requirements to produce measured comminution action on different soil types. Total energy requirements were expressed as ft lb ft^{-3} of tilled soil and were the sum of draft and rotational energy inputs. The efficiency of an operation was expressed as the ratio of the equivalent energy input to the total energy input, where equivalent energy input was the amount of energy required to create a comparable clod size distribution by the drop shatter method.

The relation of size of cut to tillage-tool efficiency was measured by Gill and McCreery (1960). Shares and mouldboards were used to cut 1,2,4,6 and 8 in. widths. The clod-size distribution (mean weight diameter) was approximately the same for different widths of cut. The efficiency of different widths of cut was obtained by comparison with the drop shatter method. The efficiency is expressed as the ratio of the work done on the soil to the work done on the tool. A mouldboard had a higher efficiency when working with a narrow width of cut. They suggested that it is more logical to so arrange the conditions of primary cultivation technique that the soil reaches the required state of comminution in one step. However the solution is dependent on the type of equipment available and the extent to which frost action can be utilized to assist tillage practices. An alternative method of expressing comminution efficiency was suggested by Regge (1965). He divided the difference in soil aggregate surface area before and after the process by the specific energy consumption.

The power requirements for field tillage operations are rarely measured in field experiments involving tillage methods over long periods. However Pendleton and Farnham (1964) indicated that the power requirements for ploughing soils carrying different crop rotations for 28 years varied according to the number of occasions in which a cultivated row crop occurred in the rotation. 42 hp were required if 3 out of 4 years had a cultivated crop compared with 37 hp if only 1 out of 4 had a cultivated crop. The information given was extremely limited with no supporting soil physical data.

Lyles and Woodruff (1961) examined the effect of density on the draft required to pull a chisel through three contrasting soils. Draft increased with clay content and density. Of particular interest was the finding that the three soils produced an equal amount of clods at the same draft requirement. The differences in comminution efficiency of different tillage operations are closely related to the operating power requirement. Byers and Webber (1957) measured bulk density and aggregation for different methods of tillage. Power requirements varied from 8 hp h acre^{-1} for a one-way disk to 35 hp h acre^{-1} for a rotary tiller.

3.3 Effect of soil properties on disruptive efficiency

The particular importance of the bulk density at the time of tillage on the size distribution of clods was shown by Lyles and Woodruff (1961). Although their interest lay in increasing surface cloddiness in order to prevent wind erosion their findings are of very considerable importance in the converse situation which is more general. Tests on three widely differing soils were made in a soil tank at densities in the range 69-90, 61-88 and 64-90% of Proctor maximum density for the sandy loam, silty clay loam and clay respectively. The soils were tilled with a full size 2 in. x 10 in. narrow point chisel. The percentage of clods greater than 6.4 mm increased markedly with increasing bulk density. Clay gave the largest percentage of clods and sandy loam the least. A weathering test (6 month out-of-doors) also indicated the greater durability of clay clods. The crushing strength of clods depended to a marked extent on the density of the soil prior to tillage. Lyles and Dickerson (1967) reported work testing the application of surface pressure in order to increase bulk density. The minimum criteria to produce a soil which had not less than 45% of the total weight present in clods greater than 6.4 mm were a surface pressure of 22 lb $in.^{-2}$, a loaded area of 17 $in.^2$ and 8.2 in. spacing between plates. The marked influence of moisture in influencing compaction and subsequent clod production was demonstrated by Lyles and Woodruff (1963). They conclude that, unless a field soil is near to the optimum water content for soil compaction it would be useless to pack and chisel it to increase surface cloddiness.

Detailed morphological studies of the results of disruption of soils submitted to a variety of compaction treatments were reported by Vomocil and Flocker (1965). Particular attention was given to duration of compactive changes in soils when followed by a thorough disruptive tillage operation which was simulated by air drying, crushing and sieving through a 1 mm sieve. Samples were taken from plots of Yolo loam after six years of light and severe compaction treatments. The former treatment gave spherical aggregates with well-developed crumb structure whilst the latter showed a strongly-developed platey structure with evidence of a permanent horizontal orientation of clay layers in the field. A number of strength tests (modulus of rupture, penetrability, unconfined compression) were made on sieved samples which were repacked by impact. Samples from previously severely compacted plots showed much higher strengths, particularly in the lower moisture content range. These differences were attributed to the changes of shape and characteristics of aggregates. It was therefore concluded that the changes induced in soil by severe compaction <u>cannot</u> be removed by a single disruptive process of comminution even when continued to give a maximum aggregate diameter of only 1 mm. These results have very far-reaching application in soil management practices and in the development of any new machinery on the lines of an "industrial pulveriser" as predicted by Hawkins (1960) for the achievement of clod size reduction in one operation.

CHAPTER 4

COMPACTIVE EFFECTS OF IMPLEMENTS AND TRAFFIC

4.1 Mechanics of soil compaction

The processes of compaction in soils have been mainly investigated in the context of civil engineering in which compaction is used as a means of increasing the strength of load-bearing soils. It is significant that a paper by Felt (1965) on 'Compactability', in a book published by the American Society of Agronomy titled "Methods of Soil Analysis", contained no reference to compaction in agricultural soils. Harris et al. (1964) considered that there is no "adequate agricultural soil mechanics" and that "the development of soil stress-strain relationships which will permit the prediction of the changes in the state of compaction caused by various implements and power units will be a major contribution towards controlling soil compaction".

4.1.1 The process of soil compaction

In the field of soil mechanics a fairly clear distinction is maintained between consolidation and compaction. The former consists of the long-term volume change in saturated soils subjected to static loads. It is of interest to note the extremely protracted research which has been required before classical consolidation theory could be modified adequately to describe real situations, Barden (1966). It is therefore not surprising that a rigorous mathematical treatment of compaction, which is a far more complicated process than consolidation, is not yet available. Compaction differs from consolidation in being the result of relatively large stresses of dynamic character, applied over small areas for short periods of time. The soil is not saturated with water and, in the case of agricultural soils, is largely composed of aggregates, of complex internal structure, which are far from incompressible. Compaction therefore consists of a complete re-arrangement of solid, liquid and gaseous phases. In practice considerable shearing deformation may accompany compaction which further complicates any attempt at analysis.

The process of compaction largely consists in the reduction in the air-filled porosity particularly the larger or macro-pores, Gill (1959a). However zero air-filled porosity is never reached by normal compaction although, as pointed out by Lewis and Parsons (1963), some experimental points may occasionally give zero or even negative air-filled porosity values through experimental error.

Compactive effort can be applied to soils through impact, static, dynamic or vibrational loading. In laboratory tests it is usual to separate the effects introduced by these different types of loads but under field conditions compactive loads are complex both in type and degree. Cooper and Nichols (1959) considered that static forces are much less effective in producing compactive change than are dynamic forces such as that produced by the slippage of a tractor tyre. The influence of vibration, which must always be present in the passage of tractors and implements, is likely to have an effect which will augment that resulting from the surface pressure under the wheels.

4.1.2 Quantitative treatment of compactive processes

(a) Parameters of compactive systems

There appears to have been no authoritative and comprehensive treatise on the quantitative aspects of soil compaction. Workers concerned with the subject, and it has application in many fields, have tended to use a highly empirical approach with a limited set of conditions relevant only to the particular study in hand. The process, if it is to be described fully, requires a set of quantitative statements of the soil and load parameters. These include the depth, breadth and length of the boundaries of the soil volume, the nature of the material at these boundaries and the modulus of elasticity of the soil. The compactability for the applied load conditions must be known including the effect of initial density, moisture content and structural arrangement. Load parameters include the shape and size of the loaded area, the surface characteristics of the underside of the load member, the type, intensity and time-dependent characteristics of the load and the distribution of load over the loaded area.

(b) Modern theories of soil compaction mechanics

The mechanics of soil compaction processes have been reviewed by Anon. (1952), Cooper and Gill (1966) and Gill and Vanden Berg (1967). No attempt will be made to discuss the difficulties which have arisen in attempts to apply classical soil mechanics theory to compaction. However within recent years there have been several attempts to use improved experimental techniques to examine certain theoretical aspects of soil compaction. Cooper *et al.* (1957) reported a study comparing stress distribution as measured with strain gauges with that predicted from elastic theory. This type of approach represents the most hopeful development in the study of the quantitative aspects of soil compaction since it is based on the direct measurements of normal stress-volumetric strain relationships under the types of dynamic loading conditions which are encountered in practice, be it civil engineering, soil-vehicle trafficability or agricultural tillage. The basis for this development appears to be a lively association between the U.S. Army Locomotion at Detroit and the Department of Agricultural Engineering at

Michigan State University. The combination of automatic recording of stress tensors, and volumetric strain as used by Harris et al. (1964) permitted a degree of detail in measurement which has not previously been possible. The variables were the depth of loose soil above the level of measurement, the rate of loading, the moisture content and initial bulk density.

McMurdie (1965) applied classical consolidation theory to the problem of stress-strain relations in unsaturated soils. The application of Mhor theory was considered to have severe limitations owing to difficulties associated with the measurement of suction stresses in soils, McMurdie and Day (1960). The deformation under initial stress was elastic (recoverable) but at a certain point inelastic (non-recoverable) deformation occurred with the creation of slip or fraction surfaces. Compactive deformation is not continuous for a given stress and they stated that "The implications of volume change in the partition of energy between recoverable and non-recoverable forms are unknown".

Many uncertainties remain in the theoretical understanding of compaction including the effect of rate of stress application, the significance of water movement on compaction at high moisture contents and the nature and importance of inter-particle bonding on the extent and type of deformation under given stress. The failure of elastic theory to explain compactive deformation of soil lead to the exploration of plasticity theory. Prandtl (1921) used an analysis in which shearing is assumed to occur in a system of wedges, some of which behave as rigid solids without deformation while others show plastic deformation. Rupture is assumed to occur along straight lines while soil lying outside the wedges is assumed to be unaffected by the loading. Although this approach uses a model with characteristics much closer to the known properties of soil than those specified by elastic theory it seems unlikely that the wedge theory can be of general application because it clearly differs considerably from morphological interpretation in real soils. However under certain situations, such as soil cutting, wedge theory has proved useful, Hettiaratchi (1965).

4.1.3 The expression of compactive changes

The exact mechanics of the re-arrangement of the solid, liquid and gaseous phases are not, in most cases, of primary interest. Of more practical importance is the overall change of physical properties from before to after the compaction process. Compaction is most simply defined as an increase of bulk density with proportionate decrease of total porosity. Standard tests for compactability are based on the use of bulk density as the criterion of compactive change. However, in both agricultural and engineering soil studies there are indications that bulk density change alone is not necessarily an adequate parameter of compactive change owing to the large inherent differences of bulk density between soils. Small changes in bulk density may be accompanied by much larger changes proportionally in certain other physical properties whilst bulk density *per se* is not a property of direct importance to plant growth. Where the compaction process is primarily of interest as an indication of the change of soil strength the direct measurement of the relevant strength characteristic may prove more purposeful.

Increasing interest is being shown in the use of the air-void percentage as an indication of compactive changes in both engineering and agricultural soils. Lewis (1962) recommended the use of air-void percentage as an indication of compactive changes in engineering soils. A common scale of values may be applied to a wide range of soil types. A specified minimum level of 10% air voids is recommended for all road-fill materials. Lewis and Parsons (1963) pointed out that on certain soils a state of compaction equivalent to 10% air voids cannot be attained owing to the uniformity of grading of soil particles. The practical limitation to the further use of the air-void criterion is the difficulty associated with methods for its direct determination in soils. Bateman (1963) paid particular attention to the use of air-void percentage in an agricultural field compaction experiment. He stressed that the use of air-void percentage eliminated the difficulties arising in bulk density comparisons for soils having different grain-size distribution and different moisture contents at field capacity. Air-void percentage values can be more easily applied to plant growth factors than can bulk density. Foil and Ralston (1967) showed that the non-capillary porosity (60 cm H_2O suction) was a very sensitive indication of compactive change in soils of contrasting texture.

Schmidt (1963) suggested that the calculated hydraulic conductivity would serve as a measure of soil compaction. However his method required the determination of a moisture-release curve for each state of compaction and it seems doubtful that the method can be of practical value for field experiments. However there is considerable evidence that actual hydraulic conductivity is a very sensitive indication of compactive changes. Taylor and Henderson (1959) found that an increase of bulk density from 1.2 to 1.4 g cm^{-3} during compaction resulted in a tenfold reduction of hydraulic conductivity. Fountaine and Payne (1952) considered that the methods then available for the measurements of bulk density were too insensitive to be used to indicate changes in compaction adequately and concluded that water and air permeability would be likely to be more appropriate properties to measure.

Similarly Vomocil _et_ _al_. (1958) reported a reduction of hydraulic conductivity from 2.05 in. h^{-1} to 0.05 in. h^{-1} when the bulk density increased from 1.31 to 1.50 g cm^{-3} following a single pass of a heavy wheel.

4.1.4 The effect of soil composition and structure on compactability

Compositional and structural effects may be attributed to predominant particle size (texture), aggregation characteristics, uniformity of grading, clay mineral type and base status, organic matter type and concentration. Since the base status, organic matter and aggregation characteristics of agricultural soils are, to a limited extent, related to soil management practices it is possible that compactability is controllable but this does not appear to have received any attention.

Predominant particle size has an over-riding influence on compaction characteristics. A well-graded gravel may give a maximum bulk density and optimum moisture values (Proctor) of 2.2 g cm^{-3} and 4% $^{w}/w$ respectively whereas the corresponding values for a heavy clay might be 1.4 g cm^{-3} and 28% $^{w}/w$. The average particle density for the two soils might be 2.60 and 2.70 g cm^{-3} respectively so that the differences in maximum bulk density cannot be attributed to differences in particle density. The reason for the striking differences is the occurrence of aggregation when silt and clay size particles are present in agricultural topsoils. Aggregation is partly due to the plate-like shape of the silt and clay particles and partly to the high surface electrical charge (particularly for clay) which causes flocculation and the subsequent development of aggregates. Because of their low internal density, irregular shape and considerable internal strength, aggregates tend to resist any attempts to force the primary particles to take up a close packed configuration.

Aggregation characteristics of relevance in compactability studies are size distribution, shape, structure (bulk density, porosity and strength). Nichols and Reaves (1955) reported that compactability of a given soil (silt loam) decreased as the aggregate size increased. Cooper and Gill (1966) included particle shape and particle hardness as factors affecting compactability but there seems to be little quantitative information available on these properties.

Soils with a wide range of particle sizes will tend to reach higher densities under a given compactive load owing to the facility for interstitial packing. This effect is absent for certain sandy soils of single-grain structure. In general clay minerals with 2:1 expanding lattice show a lower compactability than clays with a 1:1 lattice. The predominant cation absorbed on the clay also influences compactability as shown by Winterkorn and Moorman (1941). Free et al. (1947) and Russell et al. (1952) using impact compaction tests established the reduced compactability of soils following the addition of organic matter while Soehne (1955), with an hydraulic compactor, reported reduced compactability in a pasture soil compared with a neighbouring cultivated soil of the same type. Taylor and Henderson (1959) studied the effect of additions of certain organic materials on the compressibility of Yolo silt loam, a soil which possibly has been the subject of more compaction research than any other. Addition of a poly-electrolyte gave bulk density values much lower than untreated soil. Morgan et al. (1966) described reduced compactability of turf grass soils by the addition of peat, lignified redwood and calcined clay.

Field observations by Peterson (1960) showed that seed-row compaction by tractor wheels was less marked following hay and sod crops than after corn crops. This was probably related to the organic matter status as well as aggregation characteristics.

4.1.5 Effect of moisture content on compactability

The amount of change of bulk density in soils subjected to a given compactive effort is strongly dependent on the moisture content. As a result moisture content is used as a variable in compactability tests, a maximum compactability value being obtained at a moisture content which is dependent on the type of test used. The influence of moisture on compactability can be attributed to cohesional and lubricational effects, space filling effect, and aggregate expansion effect.

As the water content increases there is increasing facility for soil particles to move under load and to take up an arrangement of closer packing and hence increased density. The amount of water required to promote maximum compactability increases with the soil-particle surface area and it seems logical to explain this in terms of film thickness yet little work has been attempted to examine the detailed physical condition of soil water in relation to compactability. As the water content increases for a given density the air-filled porosity must necessarily decrease. Since the liquid phase of the soil is incompressible this acts as an important obstruction to compaction. It is particularly important in the agricultural context that the sensitivity of soils to differing compactive effort is greatly reduced at moisture contents above the optimum.

If the clay mineral composition of the soil is such that strong aggregates are formed with marked expansion on wetting there can be a decrease of compactability as the moisture content increases for a given compactive effort, Felt (1965). This results in a minimum on the density-moisture relation curve. Richards et al. (1960) demonstrated marked minima in the density-moisture curves for sandy loam and clay loam at water contents in the region of 6 - 10% using an impact compaction method. With one unexplained exception the values of equivalent water-film thickness at the minimum compaction points were in the region of $0.30-0.60 \times 10^{-6}$ cm which was later considered by Richards et al. (1965) to correspond to a water suction of 3-5 bar. This thickness of water film falls within the range influenced by the diffuse double layer of ions associated with charged surfaces. They considered that the minimum compaction effect was related to film-water thickness and not aggregation effects since the addition of soil-aggregation promoters reduced the intensity of the minimum effect.

Minima were also reported by Taylor and Henderson (1959) using a dynamic loading compactability test (20 or 30 lb $in.^{-2}$ for a 1 min period). Minima in field-compaction tests have also been reported. Weaver and Jamison (1951) demonstrated the effect, using tractor wheels, while the Road Research Laboratory, Anon.(1952) reported pronounced minima for a heavy clay soil compacted by a number of compacting implements. The significance of the minimum compactability effect has received little attention. It is likely to occur more frequently in agricultural soils owing to their generally higher clay content and greater aggregation than engineering soils.

Remarkably little attention seems to have been given to the difference in effect of tillage and traffic compaction under different moisture contents in agricultural soils. Workers have generally been content to express moisture status as the percentage by weight rather than in terms of the more fundamental concept of water potential. Allman and Kohnke (1947) compared the estimated "ploughability" of 10 soils between March and July with the water potential expressed as pF. Soils were considered dry enough to plough when a series of visual assessments were fulfilled. They found that the lowest suctions at which these conditions for "ploughability" were fulfilled were pF 2.7 - 3.0 for medium to fine textures and pF 1.8 - 2.3 for coarse textured soils. These suctions were close to the field-capacity values. Weaver and Jamison (1951) pointed out that the optimum moisture for ploughing tends to be very close to the optimum moisture content for compaction and that therefore particular attention should be given to designing tractors and implements to give minimum downward pressures on the soil. Bateman (1963) reports that, for a series of detailed experiments, ploughing and most seedbed operations were performed at moisture contents above the Proctor optimum, in fact the soil was usually near the plastic limit.

4.2 The assessment of compactability

The term 'compactability' is not widely used in description of agricultural soils but it was chosen as the title for a review by Felt (1965). Compactability is expressed in terms of the bulk density produced when soil is subject to a specified compactive effort at specified moisture content.

4.2.1 Compactability tests

The selection of a compactability test should logically be related to the type of situation in which the results are to be applied. In practical engineering the impact test (Proctor) has achieved widespread acceptance as a standard regardless of the type of loading which is involved in the field situation. This has not however been the case for agricultural soils and workers have frequently used tests which were devised to suit their particular situation or convenience. The result has been that comparisons between results for different agricultural soil workers are difficult to interpret quantitatively.

4.2.2 Impact tests

The test described by Proctor (1933) consists of the application of impact energy to the extent of 12 375 ftlb ft^{-3} of soil. The energy is applied through 75 blows of a 5.5 lb hammer falling through 12 in. on to soil in three layers contained in a mould 0.033 ft^3 in volume. The method has the advantage of simplicity. In spite of the widespread adoption of the Proctor test as a standard certain modifications have been found necessary. The modified method of the American Association of State Highway Officials (A.A.S.H.O.) uses the same mould as the Proctor test but 125 blows from a 10 lb hammer falling through 18 in. are applied using five layers of soil. The total impact energy is 56 250 ftlb ft^{-3} of soil, approximately 4½ times that of the Proctor test. This extra compactive effort was found to be necessary in order to simulate soil behaviour when very high performance compaction equipment was developed for field use, particularly in airfield construction work.

The Road Research Laboratory, Anon. (1952), investigated the effect of varying the hammer weight and distance of fall to give the same energy (15 lb through 12 in.) or the same momentum (12.25 lb through 12 in.) as the modified A.A.S.H.O. impact conditions. In general all results for four different soils lay within the experimental error and it was therefore concluded that the use of a 15 lb hammer falling through 12 in. was a suitable and more convenient alternative. The modified A.A.S.H.O. test gave considerably higher density values than the Proctor test but fine textured soil gave greater increases (+ 13 lb ft^{-3}) than those for coarse textured soils (+ 5 lb ft^{-3}). The optimum water content was reduced by about 6 and 2% for fine and coarse textured soils respectively.

The Proctor and modified A.A.S.H.O. tests are carried out on the fraction less than $\frac{3}{4}$ in. diameter. Various correction factors have been proposed for use when appreciable amounts of material greater than this limit are present, Road Research Laboratory, Anon. (1952). However, Lewis and Parsons (1963) were not satisfied with these corrections and used a 6 in. mould as a container for the Proctor test if appreciable quantities of coarse material were present.

A number of workers with agricultural soils have used impact compactability methods but the conditions of test often differ very considerably from the Proctor method. For example, Richards _et al._ (1960) used containers 5 cm diameter and 5 cm high. The soil was placed in the container, loaded with 200 g and subjected to 120 drops through a fixed distance during a 2 min period. Other methods were described by Taylor and Henderson (1959) and Richards _et al._ (1965). A specialised form of compactability test was described by Morgen _et al._ (1966) for use in studies on compaction problems in turf grass management. Loading was applied by a 70 lb force impact applied 3 times daily for 5 weeks and then 4 times a week for the remaining 3 weeks to soil in a cylinder 10 cm diameter by 43 cm high. The change of soil level was used as an index of compactability.

Weaver and Jamison (1951), working on the compactability of agricultural top-soils under the passage of loaded wheels, used modified Proctor-type tests with 20 and 4 blows of the $5\frac{1}{2}$ lb hammer falling through 12 in. and 7 in. respectively to give two compactive treatments.

4.2.3 Dynamic-load compactability tests

Most compaction processes occurring under field conditions consist of the application of variable load for a short time interval such as occurs when a wheel passes over the soil surface. Porter (1938) developed a compaction method in which samples were compressed under a load of 2000 lb $in.^{-2}$ applied with an hydraulic press. The loading rate was specified as 0.05 in. min^{-1} for the 1000-2000 lb $in.^{-2}$ increment. The full pressure was maintained for 1 min. A more versatile method was developed by Taylor (1958) who pointed out that the conditions of loading during the Proctor test bear little resemblance to field compaction processes. He developed a pneumatic soil-compactability instrument in which air pressure was used to apply a load to a confined soil sample through a floating cylinder. The rate of increase and decrease of loading and the duration of steady load could be adjusted to suit requirements. Surface loads between 5 and 60 lb $in.^{-2}$ were used. The underside surface of the piston could be fitted with projections which presumably could simulate the tread on a tyre.

Nichols _et_ _al_. (1955) pointed out that " .. the Proctor method ... does not have any very direct connection with the kind of force application common to tillage of surface soils". They preferred the compactability test originally outlined by Nichols (1929) who considered that "the reaction to pressure ... is of the greatest importance in studies of the dynamic properties of the soil". Pressure increments of 5 lb $in.^{-2}$ were applied though a piston driven by compressed air to soil confined in a mould. Compactive deformation was measured with a micrometer. The continuous relationship which was established between applied pressure and deformation was found to differ widely according to soil type. Hovanesian and Buchele (1959) studied dynamic loading effects with a mean normal stress of 27 lb $in.^{-2}$ applied for 1 s followed by a resting stress of 1 lb $in.^{-2}$ Each stress cycle was considered to be comparable to the effect of the passage of the driving wheel of a tractor. 70 - 90% of the compaction achieved after 15 cycles occurred during the first cycle. The final bulk density obtained was similar to that produced by the prolonged application of the same pressure.

Another form of dynamic loading is that provided by a kneading action which has similarities to that produced by some compacting equipment. Chancellor and Schmidt (1961) presented data on the compactability of Yolo loam and Greenfield sandy loam with compactive effort being applied by both static and kneading pressures in increments between 0.5 and 16 Kg cm^{-2}. Foil and Ralston (1967) compared the effect of different static pressures maintained momentarily with a kneading compaction action. The kneading action caused a greater increase of bulk density for loamy sand but was less effective than static compaction for loam and clay.

4.2.4 Vibrational load tests

Under certain conditions the application of mechanical vibrations to soils is an effective method of compaction and the method is used in certain civil engineering work. Little work has been done on the mode of action of vibrational forces in agricultural soils. Rosenberg (1959) pointed out the effectiveness of up to 200 Hz in compacting soils in the density range 1.08 - 1.95 g cm^{-3} with a very high degree of uniformity in both horizontal and vertical planes. Rosenberg (1960) reported that the degree of compaction decreases logarithmically with the duration of vibration. Akroyd (1957) reports the use of a 'Kango' percussion hammer in a maximum density test for sands. Vibrational energy appears to be capable of a greater degree of compaction in closely graded sands than other methods, Felt (1965).

4.2.5 Relation between laboratory and field compaction results

From Section 4.1 it will be clear that no close and constant relation can be expected between field and laboratory compaction systems which differ in so many fundamental characteristics. However it is of considerable practical importance to compare results obtained in the two systems. Lewis (1962) made a detailed assessment of the usefulness of the Proctor test in indicating expected compactability values for engineering soils. He considered that certain granular soils give misleadingly low maximum-density values and high optimum-moisture contents with the Proctor test. A relative compaction scale expressed as percentage of Proctor densities is insensitive since a large amount of compactive effort may be required to produce only a small change in the compaction scale. Lewis and Parsons (1963) state that, for general compaction specifications for a wide range of soils, "the relative compaction approach would be unpractical or unsatisfactory". A more useful measure of efficiency of compaction could be gained by the following formula according to the Road Research Laboratory, Anon. (1952):

$$\frac{(\text{Field dry bulk density} - \text{Loose dry bulk density})}{(\underset{(\text{Proctor})}{\text{Maximum dry bulk density}} - \text{Loose dry bulk density})} \times 100$$

Weaver and Jamison (1951) established that the compaction occurring below a loaded wheel (tractor) was slightly less than that obtained with the standard Proctor test. They concluded that Proctor tests "may be used with some degree of reliability as guides for field tractor compaction studies". Bateman (1963) reviewing a number of workers' efforts suggested that tyres produced similar densities to the Proctor test at moisture contents below the optimum but lower densities than the Proctor maximum density at the optimum moisture content.

4.3 Compaction systems in agriculture

Compaction can occur in agricultural soils in a variety of ways and, unlike compaction in engineering soils, the process is almost invariably the unwanted accompaniment of the passage of tractors and implements. The incidence of compactive loading will depend on the type of crop, the equipment used and the management system practiced and hence will vary markedly from farm to farm and even from field to field. The effect of a given pattern of compactive loading will depend greatly on the compactability characteristics of the soil and the moisture status at the time of loading. The relation between pressure, load and compaction has long been a subject of some uncertainty particularly among farmers. The use of tractors, tillage and harvesting machinery of ever increasing weight has frequently been considered to be of no particular consequence to the incidence of soil compaction because, with suitable wheel arrangements, the surface pressure can be kept to a low value. However the total compactive effort on the soil as a whole must depend on the load per acre and on the degree of interaction between neighbouring loaded areas. A theory relating the incidence of traffic to the overall physical properties of the soil on a field scale has been prepared by Arndt and Rose (1966b).

There appear to be few quantitative data available on the actual amount of traffic which is involved in practical farming. Blake (1963) estimated that, for potato production in New Jersey, tractors travel 20.4 miles per acre per year. Allmaras _et al._ (1967) reported that, for conventional ploughing and cultivation, 80 - 90% of the soil surface will be covered at least once by tractor tyres during each year under corn. In Sweden however Heinonen* considered that during traditional cultivation treatment for

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* Personal communication

cereals the entire land surface was covered at least twice by tractor wheels.

4.3.1 Horizontal distribution of compactive loading

The assessment of compactive changes under field conditions is complicated by the complex pattern of the horizontal distribution of compactive loading under certain operations such as ploughing and harvesting. These effects are particularly troublesome in experimental work since both current and prior traffic distribution will cause very large local variation in such properties as bulk density. Cox and Elliott(1965) attempted to equalize compaction effects from tractor wheels during inter-row potato cultivations by using alternate positioning of the wheel lines in 3 row plots. Although this may equalize total compactive loading in all furrows, compactive response is unlikely to be equalised owing to the strong probability of different moisture conditions at the times of successive cultivations.

Arndt and Rose (1966a) considered the spatial distribution of traffic on soils in some detail. They stressed the importance of recording traffic histories particularly for different crops and farming systems. Of particular significance are pest and pathogen spraying operations in certain crops such as cotton in which wheel compaction occurs on several occasions during the crop life extending to a stage when remedial surface tillage is no longer possible. Due to shading or recent irrigation the surface layers may be moist at the time of wheel passage and compactive response is therefore marked.

Cooper (1960-61) pointed out that the apparent disappearance of wheel tracks due to subsequent tillage operations may merely cover up an unsuitable condition under the surface of an otherwise suitable seedbed. If several passes of a tractor are required there may be a case for superimposing the wheel lines since the second passage causes a much smaller increment of compaction than that occurring during the first passage. This principle is logically extended to the bed or band system of crop production. Arndt (1966) demonstrated striking differences in bulk density, soil strength and clod size distribution in adjacent crop and traffic bands. He concluded that a considerable reduction in tillage operations could be achieved by relating loosening operations to the particular requirements set by the differing physical properties within the bands.

4.3.2 Vertical distribution of compactive loading

Not all compactive loading occurs on the surface. Of particular importance is that which occurs at or just below the maximum depth of disruptive tillage. This includes compaction below the furrow wheel of a tractor while ploughing, the plough sole and the lower edges of tines and rotary cultivation blades. The response to this vertical distribution of compactive loading is complicated by the frequent, marked variation of moisture content and texture with depth. As a result of these effects the study of soil reaction to tillage operations must be undertaken with careful attention to the three dimensional variation of physical properties.

4.3.3 Methods of compaction study

Many workers have found it necessary to simplify the system used because work with field soils has usually involved a very large number of variables. Reaves (1966) stated that "Variations of most natural soils as they exist in the field render them undesirable for fundamental tillage studies". Possible means of simplification include the use of artificial soils, tank studies and model studies. Several workers have used artificial soils in order to avoid the problems of ageing, drying and non-reproducible properties of real soils. Most popular are mixtures of pure clays with sand of various grain sizes in order to obtain materials which can be specified explicitly.

Korayem (1966) used ethylene glycol to moisten bentonite/ sand mixtures in place of water. The greatly reduced evaporation rate results in improved stability. Triaxial strength tests showed values comparable to natural soils. Reaves (1966) used spindle oil and ethylene glycol for the first tests of simple tillage tools with artificially moistened soils. Results were satisfactory in that cohesion and frictional properties varied in a similar way to that with water and the mixtures showed a very high degree of stability. Ethylene glycol was more volatile than spindle oil and absorbs water from the atmosphere.

Sand has frequently been used as an artificial soil but, in spite of the most rigid characterisation in terms of particle-size distribution and grain shape, uniformity of properties of the bulk material in tanks has rarely been satisfactory. Walker and Whitaker (1967) developed a technique for filling test tanks (3 ft diameter by 4 ft deep) with sand using a hopper with a roller controlling the rate of output. The height of fall was found to be comparatively unimportant compared to the intensity of fall. Using a standard method over a period of 5 months, in which respective fillings with a porosity of 42% were required, no test value fell outside the limit of ± 0.3%, a remarkable degree of uniformity. An unusual exercise in the use of artificial soil was described by Talamo (1966). The application of a magnetic field to a bed of iron ore particles was found to induce cohesional properties similar to a clay and frictional properties similar to a sand. Considerable practical difficulties were experienced.

Considerable use has been made of soil tanks for real or artificial soils but a number of problems have to be overcome. Due to the proximity of the tank walls, reaction may invalidate observations. Resilience in the lower boundary is sometimes provided by using a natural subsoil to underlay the tank volume. Workers in very small tanks such as Chancellor and Schmidt (1961) have used grease to lubricate the soil/tank interface. Tanks testing the effect of linear compactional loading, such as that under a rolling wheel, are generally long enough to eliminate end effects. Tank width is frequently reduced by confining studies to single wheels and then scaling-up results to apply to whole vehicles as used by Reed et al. (1959). Soil tanks of adequate size may contain many tons of soil which has to be mixed and settled to uniform pre-determined density prior to each test. This presents a formidable task and very few research establishments have adequate facilities for this.

A method of study intermediate between tank and field scale studies was described by Håkansson (1966) under the term "model experiment". He pointed out that the application of the results of laboratory studies cannot be made direct to field scale operations and he advocated, and used extensively, experiments in which fundamental treatments can be applied to small replicated plots of normal or artificial soil profiles out of doors under conditions of controlled moisture content using movable roof shelters.

4.4 Compaction from tractor and implement wheels

4.4.1 Tractor wheels running on soil surface

The most important factors of tractor design which affect compactive processes are total weight, wheel design and horse-power. The last factor has an indirect effect since it influences the effective working width and hence the number of wheel tracks in a given width of field. The detailed relationship of these properties to performance, sinkage and related properties is outside the scope of this review but has been considered by

Bekker (1960), Fountaine and Payne (1952), Trabbic _et al._ (1959) and Reed _et al._ (1959). Some attention will be given to measurement of compactive changes resulting from wheel traffic.

Early work on the effect of the passage of tractor wheels on soil properties was reviewed by Fountaine and Payne (1952). Their conclusion was that compaction could be considerable under certain conditions which were not readily definable. Much of this early work, however, is of limited application because the effects of wheel loads and wheel type were frequently confounded and soil measurements were frequently of very limited scope. One of the most detailed empirical studies of the compactive efficiency of different wheeled and tracked equipment was carried out by the Road Research Laboratory and reported by Lewis (1960). Test tanks 35 ft x 15 ft x 3 ft were used with naturally occurring soil as the floor of the tanks. Attention was particularly given to the relation between moisture content of the soil and the state of compaction produced, the relation between the number of passes and the compaction produced, and the variation of state of compaction with depth below the surface. 20 types of compaction equipment were tested on four soils and the bulk densities produced compared with the results for the B.S. compaction test (Proctor), modified A.A.S.H.O. and the Dietert Compaction Test. The laboratory tests gave only a poor indication of the maximum dry density and optimum-moisture content values obtained using the equipment in the soil tanks. Increases of wheel load or pressure of inflation increase the maximum dry density and lower the optimum-moisture content. In general 4 passes of the rollers were necessary to produce the state of compaction equivalent to an air-void content of 10% which was the preferred criterion of satisfactory compaction.

Interesting differences were found between the four soils. Heavy clay and sandy clay soils were compacted to the greatest extent by a 45 ton pneumatic tyred roller; densities reached 112% and 110% of Proctor maximum density respectively. However with a well-graded sand and a gravel/sand/ clay mixture greatest compaction was obtained with a 3¾ ton vibrating roller which gave densities equivalent to 113 and 112% of Proctor maximum density. The greatest densities obtained for the heavy clay and sandy clay were 94% and 95% of the modified A.A.S.H.O. maximum density. Whereas for the well graded sand and the gravel/sand/ clay mixture the greatest density was 105% and 105% respectively. These results confirm the conclusion that reliance on laboratory compaction tests for indicating performance of compacting equipment in the field should only be attempted with careful attention to the characteristics of the specific soil in question. It is of agricultural interest to note from Lewis (1960) that 40 and 80 hp tracked tractors achieved maximum densities which agreed closely with the Proctor maximum density.

One of the difficulties of compaction studies under tractor wheels is the frequent incidence of very large deformations with only minor changes in densities. Fountaine and Payne (1952) found that when a 'Rotavated' soil was used for a tractor-wheel compaction experiment, surface deformations of up to 5 in. depth occurred but that changes in density were slight or not detectable. Similarly "fluid" conditions occur under high moisture conditions. However there are numerous examples of considerable changes in soil properties as a result of the passage of tractors wheels. Vomocil _et_ _al_. (1958) found an increase of bulk density from 1.31 to

1.50 g cm^{-3} after one passage of a 11-16 tyre loaded to 2750 lb.

Kuipers et al. (1966) made tests on the distribution of loose material in tractor wheel ruts with different types of wheels, with and without cage wheels attached. The total amount of "compacted loose soil is by far the highest" using a cage wheel alone but a very much greater degree of uniformity of density in the horizontal direction is obtained.

The contact pressure is higher than the inflation pressure due to the stiffness of the wall of the tyre. Markwick and Starks (1940-41) working with road surfaces considered that the contact pressure could be taken as 150% of the inflation pressure. Little work seems to have been done on this matter in connection with agricultural tractor wheels. Turnbull and Foster (1960) pointed out that the method of marking tyres to leave an impression of contact area can be a misleading method of measuring contact pressure because of the variation of pressure over the contact area.

Detailed work on soil-tyre interface pressures was reported by Trabbic et al. (1959). Pressure transducers were embedded in the undertread, lug face and leading and trailing sides of the lug of a tractor rear wheel. The effect of variation in inflation pressure and draw-bar load on the distribution of interface pressure across the width of the tyre was measured. As inflation pressure, slip, and draw-bar load increased centre undertread pressure increased. Kolobov (1966) also used strain gauges to measure the changes in contact pressure of lugged wheels in order to explain the change of draw-bar pull with tyre pressure. It was possible to measure the difference in the pressure distribution on leading and trailing sides of lugs. This distribution was influenced by changes in draw-bar pull and inflation pressure.

Fountaine and Payne (1952) pointed out that intense compaction is likely to occur to soil lying between the lugs of a tractor wheel or track. The amount of this type of compaction will depend on the bearing capacity i.e. whether the weight is born on the area of the lugs alone or on the inter-lug area as well. Experiments suggested that compaction by spade lugs would be serious only if almost all the soil was compacted to a high bulk density. Soil falling from between the lugs is generally very dense and can form resistant clods.

Very little work has been attempted on the effect of wheelslip on soil properties, technically a difficult problem. The intense smearing action occurring in wheel slip can result in considerable deterioration in physical fertility comparable to severe puddling. Weaver and Jamison (1951) used core sampling in an attempt to establish a relationship between draught and bulk density. The greatest compaction appeared to occur at less than 1200 lb per wheel.

When a wheel is rolling along a smooth surface it exerts no impact loading but its passage over an obstruction causes an impact which can result in a local increase of surface loading. Aughtie et al. (1933-34) showed that, for hard surface roads, the passage of wheels over a one inch plank would increase load momentarily by 30%. While this effect is of trivial importance on road surfaces the passage of tractors over irregular soil surfaces in the field can cause a considerable deviation from level rolling motion. The effect does not appear to have been investigated.

Very little work has been attempted on the effect of speed of travel on compaction below wheels. Fountaine and Payne (1952) found no effect due to speed but sampling methods were not satisfactory and large differences of moisture content are reported for the three replications (30.1, 48.0, 44.2) suggesting a serious lack of uniformity of soil type. A second experiment on a clay soil gave no difference between heavy (50 cwt on rear wheels) and light (23 cwt on rear wheels) but slightly higher densities were obtained with slow speed. Vomocil et al. (1958) found that the degree of compaction increased as speed decreased and drawbar pull increased.

Multiple-wheel systems

The effective use of multiple-wheel systems has not been seriously tackled with agricultural tractors although it has found application in other off-the-road locomotion systems. A clear understanding of the diverging cones of stress influence is required if multiple-wheel systems are to be successful. Sparkes (1939) and Spangler (1942) examined the effects of multiple-wheel loading on road surfaces. The latter showed that, theoretically, two wheels at 10 in. centres each carrying 4000 lb presented no more severe stress on a flexible pavement than a single wheel with the same load. However such studies were concerned with high strength bearing surfaces in which surface deformations are negligible. No such rigorous treatment appears to have been carried out for low strength bearing materials.

Possible multiple wheel systems include 4-wheel drive and 6-wheel machines. 4-wheel drive vehicles may be in the conventional single engine form (e.g. County Super-4 and Northrop 5004) or the tandem (twin-engine) type (e.g. Doe - 130). The latter design was developed at Michigan State University, in order to provide a versatile system of either 1 heavy tractor or 2 light ones, Buchele (1959), and also to make more efficient use of power and labour for operations requiring high power (ploughing, subsoiling) and low power (planting, spraying, trailing). Reed et al. (1959) using single-wheel tests in tanks with different soils showed that, for tractors of similar total weight, power efficiency was likely to be about 10% higher for a 4-wheel drive tandem tractor than 2-wheel drive when the wheel slip was 10%. For 2-wheel and tandem 4-wheel drive tractors each weighing 9200 lb and at 20% slip the calculated draw-bar pull was 54% higher for the 4-wheel drive system on sand, 43% for sandy loam and 26% on clay.

The National Institute of Agricultural Engineering Scottish Station has produced a prototype implement carrier with four driven wheels mounted on the same axle and two non-driven wheels. Reed et al. (1959) made wheel performance tests with 1, 2 and 3 passes over the test bed in an attempt to simulate conditions for a 6-driven wheel tractor in comparison with 2- and 4-driven wheel units. However they considered that "the difficulty of manoeuvring a 6-wheel unit will defer its consideration".

4.4.2 Tractor wheels running in plough furrow

Many of the principles discussed in 4.4.1 also apply to the action of tractor wheels running in the plough furrow. In addition there are certain special features which render this form of compactive loading particularly serious. The practice of running the working-side tractor wheels in the plough furrow is almost universal for wheeled tractors and has its origins in horse ploughing. Cooper (1960-61) pointed out that more than half of the normal load is born by the wheels running in the furrow owing to the inclination of the tractor. The moisture content at the depth of the furrow bottom is frequently such that pronounced compactive deformation can be obtained whereas the surface soil may be sufficiently dry to have a low degree of compactability. Specific measurements of furrow bottom compaction were made by Fountaine and Payne (1952) with a medium loam under permanent pasture but no density changes were found even after 24 passes of a 52 cwt tractor along the same furrow. The lack of effect was attributed to the high organic matter and root content. Tests made on a sandy loam soil showed an apparent change of density after 3 passes. They also examined a number of sites at which farmers were complaining of compaction difficulties. Bulk density (core sampling) and penetrometer readings were obtained but compaction was only slight at depths below 2 in. from the furrow bottom. They concluded that it might be possible to use tractor wheels in the furrow bottom for "ten or more years with little or no influence" on bulk density. Their conclusions might have been different if they had been able to use a method of measuring bulk density with a high degree of vertical resolution permitting the measurement of narrow layers. Czeratzki (1966) reported an increase of density at 25-30 cm depth over a 6 year period which was attributed to the compactive effect of the tractor wheel running in the furrow.

4.4.3 Compaction during crop spraying

The increasing use of chemical sprays for the control of weeds and pests has led to the passage of loaded tractor wheels over or within the crop during the growth period. The distribution and effects of the compactive changes produced differ markedly between different crops. In soft fruit and orchard crops tractor sprayers may have to pass along the same wheel tracks for every spraying operation with a marked increase of surface density as a result. In field crops the use of very wide spraying booms greatly reduces the total area of wheel track per acre of crop. Repetitive loading is usually avoided but for certain crops such as cotton which require several insecticide applications in each season repetitive loading is sometimes deliberately adopted because (a) the compactive change during the initial passage of the wheels is very much greater than during subsequent passages along the same track and (b) better traction is obtained on compacted wheel tracks, an important factor on irrigated soils.

4.4.4 Compaction during harvesting operations

The increasing use of mechanical equipment for harvesting operations has represented a striking change of technique for many crops in recent years. The replacement of the binder and light trailers for corn harvesting by combines, grain trailers, straw balers, bale sledges and bale lifters represent a great increase of harvest traffic. Little attention has been given to the significance of compaction during harvest operations. Flocker et al. (1960) recognised that harvesting operations for vegetables, especially the passage of loaded trucks, could result in considerable compaction and experimental compactive treatments were therefore applied in the autumn "when soil moisture contents are generally near saturation". However extremely high moisture contents do not lead to a high degree of compactability although the puddling action may be deleterious.

4.5 Compaction from implements

The object of most tillage operations is to loosen the soil through the processes of comminution and reduced packing intensity. These objectives may however be accompanied by compactive effects either within or below the depth of working.

4.5.1 Plough-share compaction

The traditional usage of a mouldboard plough involves a considerable downward load on the soil below the plough owing to the lifting action of the share and mouldboard. As with the tractor wheel running in the furrow bottom, this load is applied to soil that is generally at a fairly high moisture content and it has long been suspected that repetetive ploughing at the same depth may result in a compacted layer usually referred to as a plough pan. Browning (1950) found little evidence for a plough pan "under present farming operations" (U.S.A.) but other workers do not share this view. Frese and Altemüller (1962) studied compactive changes just below plough depth with the aid of microsections. This technique permitted the demonstration of intense, narrow layering which had been long suspected but largely undetected. Sack (1962) used air and water permeability tests on soil immediately below plough depth and found evidence of considerable downward pressure under ploughs. The passage of the slade was found to be particularly important. The smearing action produced by its passage was found to reduce air and water permeability very considerably although the depth of the effect was very limited. He considered that undue compaction below a plough could be avoided by taking part of the weight of the plough on the tractor and the use of an automatic depth control. He noticed that the phenomenon of tongue formation in the base of the furrow, particularly in heavy soils, plays an important part in reducing compaction.

Kashirad _et al._ (1967) studied the incidence and properties of tillage pans in American soils. Pans were found to be at about 14 cm depth and to be of about 14 cm thickness. Marked differences in penetration resistance, bulk density and total pore space were found in the traffic pans through which root growth was shown to be severely restricted. Deep ploughing was considered to be a more effective treatment than subsoiling.

4.5.2 Cultivation implement compaction

Implements used in secondary cultivations for the purpose of reducing clod size may have a compacting effect. Kuipers and Van Ouwerkerk (1963) showed that spring cultivations after winter ploughing may lower the surface elevation (and hence decrease porosity) to a value very similar to that existing prior to ploughing. This effect is probably a combination of a reduction of large voids between clods together with a compactive effect towards the base of or below the depth of cultivation. Disks have a particularly vigorous compacting action. Root observations by De Roo (1960) confirmed the presence of a compacted zone beneath the penetration depth of disk cultivations on sandy loam soil. The zone was of sufficient density to show considerable, though not total, inhibition of root penetration. Below this zone root growth was more extensive in the soil loosened originally in ploughing. Gill (1959b) considered that the compaction from disk harrows may be sufficiently serious to justify the term "harrow sole" while Blake (1963) stated that "essentially all tillage other than ploughing increases the soil bulk density". Harrow compaction effects have also deen demonstrated by Trouse (1951-55).

4.6 Compaction from animals

It is frequently assumed that soil compaction in the field has only become important since the advent of the tractor. However Scott (1908) recommended the use of a subsoil plough, "a horse implement produced for the purpose of breaking up the close hard soil below the furrow, often rendered impervious to air and water by the tramping of horses". He also considered that a double furrow plough was advisable because "the bottom or pan of the furrow is not so much trodden as in single ploughing". He welcomed the use of steam ploughing tackle because vigorous treading is avoided and "the roots of plants can readily penetrate to the subsoil".

The treading of soil under pastures and certain other grazed crops has always been recognised as having an important modifying effect on soil physical properties. When the treading occurs on dry soils the effect is mainly one of compaction and should be susceptible to treatment by the laws of that process. However, when the soil is wetter than the optimum moisture content for compaction, which is generally the case throughout the winter and sometimes much of the summer under local conditions, soil deformation occurs in a less precise manner involving an alteration of the basic soil structure in a process known generally as puddling. Gradwell (1965) showed that the deep penetration of hooves into soft wet soils in winter caused a marked reduction in the air-filled porosity and hence oxygen availability. Gill (1959b) pointed out that the trend towards intensive animal production tends towards higher stocking rates for longer periods of the year. The treading action may be particularly severe where irrigation of pastures is used.

CHAPTER 5

GENERAL TECHNIQUES FOR BULK DENSITY MEASUREMENT

5.1 Limitations set by technique and soil variability

The main deficiencies of traditional techniques have been that they are:

(1) Too laborious and slow, requiring a large amount of time for sampling and analysis and hence frequently restricting the degree of sample replication to inadequate levels.

(2) Destructive, preventing analysis before and after treatment application at identical sites and hence greatly increasing experimental error and the numbers of samples required.

(3) Incapable of providing a high degree of resolution. As a result the spatial distribution of bulk density, with the abrupt changes in the vertical and horizontal directions which frequently occur in the field, cannot be readily measured.

The standardisation of soil physical measurement methods used in North America has been considerably aided by the work of Black (1965) in which most methods are described in detail together with a discussion of basic principles. In Europe a similar notable advance has been achieved by the publication of "West-European Methods for Soil Structure Determination" by De Boodt et al. (1967). Study of these two publications demonstrates that wide differences of technique exist even for a comparatively simple property such as bulk density.

Soil variability can impose a severe sampling problem as described by Mader (1963). Studies in arable soils have frequently shown very large variation of physical properties even when the visual appearance suggested uniformity. Nichols and Reeves (1955) found that the results of subsoiling operations persisted for many years and caused a very wide variation of bulk density and moisture content. They also found that marked differences of secondary aggregate-size distribution occurred within small areas of soil and appeared to be due to inherent and unexplained differences in soil properties. The problem of soil homogeneity was considered by Kuipers *et al.* (1966). They considered that, in certain situations, variability can be so bad that satisfactory sampling is impossible. They stressed the particular significance of wheel ruts in influencing uniformity of soil physical properties. They paid attention to variations in uniformity which may occur at different times. The mean porosity of the 7-12 cm depth before and after sugar beet harvest was found to be 46.9 and 47.0% respectively, indicating no change but the increase of standard deviation from 1.3 to 2.2% was considered to be a highly important characteristic.

Detailed studies on the variability of soil properties in relation to sampling techniques have been made by De Boodt and were described by De Boodt *et al.* (1967). Coefficients of variation were presented for bulk density and total pore space, stability of aggregates, macropores, 'drainage' pores, 'useful' pores and soil structural index. Results were grouped according to the size of the experimental plots (large, at least 4 m between samples, medium, area at least 16 m^2, and small, area 1 m^2). C.V. values were generally lower for bulk density and total pore volume than for the other determinations, no consistent difference was obtained at 1-3 and 3-5 cm depth nor between samples obtained on different sized plots. There was a tendency for the C.V. to decrease as the soil became more sandy. The influence of C.V. values for soil physical determinations on the number of replications required was discussed.

5.2 Methods for measurement of bulk density of whole soil

5.2.1 Core-sample method

This method has been used for agricultural top soils for many years. The size of the core varies considerably depending on the objective. Blake (1965) discusses different types of samplers including those with an inner cylinder for sample retention. He also mentions the several serious disadvantages of the method. It is very tedious, not suitable for stony or loose soils and may give erroneous results due to campaction within the sample especially on soils of high compactability. Fountaine and Payne (1952) used the core sampling method in preference to any other method but they found "considerable difficulty" in measuring the bulk density of loose soils. Lutz et al. (1960) found that compaction occurred within the sample for moist friable surface soils and the results gave no evidence of density differences between treatments in spite of visual evidence to the contrary. Gamma-ray transmission measurement however indicated highly significant differences in bulk density. It is possible that this inability of core sampling to detect the results of compactive treatments has invalidated conclusions in many experiments.

The degree of compaction within the sample is related to the wall thickness of the core cylinder. The Road Research Laboratory, Anon. (1952), investigated the effects of wall thicknesses of $^1/16$, $^1/8$, $^3/16$ and $\frac{1}{4}$ in. for a core sample 4 in. and 5 in. high. Core bulk density increased as the wall thickness decreased. "Compression of the soil caused by the insertion of the core-cutter into the ground outweighed the expansion of the soil due to stresses set up as the core is driven into the ground". The significance of wall thickness was also considered by De Boodt et al. (1967). As a criterion of wall thickness they defined an area ratio

$$Ar = (D_e^2 - D_i^2) / D_i^2$$

where D_e and D_i are the external and internal diameters respectively. They consider an Ar value of 0.08 satisfactory. The most widely-used equipment in Western Europe has a sample volume of 100 cm^3 with the shape varying from 7.63 cm internal diameter, height 2 cm (Belgium), internal diameter 5.6 cm, height 4 cm (Germany) to 5.0 cm internal diameter, height 5.1 cm (Holland). They consider that 2 cm is the minimum height of core required to prevent the sample falling out of the ring. In arid and semi-arid areas recommended core volumes tend to be larger. Dagg and Hosegood (1962) used cores of 10 cm diameter, 7.6 cm height in East Africa.

Some further disadvantages of the core-sampling method in field compaction studies were discussed by Weaver and Jamison (1951). Of particular difficulty was the selection of the sampling depth because of the variable sinkage resulting from the application of compactive loading resulting from wheel traffic on different soils.

5.2.2 Excavation methods

(a) Volume by direct measurement

When core sampling is not possible certain workers have used the excavation method in which soil is removed by hand from a measured volume in the field. Brown et al. (1954) used a frame which enables a sample to be removed 3 ft^3 in capacity (3 ft x 3 ft x 4 in. depth). As a result of the large volume sample boundary errors were considered to be unimportant. The method gave results which were virtually identical to those of the core sampling method in both accuracy and precision with the additional advantage of being less affected by stones.

A modification of this technique used at the Agricultural College of Sweden was described by De Boodt _et al._ (1967). A frame (70.7 cm x 70.7 cm x 35 cm deep) was used to provide horizontal limits to the sample volume. Vertical limits to the sample are obtained by measuring the soil-surface elevation (relative to the top of the frame) at 196 positions before and after removing the sample. The method was claimed to facilitate the division of the soil "along such natural boundaries" as can be detected in tilled soils but the time requirement is high. 5 man-hours are required to remove 4 layers in the field followed by laboratory determinations of water content.

(b) _Volume by replacement technique_

This technique consists of removing soil from the sampling site so as to leave an irregular-shaped hole, the volume of which is then measured by filling it with a material which will not enter the exposed surface of the hole. Civil engineers have long used this method with sand as the replacement medium. With careful attention to detail satisfactory results can be obtained provided a high degree of accuracy or precision are not required. The method has the special merit of being suitable for stony soils. Volume replacement methods have not been widely used in agricultural soils. Shipp and Matelski (1965) compared the use of sand, water in membrane, viscous liquid and gypsum as replacement media. Lewis and Parsons (1963) mentioned several of the errors in the sand replacement method particularly for granular material of low cohesion. A comparison was made between the sand replacement and the core sampling methods. The former method gave a higher standard deviation. However in many situations the sand or water/balloon replacement methods are the only practical methods.

5.2.3 Element volume change method

This method employs the measurement of volume change in small elements within the soil mass. Chancellor and Schmidt (1961) described one method in which X-rays are used to measure the displacement of lead spheres within a soil mass during a compaction process. Changes in the cross-section area between adjacent spheres originally in a regular grid pattern are considered to be proportional to the change in density within the volume represented by the spheres.

5.2.4 Penetrometer method

This method is dependent on a non-unique relationship between penetrability and bulk density for which soil type, moisture content and penetrometer design are critical factors. In spite of these disadvantages Lyles and Woodruff (1963), Henry and McKibbon (1967) and others have been satisfied with its performance, once the instrument has been calibrated for soil type and moisture variation.

5.2.5 Deposition method (for soil tanks)

Walker and Whitaker (1967) used a deposition method for the assessment of bulk density and porosity. Cans of known volume were placed in a test tank and the tank was filled by a free-fall technique from a hopper. The mean quantity of material 'caught' in the collecting cans was used to indicate the bulk density of the material in the tank.

5.2.6 Units of measurement

There is little uniformity in the use of units for expressing soil bulk density. Agricultural soil scientists have used the metric system ($g\ cm^{-3}$) for many years and this has been adopted as the standard unit by the American Soil Science Society. However British and American civil engineers continue to use the unit $lb\ ft.^{-3}$ In the field of terramechanics Reece (1964) has used the unit lb $in.^{-3}$ Bekker (1960) uses the unit slug ft^{-3} to indicate the density of mud where one slug equals 32 lb ft sec^{-2}. The moisture content to which dry bulk-density values refer is not always stated and as pointed out by Bateman (1963) this can be of importance for soils subject to swelling and shrinkage properties which are more apparent as the bulk density increases. Gill (1959a) showed that the change of dry bulk density with variation in moisture content is quite different for remoulded soil than for natural clods. The destruction of structure largely eliminates differences between soils of different texture. He proposed the term shrinkage coefficient (g cm^{-3} per % H_2O change) to characterise the average change in bulk density at moisture contents in the tillable range. For a heavy clay, a 3% $^{w}/w$ difference in water content could cause a bulk density difference of nearly 0.09 g cm^{-3}. Tillage or traffic treatments may well cause considerable differences in moisture content, enough to confuse any differences in bulk density which might be associated with the treatments. Miller (1966) studied the effect of drying on bulk density. He recommended the conversion of bulk density values to a field capacity basis.

5.3 Methods for measurement of bulk density of aggregates and clods

Aggregates and clods have no definable shape so that measurement of their density generally requires a displacement method of measuring individual volumes.

5.3.1 Displacement in liquid

This is a convenient method of measuring the volume of irregular shaped objects but for porous material such as soil precautions are required to prevent entry of the liquid into the specimen. This can be achieved by the application of impermeable coating or the use of immiscible liquids.

Methods employing impermeable coatings were considered by Russell and Balcerek (1944). Paraffin wax is the most widely used and it is reliable though tedious. Several workers have attempted to use alternative methods which would avoid the necessity of a heated wax bath. Brasher <u>et al.</u> (1966) described the use of Saren resin which has the property of being permeable to water vapour but not to liquid water. Volume changes due to swelling and shrinkage can be studied at temperatures up to 105°C. The material can be readily used in the field. However Brasher* has admitted that the resin does not form a satisfactory coating on sandy material.

Displacement in immiscible liquids has been less popular but may have advantages for aggregates of small diameter. Strikling (1955) proposed the use of mercury but cost seems to have restricted its use. However Gill (1959a) used mercury displacement for repetetive volume measurements on remoulded blocks of soil during a drying sequence. De Boodt <u>et al.</u> (1967) describe the use of a mercury volumeter manufactured in Switzerland for the measurement of the bulk density of aggregates with a diameter 0.5 - 3.2 cm.

5.3.2 <u>Displacement in solid medium</u>

The use of glass beads as a displacement medium for aggregates of less than 10 mm diameter was developed by Voorhees <u>et al.</u> (1966). The method has some notable advantages. It is satisfactory for aggregate sizes below the minimum suitable for use with the wax-coating method, the moisture content can vary from saturation to oven dry and a high degree of precision in measurement is obtained. Although sand displacement has been used for volume-density studies for irregular-sized sample holes in soils for many years, very little attention has been given to the use of the sand displacement for the

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* Personal communication

measurement of density of soil aggregates and clods. Kuipers (1961b) used the method in a simple form, without reference to previous work, and obtained extremely similar results for the porosity of air-dry aggregates by the sand displacement method and the kerosene displacement method according to McIntyre and Stirk (1954). The sand volume of the sand-aggregate mixtures was measured in a calibrated tube (1.5 cm diameter, 10 cm length).

5.3.3 Radiography

X-ray radiographic techniques have been used by Greacen et al. (1967) to study the gradients of bulk density in 2 mm thick slices of clods after subjection to loading. Distinct gradients of density were observed.

CHAPTER 6

GAMMA-RAY TRANSMISSION METHOD FOR MEASUREMENT OF SOIL BULK DENSITY

The application of gamma-ray backscatter techniques to the problem of soil density measurement was apparently first reported by Belcher et al. (1950) and has since been the subject of intense research effort and application in the field of civil engineering and to a very limited degree in agriculture, Phillips et al. (1960). However the backscatter method, though very successful in certain applications has never provided a degree of sample resolution consistent with the requirements of soil tillage research and it will not be considered further. A far more promising method, the gamma-ray transmission technique, was used in soils by Vomocil (1954a, b) (1955), Bernhard and Chasek (1955), Roy and Winterkorn (1957) and Van Bavel et al. (1957).

These workers recognised the significance of the unique degree of sample resolution which was possible but practical exploitation of the method was slow largely due to the lack of commercial electronic equipment suitable for field use. Although progress has since been made, some of the technical problems remain and in the following review particular attention will be given to their influence on the application and accuracy of the method as well as to possible means for their solution.

6.1 Theory of interaction of gamma-rays with matter

6.1.1 Nature of gamma-rays and their interaction with matter

Gamma-rays represent the high frequency extreme of the electro-magnetic series of radiation. They have a frequency of about 3×10^{18} Hz and wavelengths in the range 0.005 - 1.40 Å. The quantum unit of gamma-ray energy is the photon, the energy of which is expressed in electron volts. Gamma-emitting isotopes may emit photons of one, two or many energies.

Because of their very high frequency, gamma-rays have very high penetrating power. The interaction with matter is primarily with the outer electrons but collision with the nucleus may occur rarely. Interaction with the outer electrons occurs in two ways:

(a) <u>Photoelectric effect</u>: The photon is absorbed and an electron ejected leaving a charged ion. This effect is of principal importance with incident photons of low energy (below 300 KeV) and the degree of absorption is strongly related to the Z number of the atom.

(b) <u>Compton effect</u>: The photon is not absorbed but continues on a new path with reduced energy, an electron also being ejected. The process consists both of absorption and scattering of photon energy.

In practice the interaction of gamma-rays with matter will be accompanied by both effects, the proportion of each depending on the energy of the incident photons. On striking a finite thickness of material, incident photons will be distributed into the following categories:

(a) Those which pass straight through the material without interaction, absorption or loss of energy.

(b) Those which undergo Compton scattering, with a loss in energy but not absorption.

(c) Those which are first reduced in energy by the Compton effect and subsequently absorbed by the photoelectric effect.

(d) Those which are absorbed directly by the photoelectric effect without prior loss of energy.

In considering the absorption of gamma-rays on passing through matter particular attention therefore has to be given to the energy of the incident photons, the energy of the transmitted photons, the composition of the material and the mass density of the material.

Study of transmission characteristics is greatly simplified if only unattenuated (unscattered) photons are considered using a monoenergetic source. Transmission characteristics of scattered photons, to be fully described, must be studied by complex mathematical analysis which is outside the scope of this work.

6.1.2 Basic transmission equation for unattenuated photons

The empirical relationship describing the behaviour of unattenuated gamma-ray photons on passing through matter is based on the Beer-Lambert Law and is usually expressed in the general form

$$I_Y = \frac{S\,E \exp(-\mu x)}{4\pi\, Y^2} \qquad (6.1)$$

where S is the emission rate (s^{-1}) at a point source (4π), E is the efficiency of detection of unattenuated photons, I_Y is the rate (s^{-1}) of passage of unattenuated photons through a cross section of Area A (cm^2), x is the thickness of the absorber (cm), Y is the distance between source and detector (cm), and μ is the linear absorption coefficient (cm^{-1}).

The reciprocal of the absorption coefficient is known as the mean free path. The linear absorption coefficient may be transformed to a mass absorption coefficient, μ_m, ($cm^2 g^{-1}$) by the relationship

$$\mu = \mu_m d \qquad (6.2)$$

where d is the density of the absorber ($g\ cm^{-3}$). The value of μ_m is then independent of the density or state of the absorber. When the source and the detector are of fixed size and maintained at a fixed distance apart Eqns (6.1) and (6.2) may be combined and simplified to

$$I = I_o \exp(-\mu_m d\, x) \qquad (6.3)$$

in which case I and I_o are the photon count rates with and without the absorber material present. Since I, I_o and x can be readily measured and μ_m is a constant for a given material and a given photon energy, Eqn. (6.3) provides a means of determining density when rearranged in the form

$$d = -\log_e \frac{I}{I_o} / \mu_m x . \qquad (6.4)$$

Absorption coefficients have been both calculated and determined experimentally for practically every combination of absorber element and photon energy and are readily available in tabular or graphical form. Experimental results differ from theoretical values depending on whether a high or low degree of collimation of the incident and emergent beams has been used. In most detailed work, narrow beam geometry is employed together with an energy sensitive detector and discriminator. Under these conditions experimental absorption coefficients in close agreement to theoretical values can be obtained. However, for broad beam conditions and with a detector insensitive to photon energy, experimental absorption coefficients may vary very markedly from theoretical values although in practice this is not necessarily a matter of any importance.

6.1.3 The build-up effect

If the detector and counting system is not capable of eliminating all but the non-attenuated photons a number of complications are introduced. One of these is known as "build-up" which is due to the inclusion of scattered and attenuated photons in the count rate. The following represent some of the other complications:

(1) The effective sample thickness exceeds the solid angle between the source and detector.

(2) The relationship between log count rate and density may no longer be represented by a straight line throughout its full range.

(3) Sensitivity to sample composition increases owing to the contribution made to the count rate of photons of less than 300 KeV.

The build-up effect may be sufficiently important to require the following modification in the absorption equation

$$I = I_o B \exp(-\mu_m d x) \qquad (6.5)$$

where B is the factor by which the count rate is increased due to the inclusion of scattered photons. B depends on the mass-absorption coefficient, and the density and thickness of the absorber material. The theoretical calculation of the build-up effect does not appear to have received much attention. Goldstein and Wilkins (1954) stated that the effect may be calculated "in principle" but Smith and Dixon (1963) pointed out that in effect "no theoretical calculations have been made and little experimental work done".

Wilkins *et al.* (1964) stated that the build-up contribution, B', can be obtained from the expression

$$B' = A(\mu_m d x)^n \qquad (6.6)$$

where A and n are constants and $B' = B - 1$. A value of $n = 2$ was used and A was determined experimentally and found to be 0.11 for the test conditions.

Smith and Dixon (1963) determined the build-up factor for water using Co-60 gamma-ray photons ($\mu_m=0.0640$ cm^2 g^{-1}) at 2.76 mean free paths and obtained a value of 3.77. A corresponding figure for soils was 2.63. They considered the significance of the build-up effect under practical field conditions. Using a Geiger:Müller detector at 47 cm from a 9.5 mCi Co-60 source arranged under broad beam conditions a predicted narrow-beam counting rate was calculated using the computed count rate in air and the previously measured narrow-beam absorption coefficient. Measurements were then made at 22 different field sites involving combinations of 5 soil types and different levels of organic matter and moisture content. The build-up factor B was determined as the ratio between the predicted narrow-beam counting rate (based on the density measured with a core sampler) and the actual counting rate (after correction for background and coincidence losses in the detector). The value of B was found to increase linearly with soil bulk density and the number of mean free paths. The latter term is obtained from the product of the absorption coefficient, the bulk density and the sample thickness. A correlation coefficient of + 0.948 was obtained for the regression

$$B = 0.26 + 0.86\ (\text{no. of mean free paths}). \qquad (6.7)$$

For a fixed absorber distance and absorption coefficient this equation transforms into

$$B = 0.26 + 2.17\ d \qquad (6.8)$$

where d is the wet bulk density. This expression for B can then be substituted into Eqn. (6.5) to give

$$I = (0.26 + 2.17\ d)\ I_o \exp\left(-\mu_m\ d\ x\right). \qquad (6.9)$$

A tabular solution of this equation was then obtained for the fixed sample thickness and for the particular Geiger:Müller tube used and this permitted a solution for d in terms of I and the results obtained were in good agreement with density values obtained by core sampling at the 22 locations.

6.1.4 Absorption coefficient values for soils and water

Table 6.1 gives a number of results for absorption coefficient values for soils and water obtained in a number of ways for Cs-137 radiation. The results of some early work differed considerably from the computed values. Van Bavel et al. (1957) considered that their low values were due to the inclusion of some secondary radiation which must be considered probable in a system with only a very low degree of collimation. The reliance on electronic discrimination to select only unattenuated photons does not appear to be as reliable as narrow geometry since the absorption coefficients obtained with the former system are always noticeably lower than with the latter system.

TABLE 6.1

Absorption Coefficient Values for Soils using Cs-137 Gamma-ray Radiation (primary photon energy)

Author	Method	Type of soil	Mass Absorption Coefficient	
			Soil	Water
			$cm^2\ g^{-1}$	$cm^2\ g^{-1}$
Van Bavel *et al.* (1957)	Experimental (NaI detector)	Quartz sand (saturated)	0.0624	-
		Quartz sand (dry)	0.0669	-
		Lakeland sand	0.0631	-
		Norfolk sand	0.0676	-
		Cecil clay	0.0637	-
		Average	0.0650	-
Davidson *et al.* (1963)	Experimental (NaI detector)	Columbia silt loam (dry)	0.0769	0.0815
Reginato and Van Bavel (1964)	Computed from Composition	Grey Desert, Mohave loam	0.0772	0.0862
		Chernozem, Barnes silt loam	0.0780	-
		Average of 9	0.0775	-
	Experimental NaI detector		0.0699	0.0748
Grodstein (1957)	Computed	-	-	0.0855
Van Bavel (1960)	Experimental	Wide range of soils	0.0608	-
	Computed	Dry soil & concrete	0.0772	0.0862
Shalhevet and Yaron (1967)	Experimental	Brown hamra soil	0.0627	-
		Sand	0.0710	-
		Clay	0.0661	-

Bernard et al. (1956) reported values for absorption coefficients of soils using Co-60 radiation determined with the equipment described by Bernard and Chasek (1955). Since no discrimination was used to exclude secondary photons it is not surprising that the experimental value reported ($0.0134\ ft^2\ lb^{-1}$, mean for 13 soils) was considerably less than the quoted theoretical value of $0.025\ ft^2\ lb^{-1}$. The use of these units, also used by Wilkins *et al.* (1964), is very unconventional. The corresponding values in the metric system would be 0.0274 and $0.0512\ cm^2\ g^{-1}$.

Irrespective of the geometry and discrimination technique which result in such large differences in absorption coefficient value, the effect of variation in soil composition is slight. Van Bavel et al. (1957) considered that differences in absorption coefficient between soils were without importance. Van Bavel (1960) stated that the absorption coefficient of soils was virtually independent of composition with incident photon energies greater than 300 KeV. This uniformity is related to the fact that most soil constituents, with the exception of hydrogen, have an approximately equal electron density of 3×10^{23} electrons g^{-1} and as pointed out by Kuranz (1959) the chemical composition corresponds to an atomic weight/atomic number ratio of about 2.

Reginato and Van Bavel (1964) used the Grodstein (1957) values for elemental absorption coefficients to calculate absorption coefficients for nine soils of extremely wide compositional range. The range from maximum to minimum value was only 1% of the mean value. Harland and Urkan (1966) calculated mass absorption coefficients for four contrasting soils for photon energies in the range 0.60 to 0.03 MeV and found that differences were less than 1% for energies of 0.2 MeV or higher. At 0.03 MeV however the results for heavy clay, sandy clay, sand and gravel, were 1.1909, 1.2247, 1.0343 and 1.0402 $cm^2\ g^{-1}$ respectively giving a maximum difference of about 19%.

As noted by Cameron and Bourne (1958) hydrogen has an electron density twice that of other elements and will therefore contribute to the scattering and absorption of photons to a greater extent than other elements in soil and a distinct difference can therefore be found between the absorption coefficients of soil and water if high precision equipment is used as shown in Table 6.1. The implications of differences in the absorption coefficients for soil and water on the practical use of the gamma-ray transmission method are considered in Section 6.3.2 (d).

6.2 Equipment

6.2.1 Gamma-ray sources

The selection of a gamma-ray source requires a choice of the photon energy distribution and the activity of radionucleide. The theory of these choices was considered by Berman and Harris (1954). They suggested that the maximum sensitivity for a density measurement is obtained when the photon energy is such that the mean free path is equal to the thickness of the object. However practical availability and cost also have prominent effects on the selection of gamma-ray sources. The two most popular gamma-ray sources are Co-60 and Cs-137 although Ra-226 has also been used in early work with the backscatter method by Parsons and Lewis (1962) and Kühn (1960). Vomocil (1954b) considered Co-60 to be a very suitable source particularly in view of its low cost. Its high photon energies (1.17 and 1.33 MeV) are more penetrating than that for Cs-137 (0.66 MeV) but conversely the half life (5 years) is less suitable than that for Cs-137 (30 years). Recent workers have preferred Cs-137 on account of its monoenergetic photons and the reduced shielding required.

The required source activity depends on a number of factors including the source-detector separation distance, the sample thickness, the range of density to be measured, the active size of the detector, the type of discrimination employed, the degree of collimation, the mass thickness of probe and access tubing and the detector efficiency.

In some applications very considerable sample thicknesses have been employed. For instance Bernhard *et al.* (1956) described the use of a

7 ft thick sample which necessitated the use of 50 mCi Co-60 for which the shielding and handling problems were very considerable. In most studies the gamma-ray source has been of such a size as to be considered as virtually a point source as far as the geometry of the system is concerned. However Ashton (1956) used an aqueous solution of Cs-137 as chloride in a tube 2.5 in. long. The object of this unusual arrangement was to give a source of vertical height equal to that of the GM tube which was used as a detector and hence the sample volume tended towards a parallel-sided rather than a divergent shape.

6.2.2 Gamma detectors

(a) Geiger: Müller (GM) Tubes

The first testing of the transmission method for the measurement of soil density was undertaken with a GM tube detector. The robustness, cheapness and simplicity of electronic requirements of these tubes makes them particularly suitable for field use. Although the voltage stability requirements for GM tubes are not very high Carey and Reynolds (1958) point out that an error of 1% can be introduced by a 1% drift in voltage which in some equipment indicates an excessive error. Cameron and Bourne (1958) found GM tubes to be subject to erratic variations as well as unpredictable gradual changes. The resolving time (dead time) of GM tubes varies with the type of tube but is generally in the order of 100-200 µs. This means that a 5% loss of counts would be obtained at a counting rate of 500 s^{-1}. The efficiency of detection of gamma-ray photons by GM tubes depends on several design properties but is generally low owing to the low gas pressure. Jones (1962) states that about 1% of gamma-radiation passing through the tube cause an ionisation pulse in the detector. GM tubes are generally considered to be only slightly sensitive to temperature but Jones (1962) explains that changes in ambient temperature may alter the position of the plateau with respect to the applied voltage. The useful life is about 10^8 or 10^{10} counts but instability may develop before this.

(b) Scintillation detectors

An early account of the use of scintillation detectors in density measurements has been given by Roy and Winterkorn (1957) but this report mainly referred to their use in gamma-ray backscatter technique. The very high efficiency of sodium iodide - photomultiplier assemblies for the detection of gamma-rays was considered an important advantage over GM tubes but the instability under practical conditions was a cause of considerable measurement error.

The particular advantages of the scintillation detector for transmission measurements were pointed out by Van Bavel et al. (1957). A sodium iodide crystal attached to a photomultiplier was used with suitable electronic discrimination in the form of a single channel pulse-height analyser, to select primary radiation only. An additional advantage was that the crystal could be obtained in dimensions as small as 1 in. dia. and 0.5 in. thick which, when held horizontally, gave a very sensitive detector for horizontally-layered materials. Scintillator thickness has been steadily reduced as the advantages of the method became apparent. The thinnest ever used must be that of Martinelli (1960) which was only 0.5 mm (sic) thick but this was specifically chosen to improve the sensitivity to the 53 KeV radiation emitted from a Tm-170 source.

The resolving time of sodium iodide crystals is very much faster than that for GM tubes, being about 0.2 µs. This means that 5% losses due to coincident counting would not occur until count rates as high as 250 000 s^{-1} are reached. However the electronics of discrimination are not usually able to handle such a rate since the effective pulse length is usually considerably longer than the output pulse from the scintillator.

The efficiency of crystal scintillators varies according to the kind and size of crystal. For sodium iodide efficiency is high owing to the high density of the scintillator (3.67 g cm^{-3}) and the high Z number of iodine (53). According to Davisson and Evans (1952) efficiencies in the order of 10-20% can be expected. Jones (1962) used a value of 15% while Van Bavel (1960) used 10% for a 1.27 cm thick by 2.54 cm diameter crystal. The importance of crystal size was confirmed by Kohl et al. (1961) who stated that the absorption within a 7.6 cm x 7.6 cm crystal was 55% but only 33% for a crystal 3.8 cm x 2.5 cm thick. Overman and Clark (1960) also gave details of the effect of crystal size on efficiency.

Gardner (1965) used an expression for counting efficiency (K) which combines a large number of effects. K is the proportionality factor relating the product of the source activity and active detector cross section to the actual count rate

$$I_o = K \frac{a}{4 \pi r^2} Z \qquad (6.10)$$

where a is the area of collimation at crystal surface (cm^2),
Z is the source disintegration rate (s^{-1}),
r is the source-detector separation (cm),
and I_o is the count rate in the absence of the sample (s^{-1}).

6.2.3 Counting equipment

The use of a scintillator detector and photomultiplier imposes certain critical specifications on the e.h.t. supply, amplifiers and pulse height analysis system.

(a) E.H.T. voltage sensitivity

The pulse amplification which occurs in the photomultiplier tube is in the order of 10^9 for a ten-stage tube. Since this amplification is proportional to the applied voltage the sensitivity of PM tubes to voltage fluctuation is extremely marked. The problems of voltage control were considered by Van Bavel *et al.* (1957) and Van Bavel (1959). In the latter case an attempt was made to use the equipment in the field with a bank of 90 V batteries to give the required 550 V. However it was found that variations of voltage by as little as 0.5 V resulted in significant changes in count rate. Gardner (1965) considered that normal commercial laboratory equipment has warm-up characteristics which require several hours to elapse after switching on before sufficient stability is obtained.

(b) The temperature sensitivity of PM tubes and sodium iodide scintillators

Although PM tubes have been known to be temperature sensitive for a long time it is still difficult to obtain detailed information for specific tubes. Kohl *et al.* (1961) suggested that the general form was a decrease of gain by about 10% with a rise of temperature from 0 to 20°C. A detailed study on the problem was reported by Rohde (1965). Thermally-controlled test containers were used in which the temperature could be held to within 0.1°C over the range 0°C to 50°C using liquid CO_2 for cooling and electrical heating. Different PM tubes were found to give very wide variation of response to temperature change. Some types showed almost linear decreases of gain with rise in temperature while others showed a parabolic response.

Quick changes of temperature (20°C to 35°C to 20°C) resulted in a delayed recovery of about 8-10 h. Delayed recovery however was less pronounced at temperatures below 20°C. When the ambient temperature first changed there was a rapid response due to photocathode sensitivity followed by a much slower change due to dynode resister response. 12 h were allowed at each temperature for each test.

Smith, Willen and Owens (1967) used a NaI(Tl) scintillator to measure gamma-ray transmission in snow packs with commercial equipment and found that the effect of temperature was non-linear. The count rate increase with increasing temperature was 0.3% per deg C at 3°C but 1.2% per deg C at 20°C. The probe took 2 h to reach equilibrium after an ambient temperature change of 15 deg C. Hinrichsen (1964) reports that the temperature coefficient of scintillator efficiency at 20°C is - 0.12 ± 0.03% per deg C for NaI (Tl). A very detailed study of temperature coefficients of different types of sodium iodide crystal with different pulse-shape time constants is reported by Williams et al. (1966). Temperature coefficients of amplitude in the 20-30°C range were found to be in the range 0.22 to 0.90 % per deg C. These coefficients included that of the photomultiplier used.

(c) Methods of stabilisation of scintillator - PM tube assemblies

The problem of stability is important even in laboratories if long runs of high accuracy are required. With operations in the field the problem has been of such a magnitude that many workers have been unable to accept the use of this type of equipment. The problem consists of two parts, (a) the need to use an e.h.t. supply of very high stability, at least as good as 0.1% under all operating conditions and (b) the need to compensate for the temperature sensitivity of the gain in the PM tube. A less severe problem is introduced by the fact that the total gain in the PM tube is a function of the count rate. Berman and Harris (1954) also describe a performance drift during use involving a decrease of sensitivity with a subsequent recovery after a period of disuse. Early workers had to rely on frequent checking of standard count rates with manual adjustment of high voltage or threshold controls. Smith, Willen and Owens (1967) suggested the use of permanent thermal insulation around detector probes but found that, even under constant temperature conditions, it was necessary "to readjust the window several times a day". Sellers (1967) described a system for rapid switching from reference sample to unknown sample in a probe system for sediment density gauging which functioned unattended for periods of a week. The effect of the variable ambient temperature is claimed to have been eliminated. Smith, Taylor and Smith (1967), used a commercial scintillation PM tube assembly and counting equipment in the field and stated "unfortunately, the pulse-height analyser is subject to drift" and "there is no way to predict when this drift will occur". They describe a checking system which involves the necessity of repeating observations if drift had occurred. A simple but crude method of stabilisation was considered by Kohl et al. (1961). They suggested the use of a thermistor in the e.h.t. supply which will cancel out the changes in the dynode resistor values introduced by temperature variation. In oil-well logging scintillator detectors have been placed in a Dewar flask and maintained at 0°C to eliminate the effects of temperature variation. Watt and Ramsden (1964) recommended the use of a surrounding water bath or an air bath at controlled temperature. However these methods are not possible in situations in which probe dimensions are critical.

Automatic stabilisation techniques have been suggested for certain laboratory and industrial applications, generally based on the introduction of a reference signal of constant amplitude into the photocathode with a feed-back control which causes a compensating change in either the e.h.t. supply or the amplifier gain. A number of proposed systems are summarised in Table 6.2.

TABLE 6.2

Methods of stabilisation of e.h.t. and thermal sensitivity of scintillation detectors and PM tubes

Author	Reference Signal		Feed back control	Reference Signal Detector
	Type	Source		
Ageno and Kelici (1963)	light	Hydrogen thyratron	e.h.t.	-
Williams et al. (1966)	alpha part.	Pu - 239	e.h.t.	Secondary CsI scintillator
Hinrichsen (1964)	alpha part.	Po - 210	ampl. gain	Secondary plastic phosphor and pulse shape discrimination
Scherbatskoy (1961)	alpha part.	Ra - D or Pu-239	e.h.t.	Secondary crystal scintillator
Fite et al. (1961)	alpha part.	Pu - 239	e.h.t.	Main NaI (Tl) detector

The stabilisation systems summarised in Table 6.2 have been generally very effective in eliminating a number of causes of variation in stability of scintillator - PM tube assemblies. Scherbatskoy (1961) reported that using his system "very precise spectrally selective measurements have been made with geophysical instruments that are transported by truck from location to location" for tests "which heretofore required elaborate warm up periods, calibrations, and adjustments for each measurement". Williams et al.(1966) report that their system reduced the temperature coefficient of amplitude of the complete assembly, comprising detector crystal, PM tube, spectrum stabiliser and power unit between the limits ± 0.05% per deg C over the range 15° to 40°C. No workers using scintillators and photomultipliers in the field for soil density measurements appear to have used automatic stabilisation techniques.

(d) Dead time of counting equipment

The relation between the count loss due to coincidence and the dead time of the detector and counting equipment is given by the relation

$$N = \frac{n}{1 - n\,t} \qquad (6.11)$$

where N is the true count rate, s^{-1}, n is the observed count rate, s^{-1}, and t is the dead time, s. This equation may be rearranged to give

$$L = 100\, n\, t \qquad (6.12)$$

where L is the % loss in counts due to coincidence.

Davidson et al. (1963) report count losses less than 0.1% even at an incoming pulse count rate of 10 000 s^{-1} using equipment with a dead time of 1 μs. Detailed descriptions of coincidence errors are given by Gardner (1965) and Kohl et al. (1961).

6.2.4 Probe design

(a) Non-discrimination technique

The first application of gamma-ray transmission to the measurement of density of bulk materials in the field appears to have been that of Smith and Whiffin (1952). They were particularly interested in the gradient of density with depth in compacted concrete. Ra-226 and Co-60 sources were tested using a GM tube detector arranged with the long axis parallel to the gamma beam. A source of 130 mCi Co-60 was recommended for a concrete thickness of 2 ft. The lead collimating shield was sufficiently effective to permit reliable density values to be obtained within 1 in. of the surface which they recognised was an important feature of the method. Accuracies of ± 0.02 g cm^{-3} were claimed and this was more sensitive than the variation in the material justified. Different vibration procedures were found to influence the change of density with depth.

Vomocil (1954a, b) was the first worker to use gamma transmission for soil density measurement. A 1 mCi Co-60 source was used with a GM tube detector. The source and detector were mounted in probes of 1 in. diameter and 48 in. long, rigidly fixed together at a distance of 12 in. It was claimed that the accuracy was good enough to give an error of ± 0.01 g cm^{-3}. A much more elaborate instrument was described by Bernhard et al. (1956) which required a source of 50 mCi Co-60 for penetration of up to 4 ft. Difficulties were encountered in measuring the distance between the source and the detector accurately under field conditions. The high activity source and wide sample thickness necessitated a somewhat unsatisfactory winding frame to lower source and detector simultaneously. Maximum source/background count ratio with a scintillation crystal detector was obtained by varying the voltage at different distances.

Durante et al. (1957) developed an instrument which they called a radiation fork with two permanently-connected probes and a handle resembling a garden fork. One probe contained 0.5 mCi Co-60 while the other contained a GM tube. The probes were only 1.8 cm in diameter. Alternative designs were developed for other situations. In one, designed for use in earth dams, 5 mCi Co-60 was mounted 50 cm from the counter.

A special transmission-type system has been developed and used in certain engineering applications in which the GM detector is mounted in a surface probe unit whilst the gamma source is lowered into the soil. Lewis (1965) has described this technique and compared its performance with the surface backscatter method. For both methods the calibration relation was dependent on the type of material tested. This effect was more marked in the case of the backscatter method in which errors as large as 5 lb ft^{-3} could be introduced though composition differences if an appropriate calibration relation was not used.

An unusual type of gamma-transmission probe is described by Skopek (1957) in which the two probes were joined by a piece of sheet metal, the lower edge of which was sharpened to assist its penetration. The detectors used however were quite impractable, being well-insulated condensers of 1 cm^3 volume. A sensitive electrometer was required to measure the change of charge on the condensers following exposure for 16 to 24 h to a source of 2 mCi Co-60 at a distance of 30 cm. Accuracy in the order of 0.05 g cm^{-3} was claimed.

Certain workers have suggested the use of filters to enable a GM tube to have a definite energy threshold in order partially to eliminate the errors introduced by sensitivity to attenuated photons. Smith, Willen and Owens (1967) suggested that sufficient filtering action should be supplied to give a photon energy threshold of 200 KeV.

(b) <u>Energy discrimination technique</u>

Different workers have used a variety of discriminator settings and this is one reason why the absorption coefficients reported differ as the discriminator setting controls the possible contribution to the count rate from scattered photons. Either a single or a double discriminator may be used and some flexibility is permissible in the energy level at which they are set. For Cs-137 photons McHenry and Dendy (1964) used a single discriminator set at 0.65 MeV. Davidson et al. (1963) used double discriminators set to accept photons in the interval 0.66 ± 0.15 MeV.

(c) Source-detector separation distance

The optimum thickness of material through which the gamma-ray beam is to be directed is a function of the activity of the source, the photon energy and the density range. There are also the practical aspects of drilling technique and count-time duration. Van Bavel (1960) defined the decimal design distance as the thickness of material in which a change of density of 1 g cm^{-3} would cause a ten-fold change in transmitted radiation intensity. He calculated this distance to be 39 cm for Co-60 and 30 cm for Cs-137. If the source-detector distance increased to 76 cm, the change in counting rate for the same density change would be 100-fold. He calculated the required number of counts to give a standard error of 0.01 and 0.001 g cm^{-3} for source-detector distances of 30 cm and 100 cm. These varied from 254 (S.E. = 0.01 g cm^{-3}; x = 100 cm) to 299 000 (S.E. = 0.001 g cm^{-3}; x = 30 cm). The size of source depends on the period in which the required counts must be collected. If the period is to be 1 min the source strength varies from 0.7 mCi (S.E. = 0.01 g cm^{-3}; x = 30 cm) to 43 000 mCi (S.E. = 0.001 g cm^{-3}; x = 100 cm). Van Bavel's choice was 30 cm distance and a source of 5 mCi Cs-137 resulting in an instrument accuracy of about 0.005 g cm^{-3} with 1 min counts.

Kohl et al. (1961) stated that, when a given type of source was used, for maximum sensitivity the sample thickness should be such that the mass per unit area is approximately equal to the absorption coefficient. By this reasoning the useful thickness range for Cs-137 lies in the range 2 000 - 2000 000 mg cm^{-2}. For a sample thickness of 25 cm the equivalent density range would be 0.08 - 8.0 g cm^{-3}.

(d) Collimator design

The use of collimation in the gamma-ray transmission method is a means of increasing the proportion of unattenuated photons reaching the detector. The method can be used with both GM and scintillation detectors. Workers concerned with laboratory studies have usually no difficulty in employing a high degree of collimation but under field conditions this is rarely possible, since as pointed out by Berman and Harris (1954), it takes ".. many centimeters of the densest materials to attenuate hard gamma radiation by 95% .." and it is hence ".. impossible to restrict completely the flux within a desired solid angle". They investigated collimator design in detail including the use of uranium as a shielding material. The degree of collimation used may be expressed by the solid angle of absorber material subtended by the detector. Shimizu et al. (1952) consider that 0.016 sr is a suitably small solid angle to prevent all but an insignificant number of scattered photons from reaching the detector. Smith and Dixon (1963) used a solid angle of 0.0038 sr, obtained with source and detector collimators 14 cm long and 1 cm diameter with a source-detector separation of 42 cm. Davidson et al. (1963) used a collimating slit which was 0.1 cm wide and 2.0 cm high. The significance of diameter and length of collimation in bulk density and moisture measurements is considered by Gardner and Calissendorff (1967).

6.2.5 Access and sample retention in the field

Two types of access and sample retention systems have been used:

(a) Tubular access: Holes are drilled through the test sample and the source and detector probes inserted with or without the use of access lining tubing.

(b) Planar access: The sample is retained between parallel plates. The probes are thus free to move in both vertical and horizontal directions.

Tubular access is more widely used owing to its greater simplicity and reduced disturbance to the soil around the sample. Goldberg *et al.* (1955) made a comparison of a number of different types of tubular access and they found that driving in access tubing without first drilling holes was quite acceptable. Cameron and Bourne (1958) obtained a similar result but Harland and Urkan (1966) report that the use of solid spikes to obtain access holes (single probe surface transmission system) introduced considerable error in soils with appreciable gravel content. This error was associated with regions of increased and decreased density around the spikes as detected by X-radiography. Kozachyn and McHenry (1964) used a portable power-driven 2 in. auger ground to pass inside the sections of steel tubing used in the installation of access tubing. Although most workers have considered that the use of access tubing was necessary especially for "permanent" installations, Smith, Taylor and Smith (1967) used unlined holes for daily measurements over a 33 d period.

Planar access appears to have been first used by Baganz and Kunath (1963) but no retaining plates were used. Helbig and Beer (1965) and

Reichmann (1965) have also described planar access systems.

6.3 Performance

6.3.1 Sample resolution

One of the most important advantages of the gamma-ray transmission method for the measurement of bulk density is that a very high degree of sample resolution is possible. This is particularly important in cultivated topsoils because of the abrupt changes in bulk density over short vertical and horizontal distances. Initial work by Vomocil (1954b) suggested that about 2 in. was the thinnest layer that could be accurately measured but this was clearly related to the fact that he was using a GM tube which had an active length of 2½ in. without collimation.

The unique suitability of the unattenuated photon transmission method for the measurement of density in narrow layers was demonstrated by Van Bavel (1959). Interfaces of liquid/liquid and solid/solid types were used. The resolution obtained was related to the thickness of crystal detector used. With a crystal 1.25 cm thick it was shown that, even without collimation, layers of contrasting density could be approached as close as 0.6 cm from the source-detector midline without detection. This indicated that the contribution from scattered radiation was virtually nil. This performance could never be equalled by those workers such as Harland (1965), who attempted to use surface-backscatter probe for situations requiring high vertical resolution such as compaction studies. Errors may be introduced by the presence of very high (or very low) density materials outwith the normal sample volume if non-discrimination transmission techniques are used as reported by Smith and Whiffen (1952).

6.3.2 Calibration

(a) Linearity

In order to use the gamma-ray transmission method it is necessary first to obtain a calibration relationship between transmitted-photon count rate and bulk density. As already indicated in section 6.1.2 this function can be represented theoretically by a straight line when only unattenuated photons are counted and this has been confirmed in practice. The results obtained by Vomocil (1954b) using a GM detector did not give a linear relationship. He considers that this may be due to variation in the ratio of scattered photons to unscattered photons since no photon energy discrimination was used. He was able to show that the apparent increase of absorption coefficient was proportional to the density but had no explanation of a "sharp change in the second derivative" of the curve which occured at a wet bulk density of about 1.75 - 1.80 g cm^{-3}.

Harland and Urkan (1966) using a sodium iodide detector measured calibration relations with Cs-137 radiation and obtained a linear effect with a single discriminator set as low as 0.095 MeV which suggests that any departure from linearity is unlikely to be due to variable contribution from attenuated photons.

Deviations from linearity at very low density values may be due to pulse losses resulting from coincident counting as shown in Section 6.2.3 (d).

(b) Method of calibration testing

Calibration testing can be undertaken in containers of known volume or in field soils. Most calibrations have been made in containers because the method is easier, more reproducible and more suited to laboratory studies. The size of the container is important since there should be no influence from the sample boundaries. Vomocil (1954b) used a steel tank 16 in. diameter and 30 in. deep. However, when only unattenuated photons are measured, the size of the container may be greatly reduced. For example Van Bavel (1959) used wooden boxes 4 in. x 4 in. x 13.6 in. and Jensen and Mogensen (1966) used boxes 60 cm long x 30 cm x 30 cm. The wet density of such a sample of soil can be readily calculated. In order to eliminate the effects of layered packing of material within the sample container, transmission tests can be made at several depths within the box for each test and a mean count rate compared with the mean bulk density of the box. Packing errors account for much of the scatter which occurs in soil density calibrations. Davidson _et al._ (1963) report very uniform bulk-density values obtained in containers used for soil moisture-flow determinations. The maximum and minimum bulk densities were 1.2424 and 1.2641 g cm^{-3} and 80 percent of the values were within 0.0050 g cm^{-3} of the mean density. This high degree of uniformity is unusual.

(c) Effect of soil composition

Vomocil (1954b) concluded that since the elements making up the composition of soils all show similar absorption coefficients (with the exception of hydrogen) for photon energies of approx. 1 MeV, differences in calibration relationship between soils would not be expected. This has been confirmed for results obtained with unattenuated Cs-137 photons as discussed in Section 6.1.4. However when attenuated photons are also counted, as with a GM tube detector, differences dependent on chemical composition are to be expected. Lewis (1965) reports work on the effect of compositional differences when using a transmission technique with a GM tube detector. Variation in Ca and Fe content was thought to be responsible for differences in the calibration relation for contrasting soils as a result of photoelectric absorption effects at low photon energies.

The relation between received photon energy and the calibration relation for different soils was further examined by Harland and Urkan (1966) using a sodium iodide detector. No effect attributable to variation in soil composition could be detected in the calibration relation even with the single discriminator set as low as 0.095 MeV. The absence of differences was attributed to "... the relatively small number of scattered gamma rays, with energies below 0.2 MeV being counted. Despite gamma ray beam modification not enough low energy gamma rays were being detected for photoelectric absorption to have a significant effect". This conclusion seems to be at variance with that of Van Bavel et al. (1957) who stressed the importance of measuring only unattenuated photons in order to avoid complications arising from photo-electric absorption.

(d) Effect of moisture content

Vomocil (1954b) considered that the contribution to total error from variation in hydrogen concentration would be slight since a variation of 10% in moisture content would account for an error of only 0.016 - 0.024 g cm^{-3} in the wet bulk density value. Van Bavel (1960) showed that if a calibration curve had been made with oven-dry soil the presence of moisture in test material would result in density values which were too high. The magnitude of the effect was given by

$$E + 0.12 \, D \, M_v \qquad (6.13)$$

where E is the error in dry bulk density (g cm^{-3}), D is the true dry bulk density (g cm^{-3}) and M_v is the volume fraction of moisture present. He points out however that "empirical attenuation coefficients" "do not seem to differ nearly as much as the theoretical ones". The uncertainty in the calibration is in the order of 0.01 g cm^{-3} instead of 0.05 g cm^{-3} which theory predicts.

Harland and Urkan (1966) expressed empirical calibration relations in terms of "water-modified" density which was defined as

$$\rho' = \rho\left(1 + \frac{M}{9(100 + M)}\right. \qquad (6.14)$$

where ρ' is the water-modified density, ρ is the actual wet bulk density and M is the moisture content, % $^w/w$. This relationship is based on the electron density of hydrogen being about twice that of other elements in soil. This results in the apparent density of water being $^{10}/9$ greater than expected.

Reginato and Van Bavel (1964) showed that the difference in the absorption coefficients of water and soil is enough to cause appreciable error in detailed laboratory studies. However at the level of accuracy required for field studies the error introduced by failing to correct for moisture content seems to be negligible. Smith and Dixon (1963) were unable to demonstrate a change of absorption coefficient of soil as the moisture content was raised from air-dry to 30% wet weight basis in spite of theoretical expectation of a 3% change over this moisture range. McHenry and Dendy (1964) used a common calibration relation for wet density of liquid or semiliquid sediments and no correction was made for the proportions of water or solid matter.

6.3.3 Accuracy and precision

The value for bulk density obtained for a single measurement at a given position and depth in the field is only an estimate of the true value owing to inherent variation which may be attributed to a number of types of error arising from instrument, calibration or geometrical sources.

(a) Instrument error

It is generally considered that the error associated with the isotope and counting equipment can be attributed solely to the random nature of the isotope disintegration rate and hence can be expressed by the relationship

$$s = N^{-\frac{1}{2}} \qquad (6.17)$$

where s is the standard deviation (counts) of an observation and N is the number of counts collected. However in practice the error may exceed this value. Harland (1965) found the error was 1.4 times the expected value at a very high level of probability. This effect is probably associated with errors in the functioning of the counting equipment, e.h.t. instability, thermal sensitivity and error in timing. It seems remarkable that so many workers have accepted the validity of Eqn. (6.17) to assess instrument error. For example McHenry and Dendy (1964) used it in order to estimate the overall precision of their equipment (standard deviation of determination of sediment density ± 0.007 g cm^{-3}) without apparently checking the relationship in practice.

Most workers have tried to minimize the contribution of random disintegration error by using pre-set counts or time intervals such that at least 10 000 counts were collected. However Davidson et al. (1963) reduced the error still further by collecting up to 200 000 counts while Gardner and Calissendorff (1967) based a detailed theoretical assessment of experimental error on the collection of 1 000 000 counts for each reading. Such precision is only justified in very critical laboratory experiments. For field experiments in which a very high level of accuracy is not required for each reading, consideration has to be given to the random disintegration error at different levels of bulk density. If, for example, it was desired to measure bulk density with an accuracy (standard deviation) of ± 0.02 g cm^{-3} this would represent a permissible error of ± 1% at a bulk density of 2 g cm^{-3} but 2% error at a bulk density of 1 g cm^{-3}. In the former case 10 000 counts should be collected but in the latter case the number of counts required could be reduced to 2 500. A saving in total time required for a number of measurements could be made therefore if adjustments in the number of pulses collected were made based on an estimate of expected bulk density. The saving of time is not particularly great however since the count rate increases with decreasing density.

Mechanical and electrical timers fitted to some of the early commercial equipment were insufficiently accurate or reliable. Carlton (1961) found that manual control with a stop watch was more accurate than a mechanical timer and similar results were found by Gnaedinger (1961). However Carey <u>et al.</u> (1961) checked the timer fitted to a Nuclear Chicago Inc. Scaler under a wide range of weather conditions and found that the errors were within the range ± 0.06% for a 60 s count period. This was much better than the 0.5% error limit which has been suggested as acceptable for timing operations. Timing errors in modern equipment have been virtually eliminated by the use of built-in quartz oscillators which can be used to operate timing controls with an accuracy of 0.001 s.

(b) Calibration error

The error associated with the calibration relation is usually expressed as the prediction error. This can be calculated from a knowledge of the error, in the intercept and regression coefficients in the calibration relation which can be calculated according to standard statistical techniques by the method of least squares analysis. Jensen and Mogensen (1966) estimated that the precision of their calibration relation was "of the order of 0.015 g cm^{-3}". Harland and Urkan (1966) undertook regression analysis of calibration results and found a root mean square density displacement from the best fit line of about 0.016 g cm^{-3}. Van Bavel (1959) reported the precision of calibration in terms of L.S.D. ($P = 0.10$) and gave values of 0.017, 0.009 and 0.014 g cm^{-3} for densities of 1.0, 1.5 and 2.0 g cm^{-3}.

The prediction error will be compounded from a number of sources including all instrument errors as well as errors in the independent measurements of bulk density, any geometric errors introduced in the calibration tests and error due to variation of moisture content. With the increasing use of high counting rates the effect of variation in background count rate is progressively less important and many workers ignore the effect. However Carey and Reynolds (1958) considered this effect as a source of error and found a variation in count rate of up to 0.50 s^{-1} over a period of a few hours. Few workers using gamma-ray transmission technique have used any correction for background count rate but Smith and Dixon (1963) are an exception.

(c) Geometrical error

Sample thickness and source-detector separation both exert important effects on transmission count rates as shown in equation (6.1). The problem has no particular significance in laboratory studies but under field conditions the question needs close attention. Bernhard and Chasek (1955) found that a 1% error in the source-detector separation distance resulted in a 6.3% error in the measured count rate. The difficulty of drilling parallel holes was mentioned by Roy and Winterkorn (1957) and considered to be almost insuperable for certain situations. The use of rigidly aligned drilling frames as used by Van Bavel (1959) considerably improves the uniformity of spacing, especially where the depth of drilling does not exceed about 40 cm. Variation in source-detector separation can be overcome by using a rigid mounting in which both probes are clamped but it is surprising that workers do not appear to have taken the precaution of actually measuring the sample thickness under field conditions.

Only under conditions of exceptionally high degree of collimation and/or energy discrimination will the effective soil sample be represented by the solid angle between source and detector. Hence consideration must be given to the influence of adjacent layers of soil. If a GM detector is used the sample volume will extend some distance beyond the solid angle and therefore measurements made near to the soil surface or to layers of contrasting density will be in error to an extent which can only be determined by tests with the particular equipment under normal operating conditions. When the probes are at the bottom of the access tubes the geometry will be different from when the probes have some distance of air below them in the tubes and this difference could also introduce error if collimation or energy discrimination is not used.

(d) Overall accuracy of measurement

The overall accuracy of measurement clearly depends to a very large extent on the type of equipment and the circumstances in which it is used and it should represent a summation of all errors which in practice may be relevant. Vomocil (1954a) with a GM tube detector used in the field claimed an accuracy to within 0.01 g cm^{-3}. Bernhard et al. (1956) observed measurement errors amounting to ± 2.3% of the true bulk density. Van Bavel (1959) using a scintillation detector under field conditions established a measurement error of approx. 0.01 g cm^{-3}. Smith and Dixon (1963) report a coefficient of variation of 1.5% for gamma-ray transmission determinations of density (GM detector with corrections for build-up). This degree of variation was 25% better than that for the core sampling method at the same 23 locations. This can be compared with the results of Phillips et al. (1960) who found coefficient of variation values of 4% for both core sampling and surface-backscatter density gauge methods.

Smith, Taylor and Smith (1967) compared the error in measuring dry bulk density by direct sampling and by gamma-ray transmission. The former (96 samples) gave a standard deviation of 7.65 lb ft^{3} and a coefficient of variation of 9.1% . Corresponding results for the transmission method were 0.72 lb ft^{-3} and 1.08% respectively. The sampling error by the second method was well within the standard error of estimate of the calibration curve. It can be generally concluded that, with suitable precautions, the error of measurement can be reduced to a level which is acceptable for most experimental work. Indeed the error is usually considerably less than that associated with core sampling. Since the latter method is the only feasible method for field calibration, calibration relations established in the field tend to exhibit a larger error than laboratory calibration procedures even on soils of high uniformity.

6.4. Applications of gamma-ray transmission method

Applications of the gamma-ray transmission method have generally fallen into two rather distinct classes, (a) relatively broad-beam studies under field conditions in which the results are of practical interest and (b) relatively narrow-beam studies under laboratory conditions in which the results are generally of theoretical interest.

(a) Field studies using non-discrimination method

Vomocil (1954a) as a result of several thousand determinations with a gamma-ray transmission technique with a GM detector predicted that the method would be of value in soil-tillage research particularly for the detection of compacted layers. This view was also supported by Nichols and Reeves (1955) but at that time limitations in the electronic equipment available set a limit to the usefulness of the method in the field. The time required for measurement is probably just as important as the absolute accuracy in view of the very tedious standard methods for the measurement of bulk density. Lewis (1965) reports on the use of two types of surface-density gauges for which the time of a single measurement was 20 min per site compared with 30 min by the sand replacement method.

Smith and Dixon (1963) compared core sampling with the gamma-ray transmission method for the determination of density of a number of contrasting soils. There were no significant differences in the values obtained by the two methods but the gamma-ray transmission method showed the advantage of lower sampling error.

One of the most detailed studies with non-discrimination technique is that described by Baganz and Kunath (1963). Using planar access they were able to make vertical and horizontal scans of bulk density in soil which had been subjected to compaction from a tractor wheel. The distribution of zones of different bulk density were related to the stress distribution under surface loading of soil. Planar access techniques have also been described by Helbig and Beer (1965) and Reichmann (1965). The former workers used a source of 10 mCi Co-60 and a collimator 4.0 cm in length and 0.8 cm diameter for soil sections 35 cm thick. Reichmann (1965) developed a highly elaborate mechanical system for scanning soil sections using a gantry mounted on a trailer. Both source and detector probes were provided with a considerable degree of collimation. Results were converted to air-filled pore space and cross-sectional diagrams were shown for a number of field tests following the passage of loaded tractor wheels.

(b) Field studies using discrimination method

Very little experimental use has been made of the discrimination technique under field conditions due partly to the extra cost and complexity of the equipment and partly to the problem of poor stability of performance under field conditions. McHenry and Dendy (1964) reported the use of a discrimination technique for the measurement of density of sediments. The method was sufficiently sensitive to demonstrate the settling occurring in low density sediments. Although no collimation was used a high degree of sample resolution was obtained so that narrow layers of sediments could be demonstrated and measured. The method offered very considerable advantages over traditional techniques.

Jensen and Mogensen (1966) compared the vertical resolution obtained with a standard sodium iodide detector with and without discrimination. A considerable improvement in resolution was obtained when discrimination was used. However, discrimination reduced the count rate. They report field measurements to a depth of 150 cm without energy discrimination.

(c) Laboratory studies

The use of gamma-ray transmission equipment for laboratory studies of soil bulk density have been described by Durante et al. (1957) and Yaron et al. (1966). The former workers used the equipment to demonstrate the change of bulk density as a result of surface loading while the latter measured the uniformity of artificially-packed soil columns using a mechanical scanning device working in the vertical plane, in 3 cm intervals.

CHAPTER 7

CONCLUSIONS FROM REVIEW AND PROPOSALS FOR RESEARCH

7.1 Conclusions from review

(1) The review illustrates that our understanding of the effects of tillage and traffic on the physical properties of agricultural soils is inadequate to permit solutions to be gained in certain important problems in field crop production.

(2) The reasons for this inadequacy of current agricultural soil mechanics include

- (a) the intrinsic difficulties of defining the parameters of the system,
- (b) the lack of suitable methods for measuring the selected parameters,
- (c) the lack of incentive to undertake basic research because of the apparently low expectation of finding economically acceptable solutions to problems related to tillage and traffic. The physical hardships of field work during the autumn, winter and spring months also represent a deterrent.

(3) The subject is however becoming one of considerable importance because

- (a) there is increasing interest in minimum cultivation and zero tillage as a result of the further development of herbicides and
- (b) increasingly active attention is being given to the development of new harvesting, cultivation and tractive equipment with new systems of propulsion and wheel arrangement.

Research leading towards practical solutions of problems is therefore increasingly required.

(4) There is need for an approach to the subject which will embrace the disciplines of both engineering soil mechanics and agricultural soil

physics. The parameters defining the state of agricultural top soils are however specific to that medium and direct translation of methods or criteria from other fields of study is unlikely to be successful, hence the necessity to establish a new set of criteria of established relevance to the system under study.

(5) Practical diagnostic methods, to be successful, should fulfil the following limiting conditions:

   (a) A high degree of sample resolution, both vertical and horizontal, should be obtainable.

   (b) Results must be readily and quickly obtained under field conditions with a minimum of disturbance. Particular attention should be given to methods which permit automatic recording of results since the limitation of operator time in the field has been a major restriction in these studies in the past.

   (c) If possible, analytical methods should not require destruction of the soil structure since this is known to exert a considerable influence on the behaviour of a given soil. If structure destruction is unavoidable, the effect of this change of properties should be noted in the interpretation of results.

(6) Much further information is required on the change of bulk density under different tillage and traffic systems and this will be forthcoming only if the conditions of 5 (a), (b) and (c) can be fulfilled. It also appears that bulk density alone may be a rather insensitive parameter of compaction and disruptive change in certain soils particularly when viewed from the point of view of plant-root activity. Consideration should therefore also be given to the use of other parameters such as

air-filled porosity which can be obtained from bulk density measurement.

(7) Current methods for the determination of soil water content do not satisfy 5 (a), (b) and (c) and there is therefore need to develop new methods. There is a marked failure to relate the known importance of soil water in influencing compactability and strength to soil-water matric potential characteristics. Reliance on the expression of soil water solely in terms of percent by weight represents a severe limitation in comparisons between soils and the understanding of the rôle of water in soil mechanics.

(8) There are clearly many important differences in mechanical behaviour between different soils. Particular attention must be paid to these differences since they may serve to illustrate particular aspects of the classification of soils in terms of mechanical properties.

(9) Particular attention must be paid to the influence of time in all studies of the mechanics of agricultural soils since the rate of working is frequently quite different from that in some engineering systems. For instance the rate of application of stress during both compactive and disruptive phases may be very high and the duration of stress may be very short. Quite different results must be expected from mechanical tests involving long periods of low stress as are sometimes used in shear-strength measurements.

(10) Because of the particular sensitivity of the structure of agricultural topsoils, compactive and disruptive change will probably not be reversible. This may have important applicationsin the testing of soil-management systems in the field. It is also important in the use of soils in tanks. Changes of certain structural properties may occur with usage which may have important effects on mechanical properties. Repetitive tests may show a drift of properties which are not related to differences in the applied treatments.

7.2 Proposals for research

(1) To compare the use of a small GM detector and a sodium iodide scintillation detector in a twin-probe assembly with particular emphasis on the problems arising in field studies of tillage and traffic.

(2) To study the effect of different soils and moisture contents on the calibration relation.

(3) To prepare computer programmes for use in all computations required, including the corrections for non-standard geometry and the co-ordinate plotting of bulk density results. In addition, to examine the use of trend-surface analysis technique for the automatic plotting of "smoothed" contours of bulk density.

(4) To examine the problem of instability associated with the use of a sodium iodide detector under conditions of variable ambient temperature.

(5) To investigate the effect of variation in discriminator technique on the performance of a sodium iodide detector.

(6) To use gamma-ray transmission equipment for bulk density determination in a field uniformity trial in order to examine the problem of between-plot and within-plot variation and to use the results to determine the most efficient method of field sampling.

(7) To determine the effect of different methods of autumn ploughing, including zero-ploughing, on the variation of bulk density with depth after spring sowing of cereals at two sites.

PART B EXPERIMENTAL

CHAPTER 8

METHODS AND MATERIALS

8.1 Objective and principle of method

The objective was to compare the use of a small GM tube and a scintillator detector for gamma-transmission measurement in field-tillage studies and to explore the problems of one and two dimensional scanning of field soils. In addition particular attention was to be given to the contribution which a digital computer could make to the handling of calculations and data display in order to improve the efficiency of the method.

8.2 Equipment

(a) Nucleonic equipment for GM detector

A general view of the equipment is shown in Fig. 8.1. On the right is the control frame, bearing the source and detector probes. This is connected by 15 m of six-way screened cable to the power supply and counting equipment which, for field use, is mounted in a four-wheel drive vehicle.

The source probe contained 30 mCi Cs-137. The detector was a small Geiger-Müller tube* of active length 3.5 cm, active diameter 1.5 cm and wall mass thickness 250 mg cm^{-2}. The unshielded background count rate was approximately 0.75 s^{-1} and the dead time was 100 μs. The detector was coupled in the detector probe to a pre-amplifier with a gain of unity. Source and detector were mounted within stainless steel probe tubes 3.81 cm o.d., wall thickness 0.157 cm. The probe wall mass thickness was 1250 mg cm^{-2}. The probe tubes were mounted in a control frame in such a way that each probe could be lowered manually in increments of 1.27 cm until the line joining the active centre of source and detector was 41 cm below the underside of the

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* Mullard Ltd., Type No. MX 146.

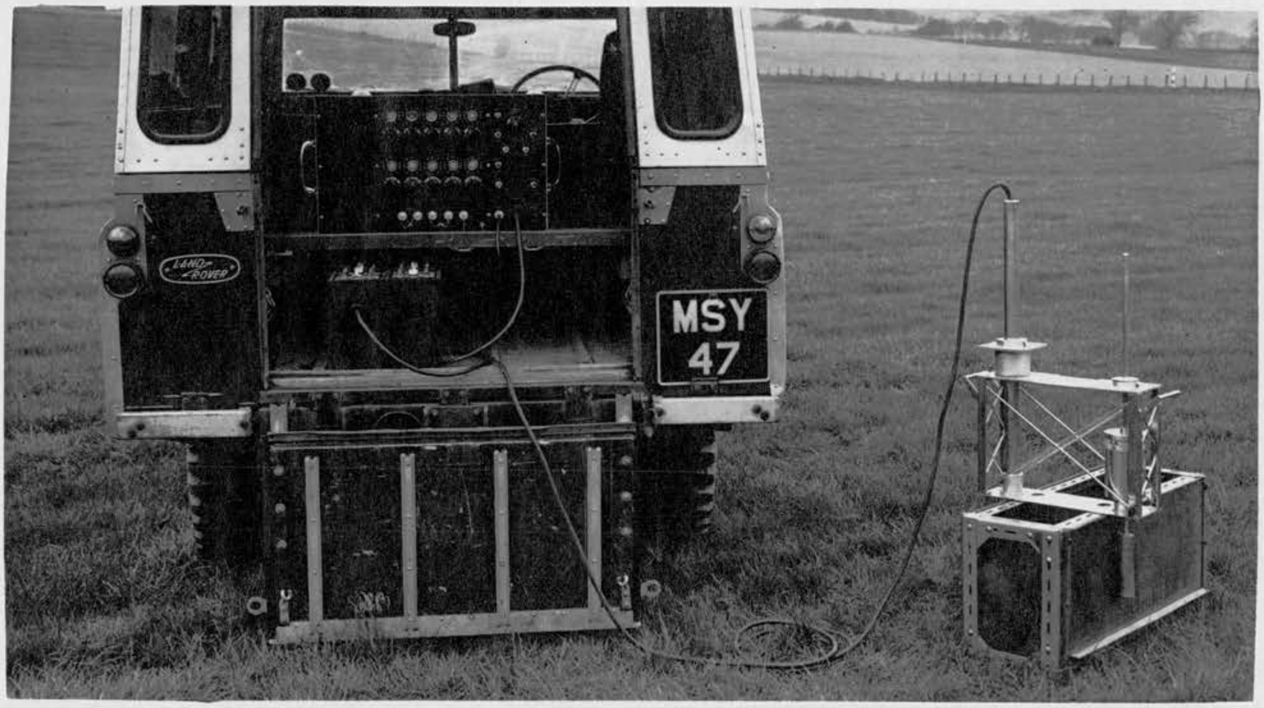

Fig. 8.1 General view of soil density equipment assembled for field use (planar access)

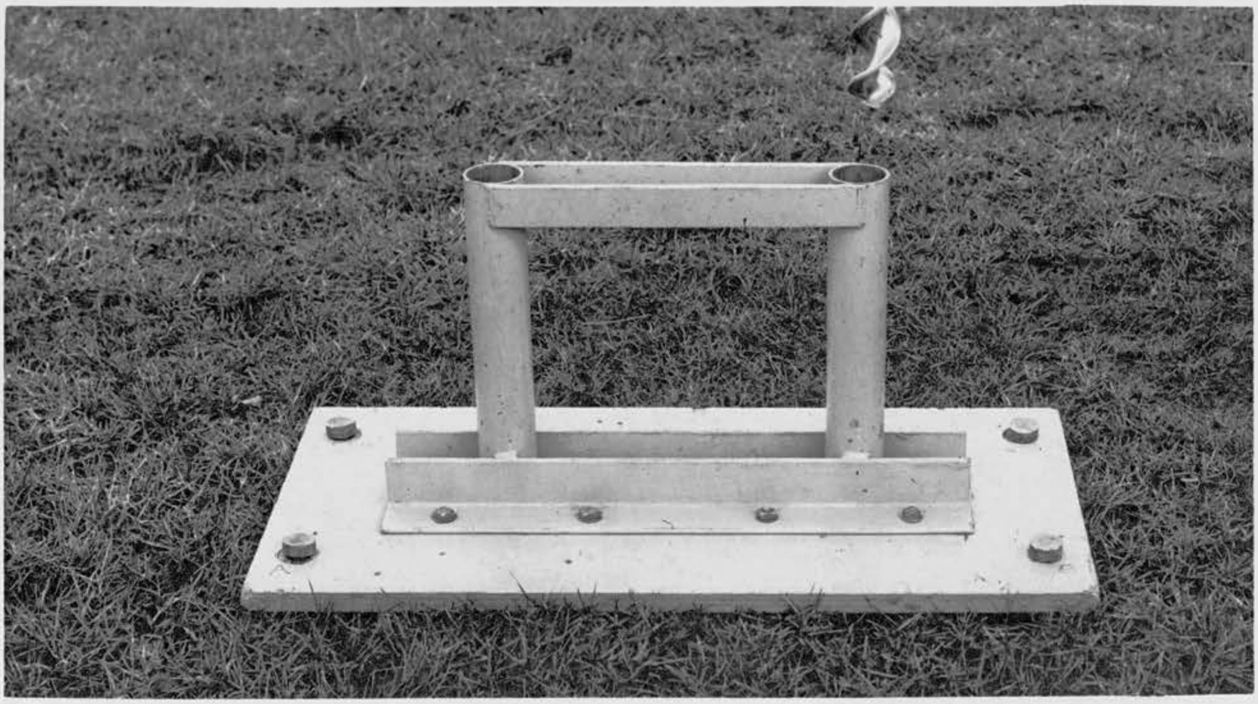

Fig. 8.2 Tubular access alignment jig with auger assembly

control frame.

When in the fully-raised position the source probe was surrounded by an external lead shield of 2.54 cm wall thickness within which the probe could be rigidly secured during transit. Within the source probe a small amount of lead shielding enclosed the source capsule (1 cm wall thickness along the horizontal radius). A hole, 0.6 cm diameter was drilled through this shield to permit a broad beam of gamma rays to be directed towards the detector.

A combined scaler/timer/e.h.t. supply unit[**] provided a 460 V supply for the detector and permitted pulse counting with either preset count or preset time facility using two registers of five decade 'Dekatron' display tubes. A 10 KHz quartz crystal oscillator provided a variable time base to suit requirements. The low tension supply was obtained from 7 heavy duty lead/acid accumulator cells (CX13) with the output maintained at 12.5 V by a voltage regulator.

(b) Nucleonic equipment for scintillator detector

For these tests a twin channel e.h.t. and pulse-height analyser unit[**] was employed. This unit was provided with controls for adjusting the voltage (300 - 2000V), gain (x1 to x50), threshold voltage (0.2 - 10 V) and aperture (0.2, 0.4, 0.6, 0.8, 1.0 V and a maximum aperture using a single discriminator). Initial tests were made to examine the stability and optimum mode of use of this instrument which, for counting purposes, was linked to the scaler/timer described in (a). A NaI (Tl) scintillator (2.54 cm diameter x 0.635 cm thick) was mounted in an integral assembly with an EMI9524 photomultiplier. The output from the latter was fed to a pre-amplifier mounted within stainless

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[**] Constructed at N.I.A.E. S.S. by Mr. C.A. Carlow.

steel probe tubes as in (a). A 5 mCi Cs-137 source was mounted in a similar probe tube and the two probes were mounted in the control frame as described in (a).

(c) Ancillary Equipment

(i) Facilities for soil access

Provision was made for both tubular and planar access for the probes into field soils. The former system permitted probe movement in the vertical direction only whilst with the latter system both vertical and horizontal movement was possible. For tubular access two vertical holes were drilled at 30.5 cm distance between centres using a 4.0 cm diameter screw auger mounted in a rigid alignment jig as shown in Fig. 8.2.P.V.C. access tubing, 4.30 cm o.d., 3.88 cm i.d., was carefully inserted into each hole leaving about 2 cm projecting above ground level. Soil thickness between the tubes was approximately 26.2 cm.

For situations requiring both vertical and horizontal scanning, mild steel plates, 139 cm length, 52 cm depth, 0.157 cm thickness, were inserted into the soil using an alignment frame to insure that the plates were parallel and separated by approximately 25.9 cm thickness of soil. The plates could be raised and lowered with their vertical edges supported in slotted members on the alignment frame. The plates and frame are shown in Figs. 8.1 and 8.3. In the latter case a section through potato ridges has been prepared. The lower edges of the plates were chamfered on the outside and a mild steel angle member rivetted to the plate 4.2 cm above the sharpened edge. This served to stiffen the cutting edge and thus to prevent outward bowing of the plates during insertion. Insertion took place in two stages. First the frame was placed in position by digging out slots to receive the end supports. The plates were

Fig. 8.3 Probes and control frame mounted on planar access alignment frame for exposure of section through potato ridges

then lowered on to the soil surface and pushed slowly into the soil in increments of 2-4 cm. Between each increment of downward movement, soil was cleared away from the outside of the cutting edge and any plant material or stones which were found to be interfering with the free passage of the cutting edge were carefully removed before further downward movement was continued. After full insertion of the plates the control frame was placed on the top of the alignment frame and was advanced horizontally by hand in increments of 5.08 cm after each series of vertical movements of the probes. The limit of horizontal movement was 125 cm.

For tubular access samples for moisture content measurement were obtained in 5 cm increments as the auger was inserted. For planar access samples were taken in a 5 cm x 5 cm grid after the access plates were removed. The disturbed samples were placed in tins and dried in a forced draught oven at 105°C for 24 h.

(ii) Sample thickness measurement

The gamma-ray transmission method is particularly sensitive to variations in the source-detector separation and sample thickness. In spite of the use of rigid alignment control during the insertion of access tubes and plates it is not always possible to maintain the source-detector separation and sample thickness within the desired limits. It was therefore decided to measure deviation from the standard conditions using a pair of long-armed spring-loaded calipers as shown in Fig. 8.4. The lower caliper arms were 40 cm in length and were inserted into the access tubes or around the plates according to the type of access used. A reading was obtained across the upper arms of the calipers with a micrometer as shown in Fig. 8.4 for each depth and position at which gamma transmission measurements were made. The reading was

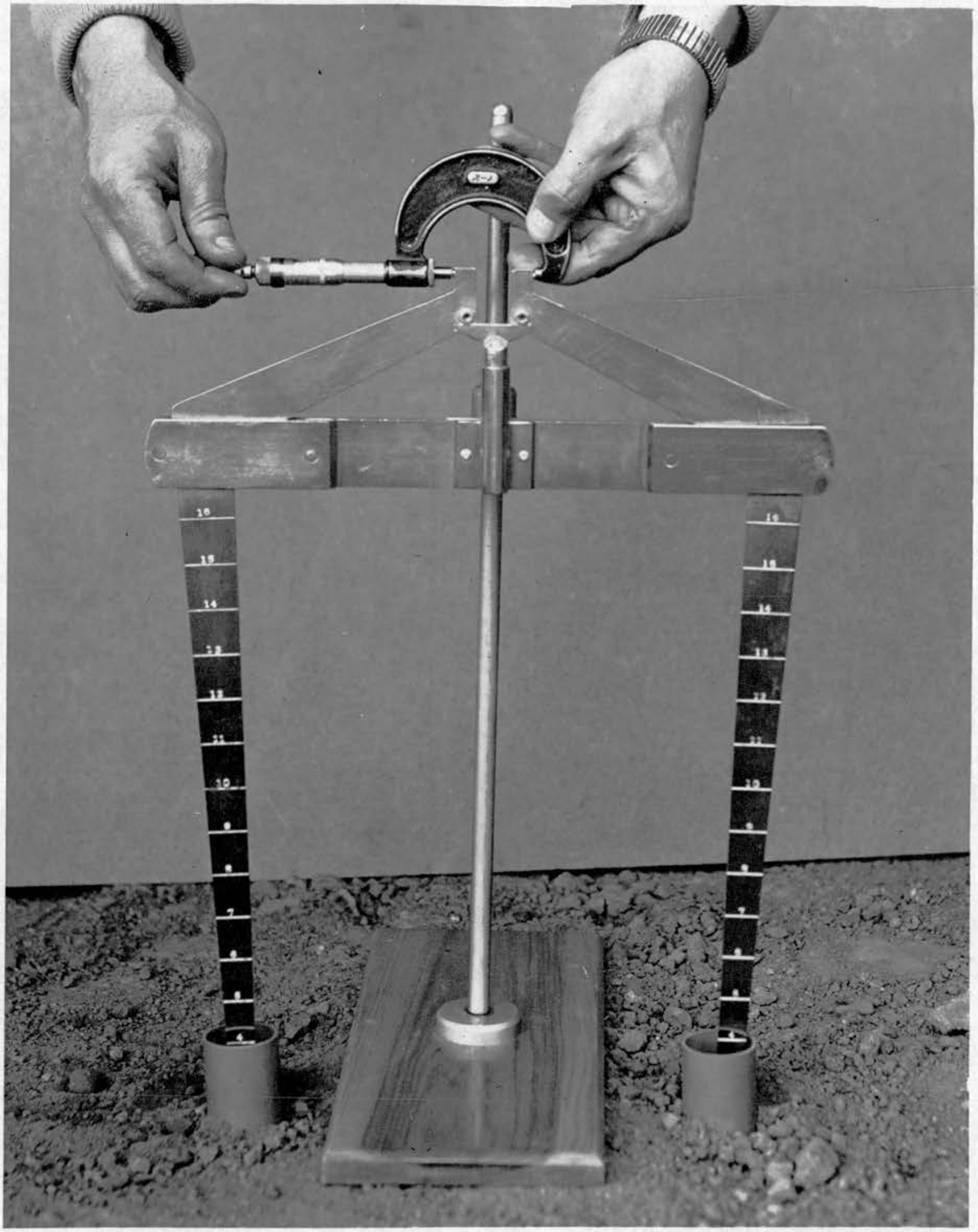

Fig. 8.4 Long-arm calipers used for measuring distance between access tubes

subsequently used to find the actual source-detector separation and sample thickness and to apply the necessary corrections to convert to standard conditions.

By mounting the 4.13 cm diameter screw auger in the alignment tubes shown in Fig. 8.2 it has been found that reasonable accuracy can be achieved. Test borings were made at three sites with four replications at each site. Access tubing was inserted into the holes and the displacement between the tubes measured with the calipers at depths of 15 and 40 cm. The results are shown in Table 8.1.

TABLE 8.1

Measurements of the distance between access tubes inserted in field soils

Site	Depth cm	Deviation from 30 cm distance between centres, cm			
		Rep I	Rep II	Rep III	Rep IV
P/27	15	- 0.25	+ 0.30	- 0.08	- 0.05
	40	- 0.18	+ 0.15	- 0.02	- 0.02
Difference		(D) 0.07	(C) 0.15	(D) 0.06	(D) 0.03
P/24	15	+ 0.41	+ 0.36	+ 0.53	- 0.13
	40	+ 1.52	+ 0.58	+ 0.51	+ 0.10
Difference		(D) 1.11	(D) 0.22	(C) 0.02	(D) 0.23
P/23	15	- 0.30	- 0.41	+ 0.28	- 0.43
	40	- 0.23	+ 0.68	- 0.05	- 0.02
Difference		(D) 0.07	(D) 1.09	(C) 0.33	(D) 0.41

D indicates diverging with depth

C indicates converging with depth

These results were obtained with no previous experience of using the equipment. It seems clear that, with care, satisfactory installation can often be obtained but the use of the long-arm calipers was adopted as standard procedure to check displacement and the necessary corrections can be readily applied as described in Section 8.5.

8.3 Health hazards

Attention has to be given to the design and use of equipment of this type to ensure that the radiation received by the worker is not only well below the maximum permissible dose but that it is as low as possible compatible with the effective use of the equipment. Lead shields were made for storage and transport and the source probe was itself provided with a small amount of internal shielding. The restriction on the diameter of the source probe to 3.8 cm limits the amount of internal shielding which is possible.

Dose rates external to the equipment and shields were measured with an Ekco Dose-Rate Meter Type N 596 and the results obtained are given in Table 8.2. The results indicate that, when the source is in the capsule storage shield, probe storage shield and the control frame shield, the dose rates at a distance of 2 cm from the container surface are in the range 4 - 8 mrad h^{-1}. At distances of 30 cm the dose will drop to below 1 mrad h^{-1}. The only serious risk of exposure occurs when the probe is lowered out of the control frame shield when dose rates up to 40 mrad h^{-1} could be obtained at a distance of 15 cm from the probe. In practice the period of time during which such exposure is incurred is limited to the few seconds required for moving the probes between readings with planar access.

TABLE 8.2

Gamma-ray dose rates exterior to shielded containers and transmission source probe (30 mCi Cs-137)

Source Container	Surrounding Container	Alignment to transmission beam, degrees	Dose Rate, mrad h^{-1}		
			Horizontal distance*, cm		
			2	15	30
Source capsule storage shield	Air	All	3.5	0.4	-
Transmission probe	Probe storage shield	0	16	6	2
		90	12	3	1.3
		180	13	3	1.3
Transmission probe	Control frame shield	0	n.a.	n.a.	1.4
		45	n.a.	1.6	1.2
		90	9	1.8	1.0
		180	9	1.8	1.0
Transmission probe	Air	0	>300	80	30
		180	260	40	18
Transmission probe	Concrete standard	0	n.a.	n.a.	0.9+
		90	90	30	12
		180	70	20	10

* Measured from outer surface of source container

\+ Measured through length of concrete box, 37 cm from source

n.a. Not accessible

Throughout the laboratory and field testing of the equipment film badges supplied by the Radiological Protection Service were worn. With very few exceptions the dose received was less than 20 mrem/2 weeks (the minimum detectable). The maximum dose was 30 mrem/2 weeks. It is therefore considered that the equipment does not represent a health hazard during normal usage with tubular access provided that the transmission probe is never removed from the control frame shield without additional shielding being provided in the form of soil or the probe storage shield. During planar access the lack of lateral shielding does represent a possible source of exposure and special precautions, such as remote control, will be required if this method is to be used extensively.

During periods when the probe was not in use the source was stored either in the probe storage shield or the source capsule storage shield which were placed within the locked metal storage safe in the radiation laboratory. The dose rate exterior to the safe was found to be 0.2 mrad h^{-1}. A set of Local Rules for the use of sealed radioactive sources was prepared with assistance from the Radiological Protection Service and the Ministry of Labour Advisory and Information Unit.

8.4 Background radiation

The accuracy of density measurements may depend on the background count rate if low counting rates have to be employed. In order to assess the possible need for corrections due to background a number of tests were made both in the laboratory and in the field.

(a) Laboratory tests

Readings were obtained with a large GM tube detector (MX 120/01) with various materials placed in 22.5 l containers. The detector was placed centrally in a standard P.V.C. access tube. All radioactive sources were removed from the laboratory. Readings were obtained in the different containers in a random order with four replicates using a count time of 1000 s for each reading. The results are shown in Table 8.3.

TABLE 8.3

Background radiation for different materials

Container	Material	Wet Bulk Density, g cm^{-3}	Mean Count Rate, s^{-1}
A	Sandy loam (S/30)	1.45	1.594
B	Sandy loam (S/30)	1.83	1.512
C	Water	1.00	1.331
D	Sand (S/36)	1.55	1.486
E	Sand (S/36)	1.70	1.378
F	Air	0.0	1.693
S.E. (Mean)			0.0109
L.S.D. (P = 0.05)			0.0328
(P = 0.01)			0.0453

These results suggest that significant differences in background count rate can be expected in different materials. The highest count was obtained with only air in the container whilst the lowest was obtained for water. Sandy loam (S/30) had a higher background than sand (S/36). Compaction of both samples resulted in a reduction of count rate. The explanation of these effects is not obvious but probably is related to an interaction between the natural radioactivity of the materials and their shielding action for cosmic-rays.

The overall range of count rate in the materials tested amounts to only about

0.30 s^{-1} so it seems unlikely that the effect will be of importance in influencing the accuracy of calibration. Some field tests were conducted however in order to investigate background characteristics in undisturbed soil.

(b) Total gamma-ray background tests in situ

The MX 120/01 detector was used for this work with a standard pre-set count time of 1000 s. Sufficient replication of readings was allowed to give at least 4000 s total counting time at each position. The GM tube detector was surrounded by the stainless steel probe tube in the usual way. This would effectively cut off beta radiation so that only gamma-rays and high energy cosmic particles will be counted. The former component in the soil would be expected to be mainly associated with Cs-137 from radioactive fallout and K-40, uranium and thorium decay products from natural rocks.

Holes were drilled to a depth of about 1.5 m with a 4.1 cm diameter screw auger. Where boulder clay was struck it was found necessary to make the hole by driving in a 5 cm diameter steel pipe. The hole was lined with Polyorc BH tubing in all cases before insertion of the detector probe. Five positions within the N.I.A.E.S.S. Field Station were used. The effective depth of measurement was taken as the active centre of the detector in the horizontal plane. Details of the positions are shown in Table 8.4 and the count rate results in Figs. 8.5 and 8.6.

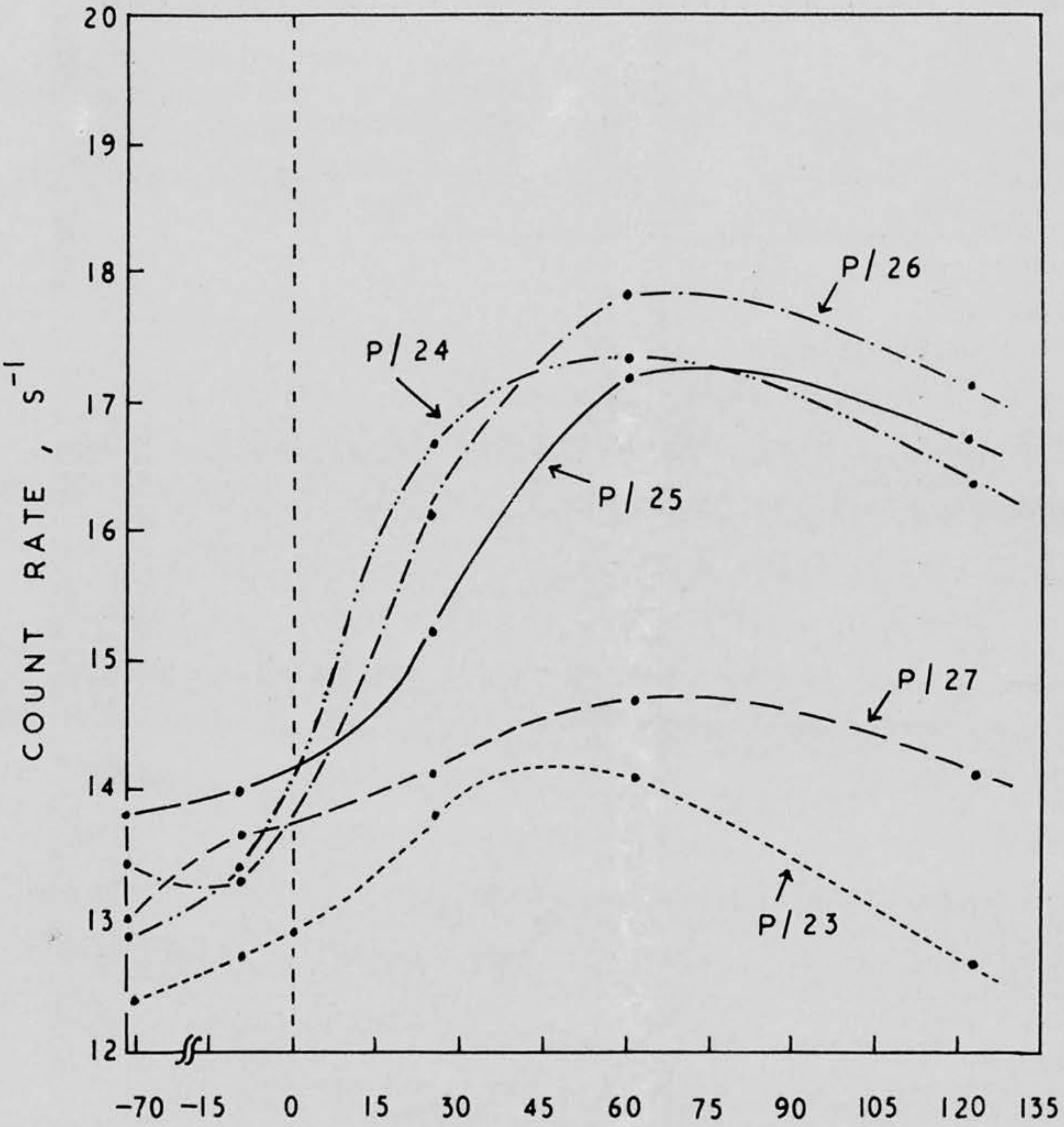

Fig 8.5 Background radiation at different depths for five positions in the field

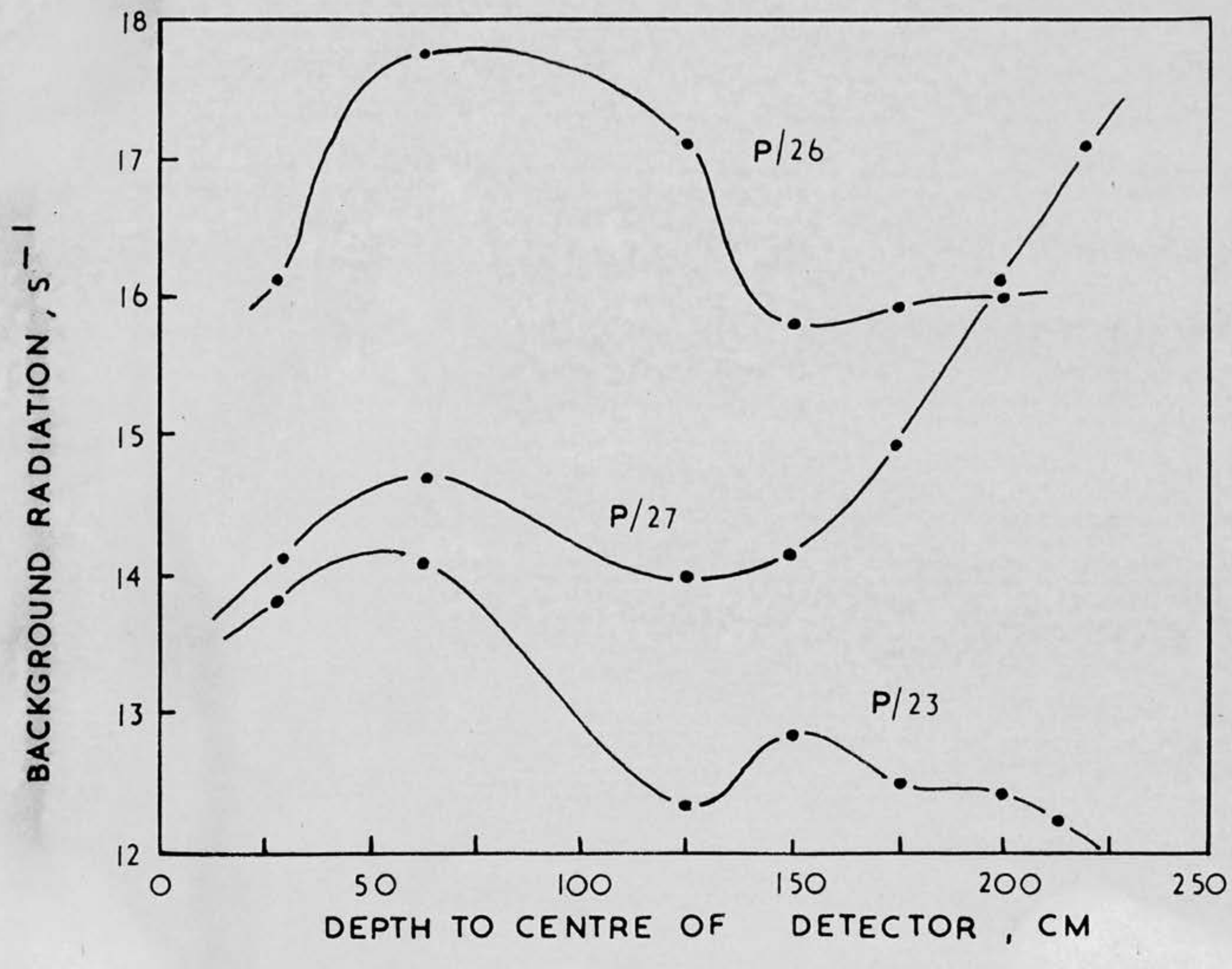

Fig. 8.6 Background radiation in three deep borings

TABLE 8.4

Positions used for field background measurements

Position No.	Location in N.I.A.E.S.S. Field Station
P/23	Top of Roundel
P/24	North Side of Plough Testing Area
P/25	In wood to south of Grain Drying Section (1)
P/26	" " " " " " " " (2)
P/27	" " " " " " " " (3)

It is not possible to attribute the variation of background count conclusively to any cause at this stage. However, it is of interest to note that the results appear to fall into three groups according to profile characteristics. Positions P/23, P/26 and P/27 were representative of these groups and results to greater depth are shown in Fig. 8.6. Position P/23 was situated on the summit of the Roundel and the texture was medium to fine grain sand with no restriction in drainage to a depth of 2.5 m. The count rate decreased from a maximum at 50 cm depth with a slight secondary rise at 150 cm. For position P/27 a layer of fine sand and silt occured at about 200 cm with pronounced orange ferric-iron mottling. Above this drainage appeared to be restricted. At position P/26 gravel and clay till occured at about 75 cm with evidence of restricted drainage below this depth.

(c) Identification of radio-elements in field soils

The established variations of total background might be due to differences in quantity or type of radio-elements present. Processes which might be responsible for these variations include:

(i) fall-out occurring on the surface and the subsequent distribution through biological or physical processes of dispersion,

(ii) variations of soil parent material,

(iii) variations in pedogenesis and drainage characteristics.

A number of disturbed samples was obtained from sites at which background had been measured in the field. Gamma-ray spectrometry tests were carried out at the Scottish Research Reactor Centre and at Nuclear Enterprises Ltd. using a 7.5 cm diameter, 7.5 cm thick sodium iodide detector, mounted in a heavily-shielded container, linked to a Laben 512-channel pulse height analyser (only 127 channels used). Background counts within the empty container were made and the results for each channel subtracted from the results obtained for each sample. Counting periods between 16384 and 32768 s were used.

An example of the results obtained is shown in Fig. 8.7. All samples showed a well defined peak for K-40 at an energy of about 1.46 MeV. The prominence of the K-40 peak tended to be related to the level of total background. Most samples showed a peak in the region of 0.60 MeV which may be due to the presence of Cs-137 however evidence produced by the Radiobiological Laboratory, Wantage, suggests that the penetration of this element from fall-out received at the surface has seldom exceeded 3 - 4 cm. Several other peaks were found but their identification was not possible owing to the relatively low degree of stability in the pulse-height analyser. For multi-channel gamma-spectrometry, involving counting periods of many hours for each sample, special precautions and gain stabilisation are required. Further work would therefore be required before any positive identification could be made of radio-isotopes other than K-40.

8.5 Computation and data display

Measurement of the time required for collection of 10,000 counts using the

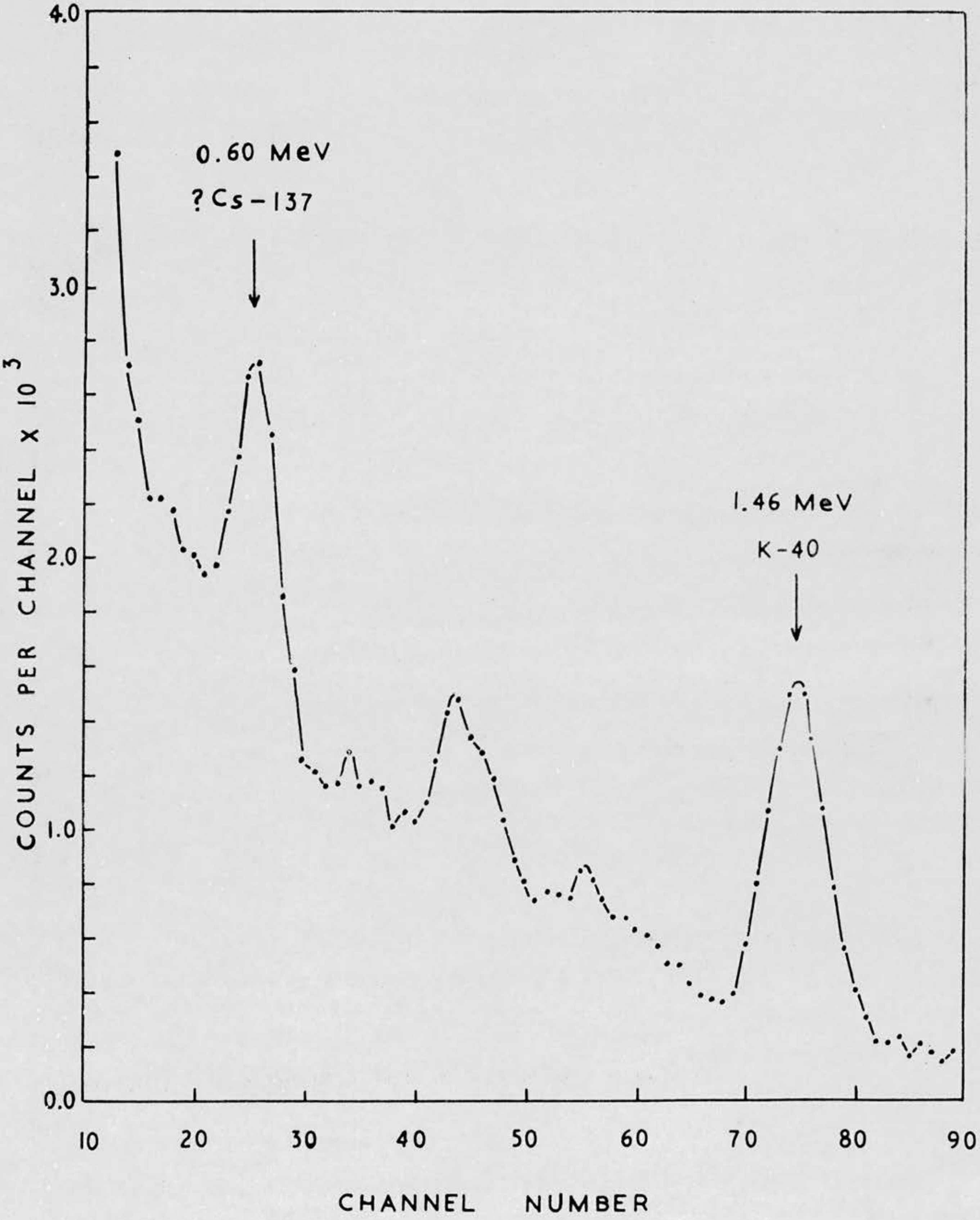

Fig. 8.7 Background gamma-ray spectrum for sample S/82(120-135 cm depth at P/26) for 16384 s count period

standard exposure was made before and after test readings at each position in the field. Test readings were obtained at depth increments of 2.54 or 5.08 cm depending on circumstances and the time for the collection of 10,000 counts was measured at each depth. Inter-probe or inter-plate distance was then measured with the long-nosed calipers. Disturbed samples for moisture content determination by oven-drying were obtained in 2.54 or 5.08 cm depth increments either during initial drilling of the access holes (tubular access) or from soil removed from between the plates (planar access) after test readings had been completed.

The following data for each test reading were recorded in the field:

R = Horizontal displacement (cm) (only used in horizontal scanning).

D = Depth below underside of control frame (cm).

T_t = Time for collection of 10,000 counts for test reading (s).

T_s = Time for collection of 10,000 counts for standard exposure (s).

L = Micrometer reading on caliper (cm).

M = Moisture content ($\% \ ^w/w$).

These data, together with the appropriate calibration characteristics, were subsequently punched on paper tape in sequence for each test position and the following computations were performed by a KDF9 computer using a programme* specially prepared in Atlas Autocode.

Correction for variation in source-detector separation

The time required to collect a fixed number of counts for a given sample thickness and density is approximately proportional to the square of the distance between the source and the detector. The tubular access system

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* IAE 001/0005.

had a standard source-detector separation, SD_n, of 30.5 cm. The actual source-detector separation, SD_a, could be obtained from the micrometer reading, L, knowing the characteristics of the calipers. The actual time interval reading, T_t, for each depth was therefore corrected by the factor $(SD_n)^2/(SD_a)^2$ in order to obtain a corrected reading for standard geometry. A similar correction was applied to the results from planar access to give a corrected reading for the nominal source-detector separation in planar access.

Conversion to wet bulk density

The appropriate calibration relationship for slope, B, and intercept, A, were selected depending on whether tubular or planar access was in use and a value for uncorrected wet bulk density, D_{bw}', was obtained from the expression:

$$D_{bw}' = \frac{\log_{10} \left[\frac{T_t \times \frac{(SD_n)^2}{(SD_a)^2}}{T_s} \right] - A}{B} \qquad (8.1)$$

Correction for variation in sample thickness

The calibration relation depends on a knowledge of the sample thickness and a separate correction is required if variation occurs from the standard sample thickness, ST_n, of 26.2 cm (tubular access), 25.9 cm (planar access). The micrometer reading, L, is again used, this time to calculate the actual sample thickness, ST_a, and the uncorrected wet bulk density is multiplied by the factor ST_n/ST_a. The corrected wet bulk density, D_{bw}, is then converted to dry bulk density, D_b by the relation

$$D_b = \frac{D_{bw} \times 100}{M + 100} \qquad (8.2)$$

The combined calculation performed by the computer for each test reading is therefore

$$D_b = \frac{\left[\frac{\log_{10} \left\{ \frac{T_t \times ((SD_n)^2/(SD_a)^2)}{T_s} \right\} - A}{B} \right] \times \frac{ST_n}{ST_a} \times 100}{100 + M} \qquad (8.3)$$

Data display

The calculated values of dry bulk density can be obtained in a number of output forms from the computer. For situations in which tubular access is used the results are presented in tabular form but for planar access the line printer output can be programmed[*] to place the calculated dry bulk density data on rectangular coordinates according to the horizontal and depth displacements, R and D, given for each test position. This method enables contours[**] of dry bulk density to be drawn in readily by eye on the output sheet. For certain situations however it may be desirable to analyse the data in order to display smoothed contours of bulk density with the elimination of local irregularities resulting from stones, voids, etc. This is particularly appropriate when studying bulk density changes resulting from soil-surface loading under plates or wheels in which soil-mechanics theory predicts specific geometrical distributions of bulk density depending upon the pressure, loaded area and soil characteristics. Trend-surface analysis employing two dimensional polynomial least squares analysis was employed as a possible method of 'smoothing'.

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[*] IAE 001/0005 (Edit 5)

[**] A contour of points of equal bulk density could be termed an isodens (L. densus) or an isopycnon (Gr. pyknos).

This technique has been used in the analysis of geological and other complex surfaces, see for example Merriam and Harbaugh (1964). A computer programme* was used to undertake the complex calculations required and to provide a graphical display on the line printer output. Bulk density contours were indicated for pre-arranged class intervals of bulk density. An example of such a display is shown in Fig. 11.12 which illustrates the bulk density distribution following the passage of a tractor wheel over loose surface soil. The position of each contour is indicated by the omission of print-out letter characters at the junction between areas of adjacent bulk density class intervals. Detail of the print-out in the vicinity of the contour is shown in Fig. 8.8. The trend-surface analysis can be made with different order polynomials. For the data obtained in this test the relationships between the order of polynomial and the correlation coefficient is shown in Fig. 8.9. Appreciable correlation (i.e. greater than 95%) cannot be achieved for the surface in question without extending the analysis to include the heptic (sixth-degree) components.

8.6 Soils used in calibration tests

A number of local soils was used in calibration and other tests. These were selected in order to be representative of the areas in which the equipment was to be tested in the field. A wide range of texture was selected but calibration relations should be interpreted with caution for other soils since compositional differences may affect results in certain circumstances.

The soils were sampled in the field and were then air-dried, gently crushed and prepared for analysis according to the provisions of BS 1377:1961. The

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* IAE 001/0008

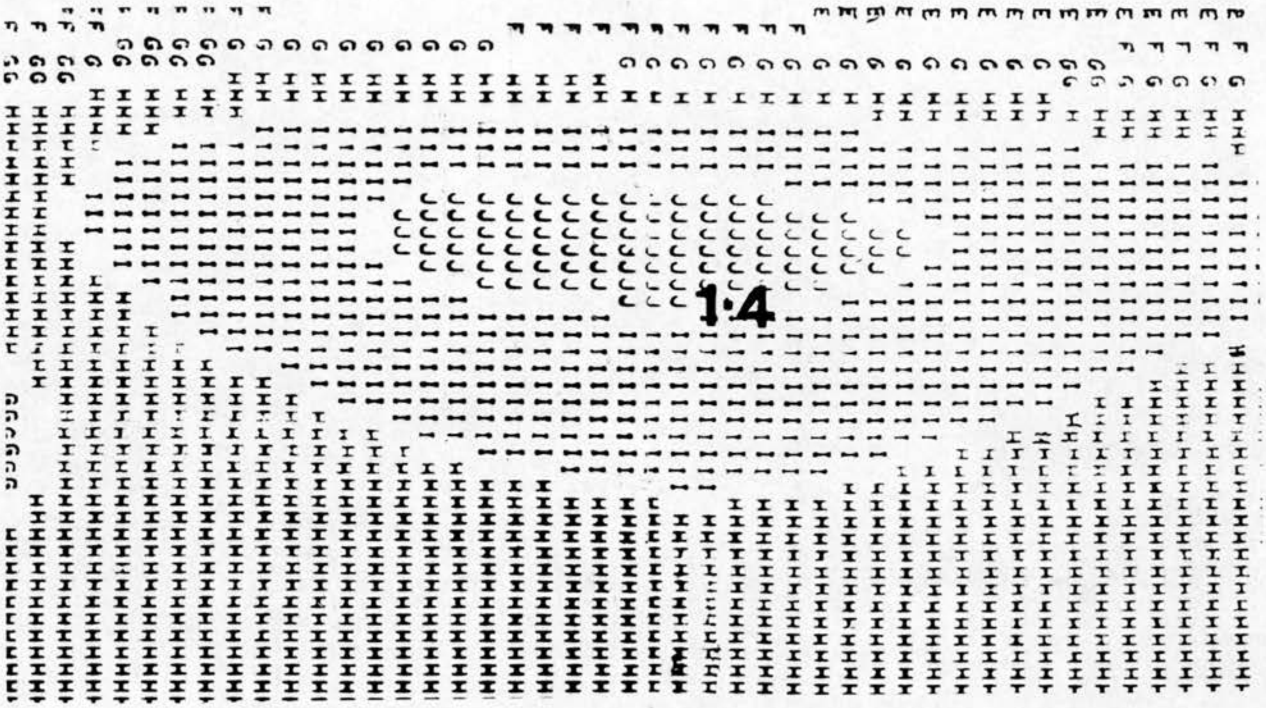

Fig. 8.8 Details of dry bulk density contours on trend surface analysis print-out

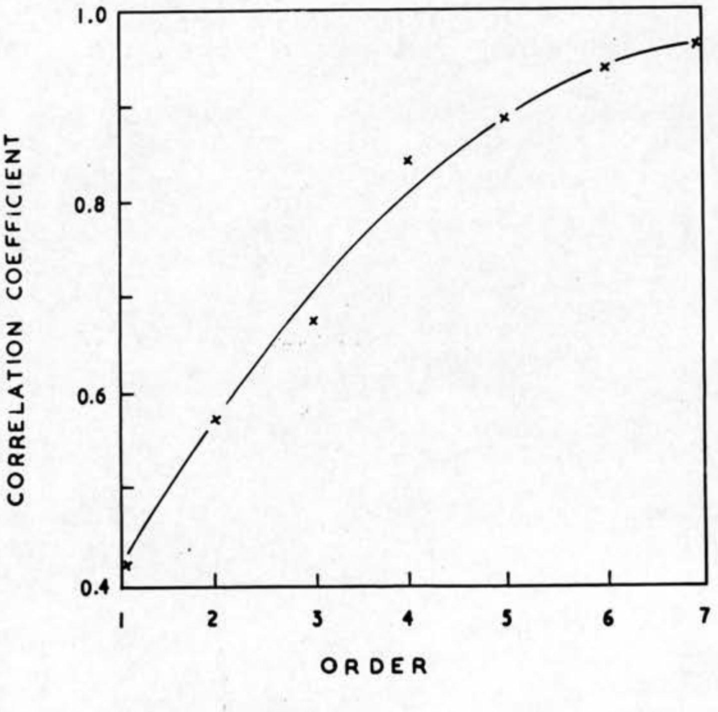

Fig. 8.9 The variation of correlation coefficient with the order of polynomial used in trend surface analysis of the results shown in Fig. 11.12

liquid limit and plastic limit tests were made on material passing a No. 36 sieve and the Proctor compaction test for maximum density and optimum moisture content was made on material passing a $\frac{3}{4}$ in. sieve. The results of analyses are shown in Table 8.5.

TABLE 8.5

Some properties of soils used in calibration tests (1)

Lab. Sample No.	Texture	Sand %	Silt %	Clay %	Liquid Limit %	Plastic Limit %	Proctor Max. Density g cm^{-3}	Optimum Moisture Content % $^{w}/w$
	(2)	(3)	(4)	(5)	(6)	(6)	(6)	(6)
S/36	S	91	5	4	n.p.	n.p.	1.57	17.0
S/122	LS	84	12	4	n.p.	n.p.	1.71	16.0
S/30	SaL	74	11	15	26	n.p.	1.60	20.8
S/120	SaL	71	20	9	26	n.p.	1.68	17.2
S/124	SaL	58	33	9	31	n.p.	1.55	19.0
S/121	SaL	73	19	8	n.p.	n.p.	1.65	17.5
S/116	SaL	63	28	9	34	28	1.58	19.0
S/123	L	45	43	12	32	n.p.	1.69	16.0
S/34	CL	37	28	35	38	19	1.73	18.0
S/142	SiC	6	44	44	67	39	1.41	25.8

(1) The assistance of Mr. J.M. Ragg in the selection of soils is acknowledged.
(2) U. S. Dep. Agric. (1951) classification.
(3) 2.0 - 0.05mm.
(4) 0.05 - 0.002 mm.
(5) < 0.002 mm.
(6) According to BS 1377:1961; n.p. indicates "non-plastic".

CHAPTER 9

LABORATORY STUDIES WITH GM DETECTOR

9.1 Stability and precision

The satisfactory operation of equipment of this type in the field depends to a large extent on a high degree of operating stability. Instability, as detected by a variation in count rate under conditions of standard exposure, may be due to several effects some of which can be readily eliminated. Variation attributable to the random disintegration rate in the radioactive source can be reduced to an error of ± 1% (standard deviation) by the collection of at least 10 000 counts for each test reading. Variation due to the decay characteristics of the source can be eliminated by using a standard exposure as a reference at the time of each set of readings. Variation of performance may also occur because of instability in the l.t. or e.h.t. supplies, malfunction of the scaler/timer unit or faults in the cables and connectors. Changes of geometry may also occur such as variation in the source-detector separation distance, sample thickness, and in the distribution of media surrounding the source and detector.

(a) Precision with static equipment in the laboratory

A preliminary study was made of the statistical characteristics of count-rate variation in order to assess the influence of random disintegration rate on the error of count-rate measurements. A series of counts was made in a 22.5 l container containing sand at a wet density of 1.55 g cm^{-3}. The probes were not moved throughout the tests. The scaler/timer was set to count 100 counts and the corresponding time intervals were recorded in milliseconds, using the internal quartz oscillator timer. The operation was repeated 1000 times. The results were then grouped into units of 100, 500, 1000, 2000 and

4000 counts. A statistical analysis was carried out on the results for each group. Mean, standard deviation and coefficient of variation values were obtained. The results are shown in Table 9.1. Another statistic calculated was the factor K defined by Kohl et al. (1961) as

$$K = \frac{S}{N^{\frac{1}{2}}} \qquad (9.1)$$

where S is the measured standard deviation of a number of observations and N is the number of counts in each observation. The extent by which K exceeds unity is a measure of the amount of variation other than that attributable to random disintegration.

TABLE 9.1

Variation in statistical parameters with number of counts in counting period

	Number of counts (N)				
	100	500	1000	2000	4000
No. of counting periods	1000	200	100	50	25
$1/N^{\frac{1}{2}}$	0.100	0.045	0.032	0.022	0.016
Mean time, ms	7672	38361	76721	153443	306886
Standard deviation, ms	750	1718	2480	3550	5504
Coefficient of Variation, %					
determined	9.78	4.48	3.23	2.31	1.79
theoretical	10.00	4.47	3.16	2.24	1.58
K	0.98	1.00	1.02	1.03	1.13

In order to show that these results are in line with accepted statistical theory, the coefficient of variation results were plotted against the reciprocal of the square root of the number of counts in each observation. As shown in Fig. 9.1 the expected straight line relationship was obtained. On the basis of these results it is possible to select the number of counts required to give a specified standard deviation in the results. When the

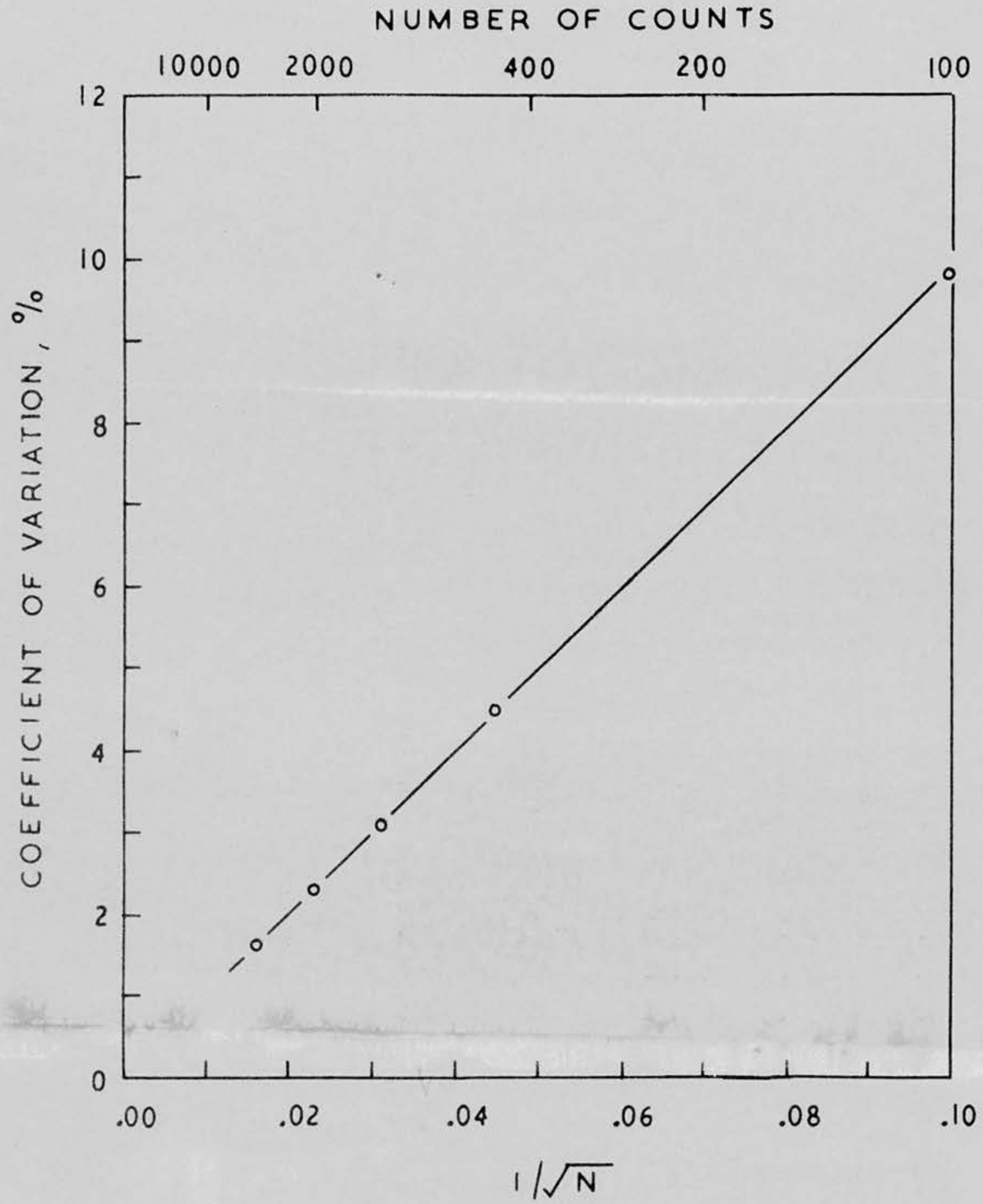

Fig 9.1 The influence of number of counts on the coefficient of variation

number of counts exceeded 4000 the coefficient of variation tended to be lower than that expected from the extrapolation of the straight line.

(b) Effect of different detectors on precision

The tests described in (a) were extended to include a large GM tube detector (MX 120) and a sodium iodide scintillator-crystal detector as described in section 8.2. The number of counts collected was varied between 5000 and 20000. The results are shown in Table 9.2. χ^2 is the chi-square value calculated according to the relation

$$\chi^2 = \frac{\sum (R_i - R)^2}{R} \tag{9.2}$$

where R_i is the count rate for test i and R is the mean count rate. P is the probability that the calculated value of χ^2 could occur by chance. Values of P less than 0.05 therefore indicate that the degree of variation among the test results exceeds expectations at a probability level of 95%.

TABLE 9.2

The influence of type of detector and number of counts collected on precision of measurement

Detector	Discriminator Setting		No. of Counts	No. of Count periods	R s^{-1}	χ^2	P	K
	Aperture V	Threshold V						
MX 146	Max	0.2	5000	20	65.7	16.7	0.50	0.94
			5000	20	405.3	17.2	0.50	0.95
			10000	20	65.0	14.0	0.70	0.86
			10000	20	403.9	15.2	0.70	0.90
			20000	20	63.8	20.1	0.40	1.03
			20000	19	405.1	14.0	0.70	0.86
MX120	Max	0.2	20000	20	87.6	53.2	0.001	1.67
			20000	20	368.0	23.3	0.20	1.11
Na I	0.2	Peak	10000	20	81.0	37.4	0.01	1.40
	0.2	Peak	20000	20	106.1	-	-	0.85
	Max	Peak	20000	20	244.9	-	-	1.36
	0.2	Peak	10000	20	106.2	-	-	1.41
	Max	Peak	10000	20	234.4	-	-	0.87
	0.2	Peak	5000	20	108.2	-	-	1.05
	Max	Peak	5000	20	266.7	-	-	1.01

The results for the MX 146 detector are satisfactory. K values are close to or somewhat below unity and the P values are all greater than 0.05. However results for the MX 120 and NaI detectors show much greater variation. There is a tendency for K values to be high when the mean count rate is low. This may be associated with the much longer counting period and consequent greater opportunity for instability in the counting equipment to affect the results. For certain tests K values exceeded 1.3 and these were reflected in P values less than 0.05 and hence indicate that variation among count periods was greater than could be explained by chance.

9.2 Sample resolution

Perhaps the most important attribute of the gamma-transmission method is the high degree of sample resolution which is possible. A number of tests was made in order to examine the resolution obtained experimentally with the MX 146 detector.

(a) Transmission-beam characteristics

The gamma-ray transmission method employs a beam of primary radiation of sufficient width to cover the solid angle subtended by the detector at 30 cm distance but without unnecessary spread at wider angles. A 0.635 cm diameter hole was used in the lead shield of the transmission probe as a partial collimator. In order to test the resulting characteristics the MX 146 detector was placed at varying positions on an arc at 30 cm distance from the transmission probe. The results are shown in Fig. 9.2. The centre line of the beam was indicated by a punched dot on the outside of the stainless steel probe tube. It is clear from the results that there is an error of about 3.5° in the alignment of the beam, relative to the assumed centre line. The projected angle of the 2.54 cm diameter sodium iodide crystal detector at

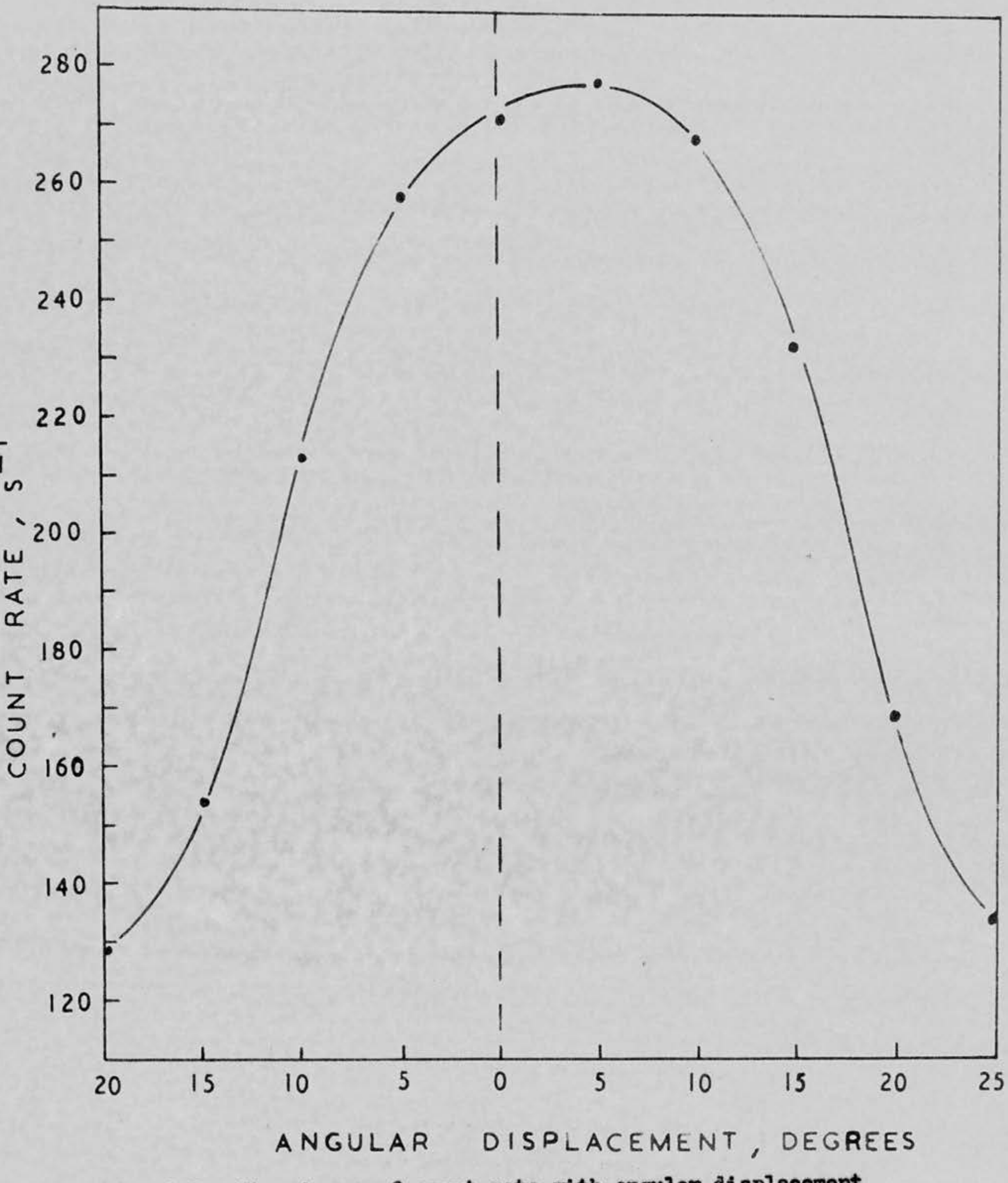

Fig. 9.2 The change of count rate with angular displacement of gamma-ray transmission probe

30 cm will be 4°46'. Since the total width of the beam at 99% of full intensity is approximately 8° there appears to be no difficulty in adjusting the beam to cover this detector.

(b) Comparison of sample resolution at water/concrete interface

Tests were made to examine the sample resolution obtained with three probe systems (A, B and C) as shown in Table 9.3. A water/concrete interface was used to test resolution since the densities of the two phases lie within the range found in field soils. Readings were obtained with the probe midline at different distances above and below the interface. The variation of count rate, relative to that in water, with displacement from the interface is shown in Fig. 9.3.

TABLE 9.3

Vertical resolution for three probe systems using a water - concrete interface

	System	No. of Probes	Dector		Vertical Displacement of Source and Detector Midline cm	Critical Approach Distance cm
			Type	Active Height cm		
A.	Transmission	2	GM(MX 146)	3.5	nil	4.7
B.	Transmission	2	NaI(Tl)	0.64	nil	2.0
C.	Backscatter	1	GM(MX 146)	3.5	29	7.5

The sodium iodide detector was used with a differential pulse energy discrimator set to enclose the photopeak of Cs-137 radiation at 660 KeV. No collimation was used in any system. The critical approach distance is defined as the minimum distance which the horizontal midline of the probe may be set from an interface with a medium of highly contrasting density without a change in count rate being measured. As expected the sodium

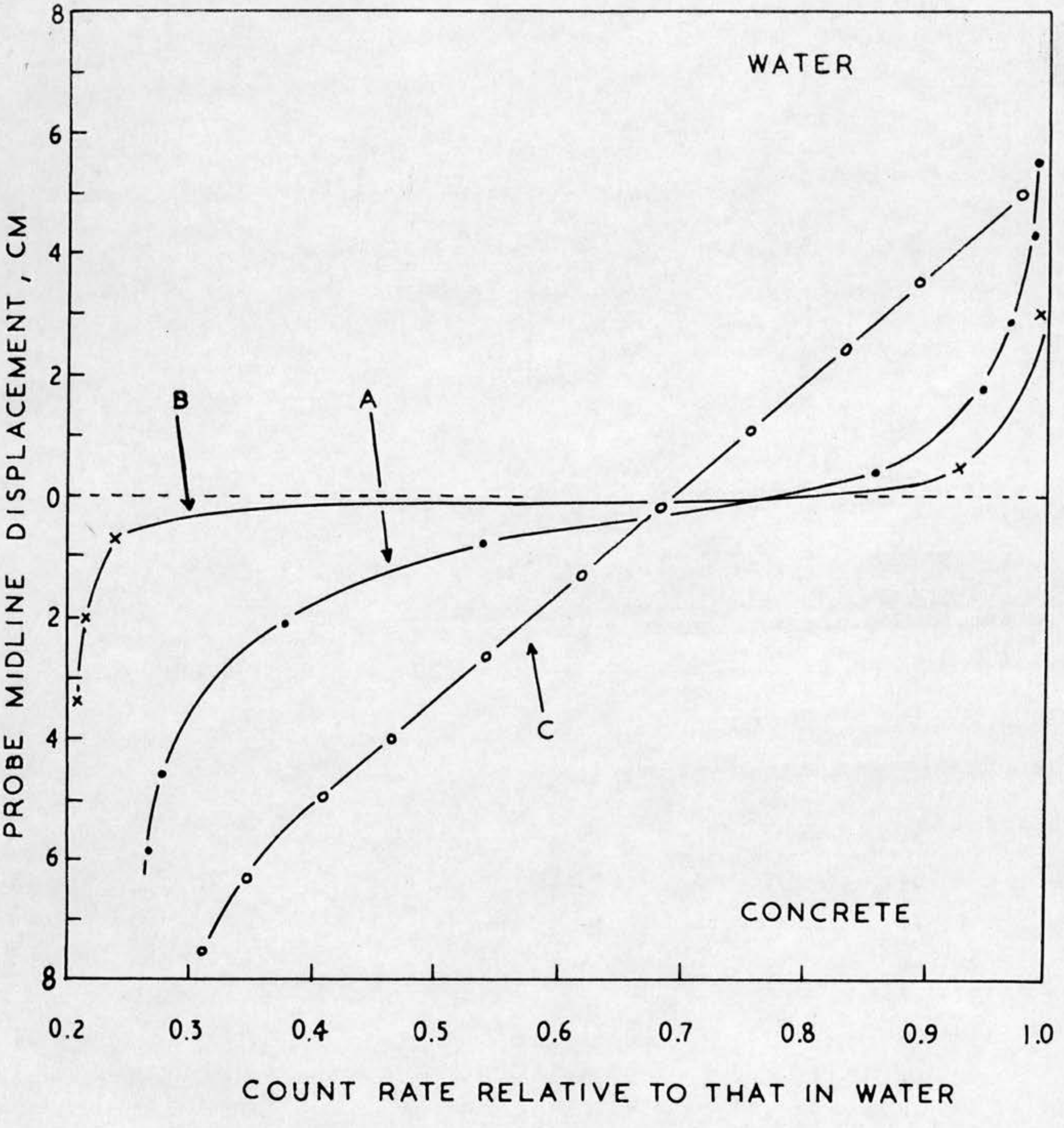

Fig. 9.3 The variation of count rate with probe displacement from concrete-water interface for three probe systems, (A) MX146 detector, transmission, (B) NaI detector, transmission, (C) MX146 detector, backscatter

iodide detector shows the smallest critical approach distance whilst the backscatter GM tube detector shows the largest. For media which do not differ in density as markedly as those used in this test the effective critical approach distance will be reduced. For practical purposes it appears that the critical approach distance for the MX 146 and sodium iodide detectors can be taken as 4 cm and 1.5 cm respectively.

(c) Effect of vertical height of simulated clods

This test was carried out to examine the possible use of the equipment for the measurement of the density of clods. Wood blocks of approximately 5 cm thickness and 7.5 cm width were cut to give heights of 1.25, 1.88, 2.54, 3.17, 3.79, and 5.08 cm. Each block was mounted in turn on a light P.V.C. stand and the source and MX 146 detector were moved in equal increments from a position in which the gamma-ray beam was clear above the block to one in which it was clear below. Whilst traversing the block vertical increments of 0.64 cm were used. The variation of count rate with position relative to the block for the different sized blocks is shown in Fig. 9.4. For all sizes the maximum count rate obtained was the same within experimental limits, indicating that satisfactory results would be obtained for a clod only 1.25 cm high if the beam were accurately aligned through its centre. However, in practice, this would not be reliable and a minimum vertical height of about 2.5-3.0 cm for the clod appears desirable. Over this vertical distance the specimen must be bounded by flat vertical parallel faces normal to the direction of the beam. This requirement appears to be a severe restriction to the routine measurement of clod density by this method.

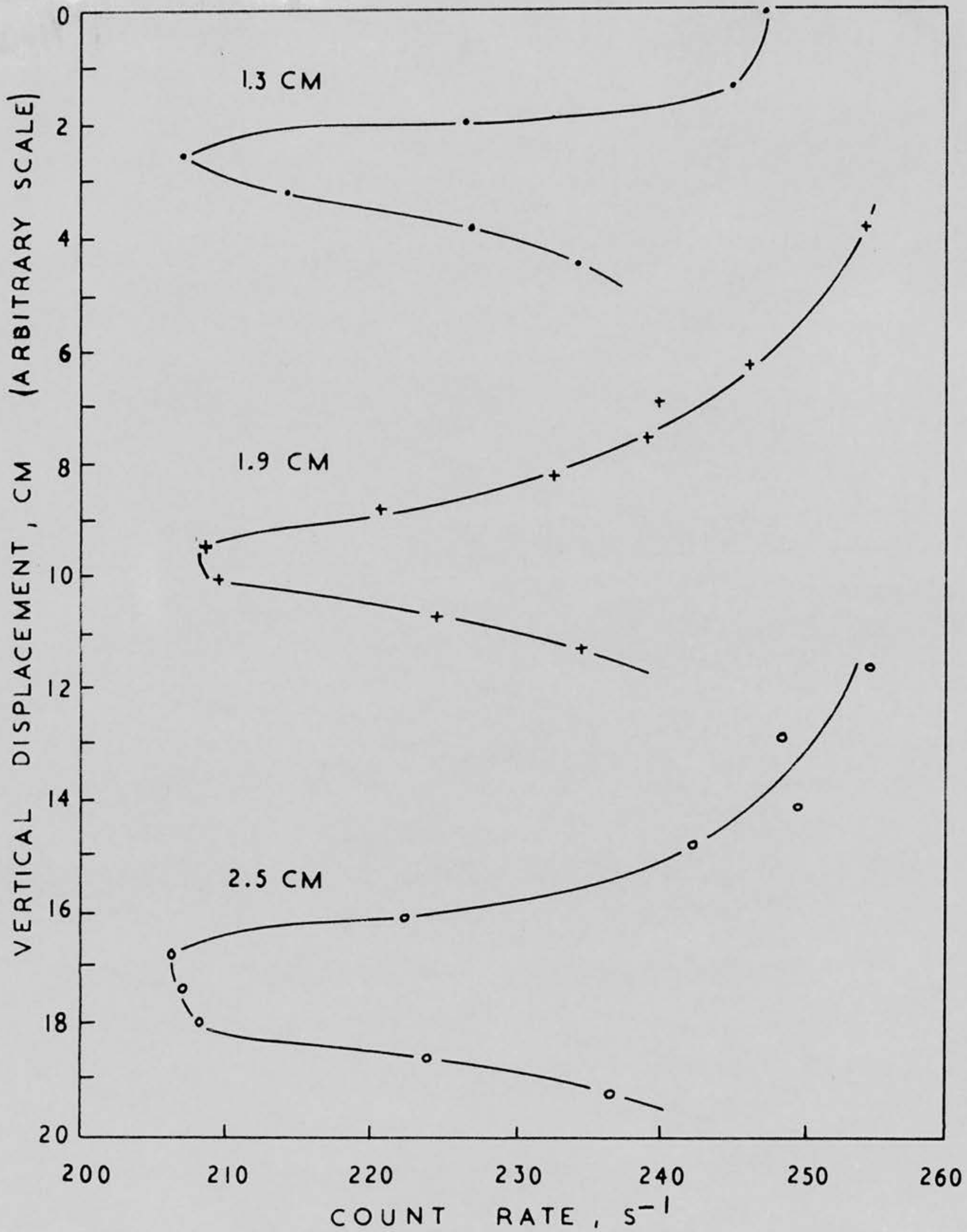

Fig. 9.4 The variation of count rate with vertical displacement of probe midline for three thicknesses of wood

9.3 Calibration with simple materials

Tests were made with steel and glass plates in order to test the equipment over a wide range of sample mass thickness. Tests were made (a) with the 5 mCi Cs-137 source in order to test its use for clod-density measurements and (b) with the 30 mCi Cs-137 source in order to indicate the likely performance for *in situ* density measurements with a sample thickness fixed at 26.2 cm.

(a) Tests with 5 mCi Cs-137 source The relationship between count rate and mass thickness of glass and steel plates is shown in Fig. 9.5. Good linearity was obtained over the range 0-25 g cm^{-2} mass thickness with no evidence of count losses at the maximum counting rate of 250 s^{-1}. In order to see whether reduced source-detector separation could be used for clod density studies, tests were made with S-D separations of 15, 22.5 and 30 cm, with mass thicknesses (plywood) in the range 0-5 g cm^{-2}. The results are shown in Fig. 9.6. The results indicate that S-D separation could be reduced considerably below 30 cm without appreciable count losses at low mass thicknesses. However there is evidence for count losses when the count rate exceeds about 700 s^{-1}. This occurs at mass thicknesses less than 1 g cm^{-2} for 15 cm S-D separation.

(b) Tests with 30 mCi Cs-137 source For nominal thicknesses in the order of 26 cm (S-D separation 30 cm) it became apparent that a source strength of 5 mCi Cs-137 was inadequate for materials of density in the range 1-2 g cm^{-3}. A Cs-137 source of increased activity (30 mCi) was therefore obtained and a further set of tests were made with steel plates. In order to relate performance to expected soil conditions an equivalent density value was calculated for each number of steel plates using the

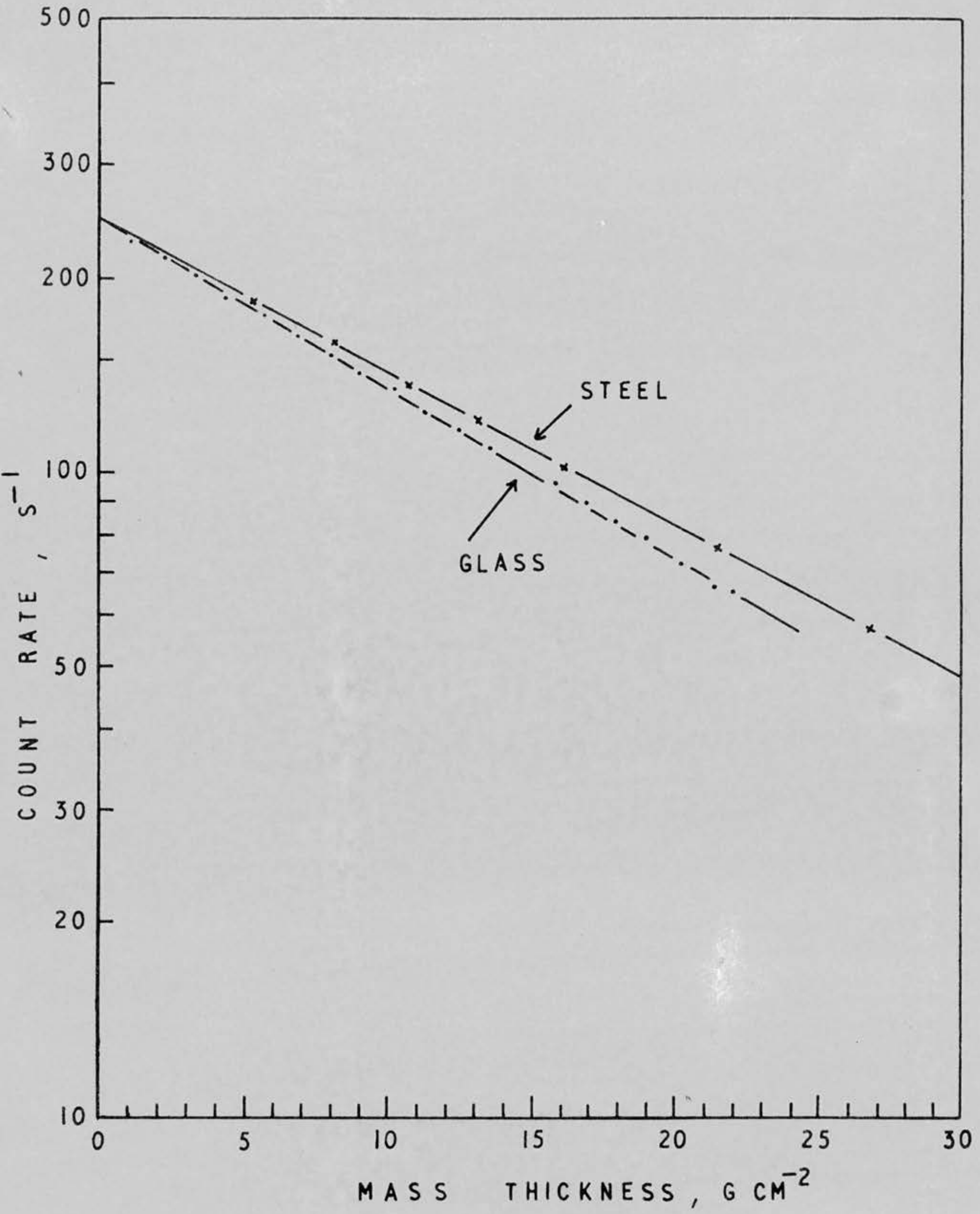

Fig. 9.5 The relation between the mass thickness of glass and steel and count rate (MX146 detector, 30 mCi Cs-137 source)

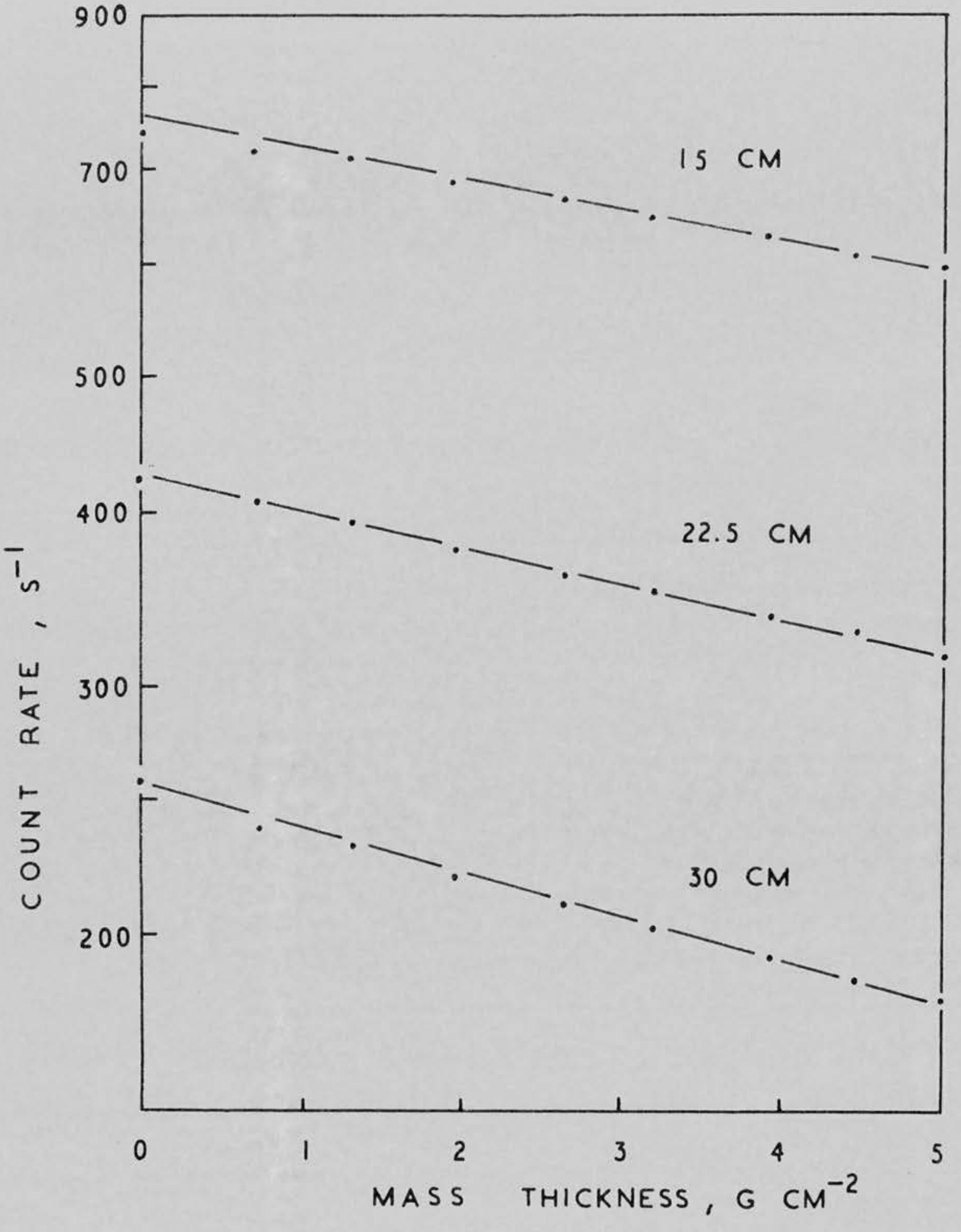

Fig. 9.6 The effect of source-detector separation on the relationship between mass thickness and count rate for wood

relationship:

$$\text{Equivalent density} = \frac{\text{Density of steel x thickness of plates}}{\text{Nominal sample thickness}} .$$

The results obtained are shown in Fig. 9.7. A satisfactory degree of linearity was obtained for equivalent densities in the range 0.6-3.0 g cm^{-3}. At densities below 0.6 g cm^{-3} (and count rate above about 500 s^{-1}) a progressive count loss occurs. Since densities less than 0.6 g cm^{-3} are not likely to be found in mineral soils, it is concluded that a source activity of about 30 mCi Cs-137 would be satisfactory for use with the MX 146 detector and sample thicknesses of 26 cm. A reasonably high count rate (150 s^{-1}) is obtained at a density of 2.0 g cm^{-3} which is likely to be the maximum found in field soils. Apart from those lying in the non-linear region, results were submitted to linear regression analysis and the following results were obtained:

$$\log_{10} \text{count rate } (s^{-1}) = 2.957 - 0.389 \text{ Equivalent Density } (g\ cm^{-3}) \qquad (9.3)$$

S.E. (A) = 0.0049, S.E. (B) = 0.0023, T (B) = 170.3, N = 13, r^2 = 0.9996.

9.4 Calibration with soil-water mixtures

For a given source and detector system of fixed geometry and in the absence of photon-energy discrimination, the theoretical relationship between the transmission of photons through moist soil of thickness x cm is given by the equation

$$I = I_o\ b \exp - (\mu_s D_b + \mu_w D_w)x \qquad (9.4)$$

where I and I_o represent the count rate, s^{-1}, with and without the sample present respectively. μ_s and μ_w represent the mass-absorption coefficients, $cm^2\ g^{-1}$, of dry soil and water respectively and D_b and D_w are the mass concentrations per unit volume, g cm^{-3}, of dry soil and water respectively.

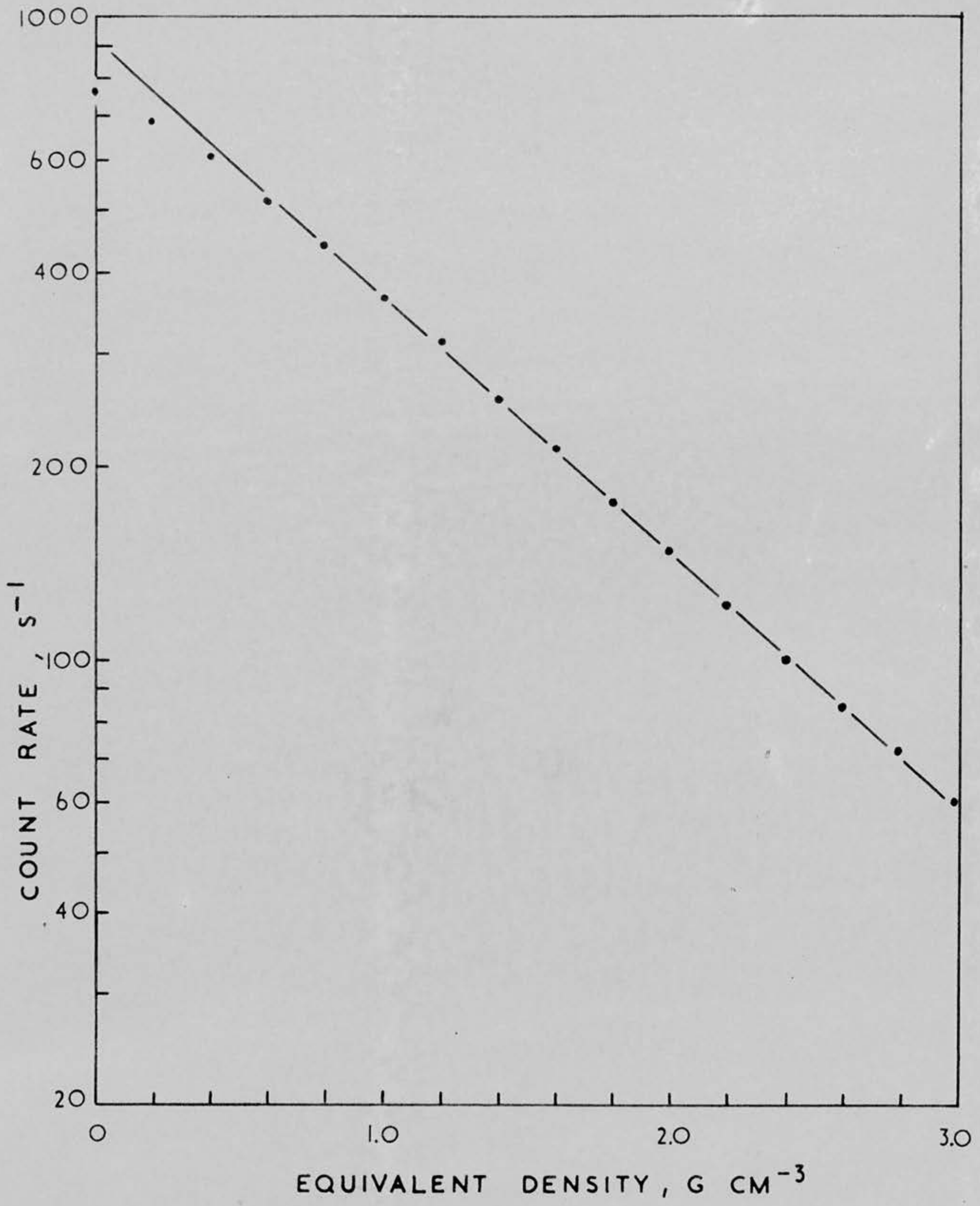

Fig. 9.7 The relation between count rate and equivalent density of steel plates (MX146 detector, 30 mCi Cs-137 source)

The build-up factor, b, is a function of the extent to which the count rate I is influenced by photons which have lost energy as a result of interaction with matter in traversing the sample but which are nevertheless detected and counted.

In practice Eqn. (9.4) is not solved explicitly but an empirical solution is obtained by calibration. The equation may be simplified if the following tentative assumptions can be made:

(a) that b is a constant within the range of bulk density to be measured,

(b) that no appreciable difference between μ_s and μ_w exists for the photon energy used and that the term μ can be used to represent the mass-absorption coefficient of the soil-water mixtures tested in the calibration.

If these assumptions can be shown experimentally to be acceptable then Eqn. (9.4) can be simplified to

$$\log_{10} I = \text{constant} - \frac{\mu D_{bw} x}{2.303} \qquad (9.5)$$

where D_{bw} is the total mass concentration per unit volume or wet bulk density, g cm^{-3}. A plot of $\log_{10}$ I against D_{bw} should therefore give a straight line if the assumptions are valid. A number of tests were made to study this effect.

(a) <u>Tests with 5 mCi Cs-137 source using samples of variable length</u>

10 cm diameter open-ended cylindrical tubes were used as retainer rings. The length varied from 6.8 to 19.0 cm. Tests showed that the presence of the tube had no effect on the count rate, whether soil was present or not, provided the gamma-ray beam passed along or very close to the longitudinal axis of the tube.

A sandy loam, representative of some parts of the N.I.A.E.S.S. Field

Station (S/116), was used for the tests at two moisture contents, approximately 11% $^w/w$ and approximately 20% $^w/w$. Samples were packed at different densities into tubes of different lengths. In order to permit comparison between all the determinations the mass thickness of each sample was calculated by multiplying the wet density (g cm^{-3}) by the length of the sample (cm). The results obtained are shown in Fig. 9.8 and merit the following conclusions:

(a) A very strong correlation between $\log_{10}$ count rate and mass thickness was obtained in the range 8 - 26 g cm^{-2}.

(b) The extrapolation of the regression to zero mass thickness gave a value of count rate which was virtually identical to that obtained when transmission occurred through an empty tube.

(c) There was no apparent dependence on the moisture content of the sample within the limits 11 - 20% $^w/w$.

Part of the dispersion in the results is probably due to error which is introduced by calculating the mass thickness from the average density of the whole sample whereas the transmission determination is influenced only by the density of the soil close to the longitudinal axis of the sample. In order to reduce this effect count-rate determinations were made 1.27 cm above and below the axis as well as along the axis and the mean of these three readings was used to represent the sample. Compaction by tamping is most unlikely to give uniform density over the cross section of the sample. The use of additional positions for transmission readings would reduce this error but the number of possible additional positions is limited by the vertical and horizontal resolution of the MX146 detector and the need to avoid any interference from the wall of the tube.

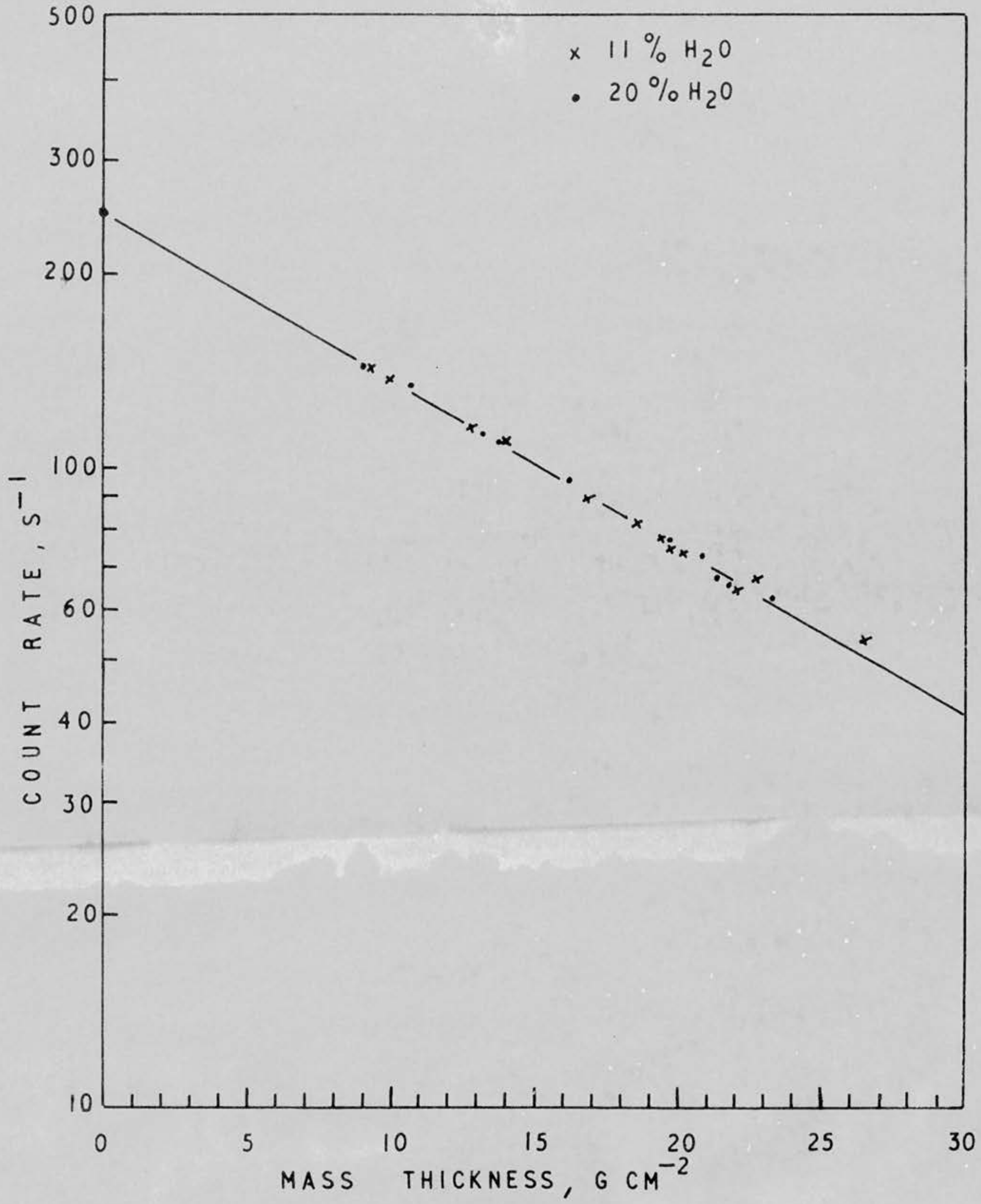

Fig. 9.8 The effect on count rate of mass thickness of soil (S/116) at two moisture contents in open-ended cylinders (MX146 detector, 5 mCi Cs-137 source)

(b) Tests with 5 mCi Cs-137 source using samples of fixed length (tubular access)

Five soils* of contrasting texture (S/34, S/124, S/120, S/121, S/122) were used for these tests. Moisture contents were adjusted to values similar to that found in the field during certain field tests reported in Section 10.3. The samples were packed into wooden boxes with internal length 41 cm, width 10 cm and depth 10 cm (Type A). 'Polyorc' access tubing was located within the boxes to give a source-detector separation of 30 cm. The degree of compaction was varied to give wet bulk-density readings in the range 0.9 to 1.7 g cm^{-3}. The results are shown in Fig. 9.9. A pronounced linear relationship was obtained over the density range used but the use of the 5 mCi Cs-137 source for this application is clearly unsatisfactory since the count rate at a wet bulk density of 1.7 g cm^{-3} was only 20 s^{-1}. A linear regression analysis was undertaken on the results and the following values obtained:

$$\log_{10} \text{count rate } (s^{-1}) = 2.376 - 0.598\, D_{bw}\ (g\ cm^{-3}) \qquad (9.6)$$

S.E. (A) = 0.0321, S.E. (B) = 0.0237, N = 19, T (B) = 25.24, r^2 = 0.974.

(c) Tests with 30 mCi Cs-137 source using samples of fixed length (tubular access)

For these tests a much wider range of soils and moisture contents was used. Calibration was initially carried out in type A boxes as described in (b). As there was slight evidence of a non-linear effect at high bulk densities a larger box was used to reduce any error resulting from insufficient sample size. These boxes (type B) were 17.3 cm depth, 17.8 cm width and 40.6 cm length. The soils were loaded into the boxes with light,

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* For details of soils see Table 8.5.

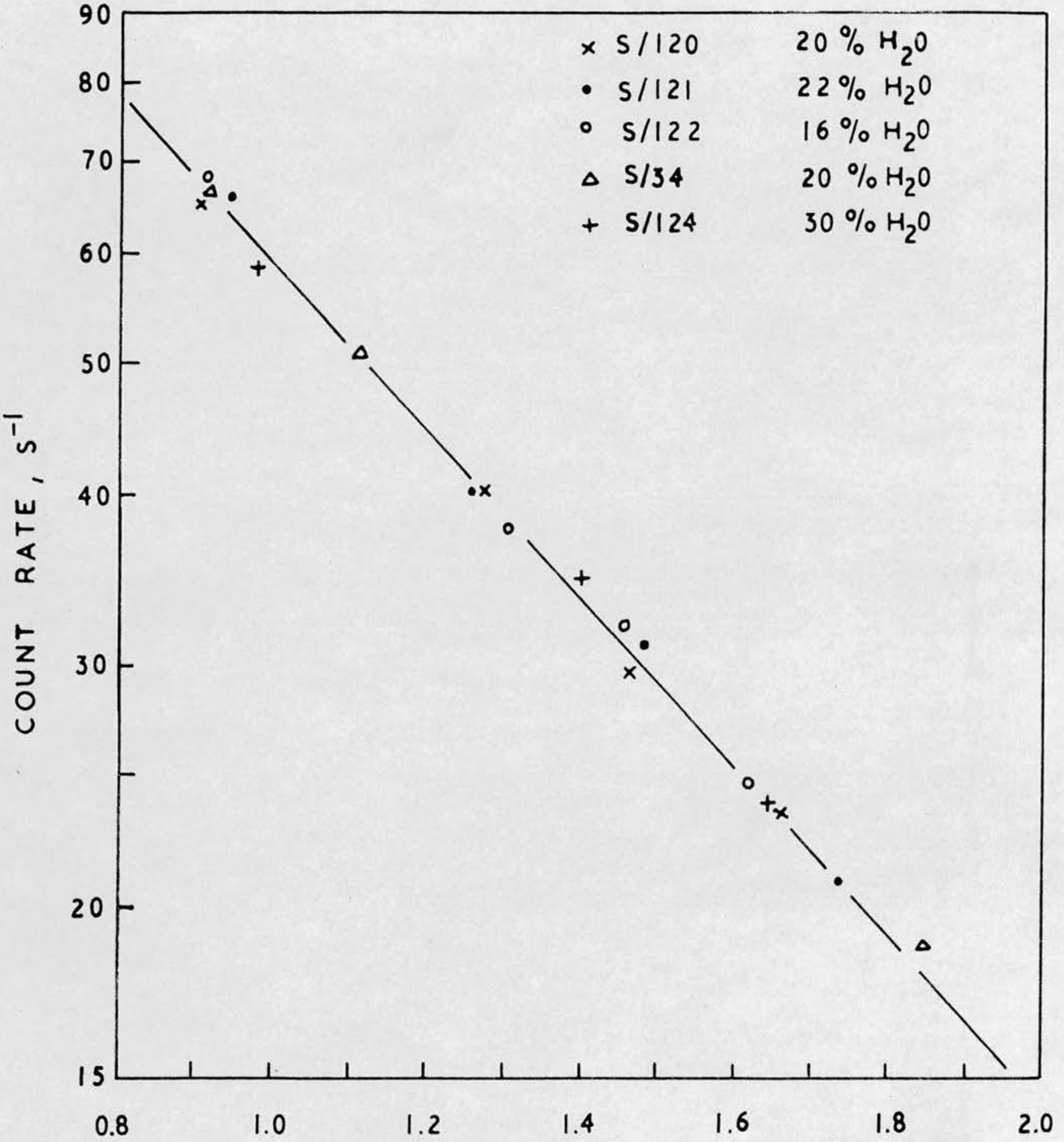

Fig. 9.9 The effect of wet bulk density on count rate for five soils (MX146 detector, 5 mCi Cs-137 source)

medium or heavy tamping to give a range of bulk densities for each moisture content. A spacer plate was used to ensure that the polyorc access tubes were maintained at the correct distance during filling operations. After filling, the box and contents were weighed and a value for the wet bulk density calculated. Standard exposure tests using a cement-filled box[*] were taken before and after count-rate measurements on each box. With type B boxes readings of the time required to collect 10 000 counts were made at 2.5 - 12.5 cm (9 positions) below the surface. A mean counting time was calculated for each sample, T_t, and this value was divided by the mean standard-exposure counting time, T_s. $\text{Log}_{10}\, T_t/T_s$ was then plotted against wet bulk density. The results obtained with type B boxes are shown in Fig. 9.10. Fig. 9.11 shows the results obtained with both type A and type B boxes.

The results shown in Figs 9.10 and 9.11 were subjected to a number of multiple linear regression tests[**] using the model equation

$$\log_{10} T_t/T_s = A + B_1\, D_{bw} + B_2\, (D_{bw})^2 + B_3\, (D_{bw})^3 + B_4\, M + B_5\, (Si + C) \quad (9.7)$$

where B_1 to B_5 are regression coefficients, M is the moisture content, % w/w, and (Si + C) is the silt plus clay content, %. The terms $(D_{bw})^2$ and $(D_{bw})^3$ were included in order to test for any non-linear effect while M and (Si + C) were added in order to test whether any of the variation about the simple linear relationship could be accounted for by the moisture content or the soil texture. The latter would serve as an indication of possible influence of chemical composition. Various combinations of the five dependent variables were tested by regression analysis and the results shown in Table 9.4a and 9.4b.

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[*] See Section 10.1 for details

[**] Programme IAE 001/0014

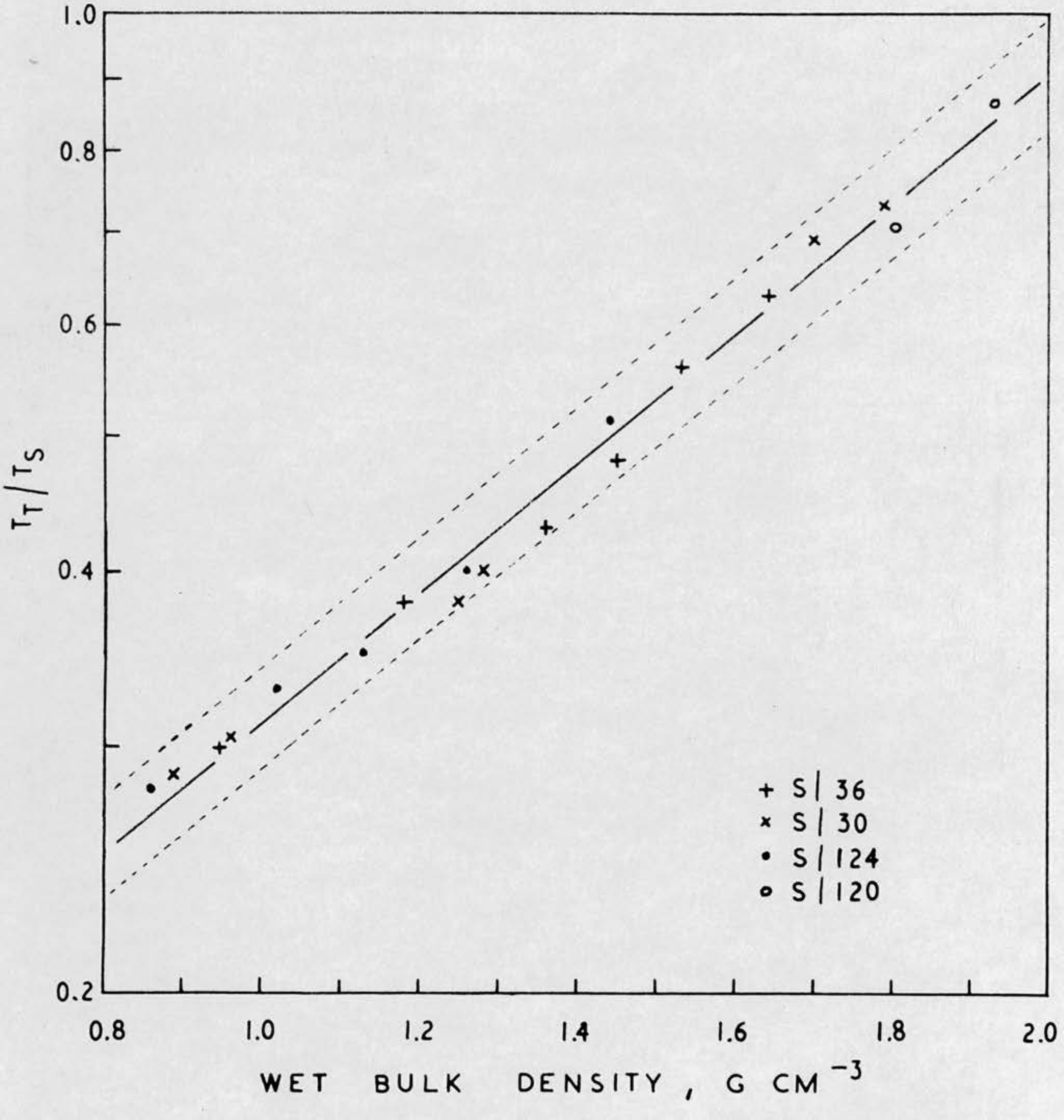

Fig. 9.10 The effect of wet bulk density on $\log_{10} T_t/T_s$ for four soils at various moisture contents contained in type B boxes with 95% confidence limits (MX146 detector, 30 mCi Cs-137)

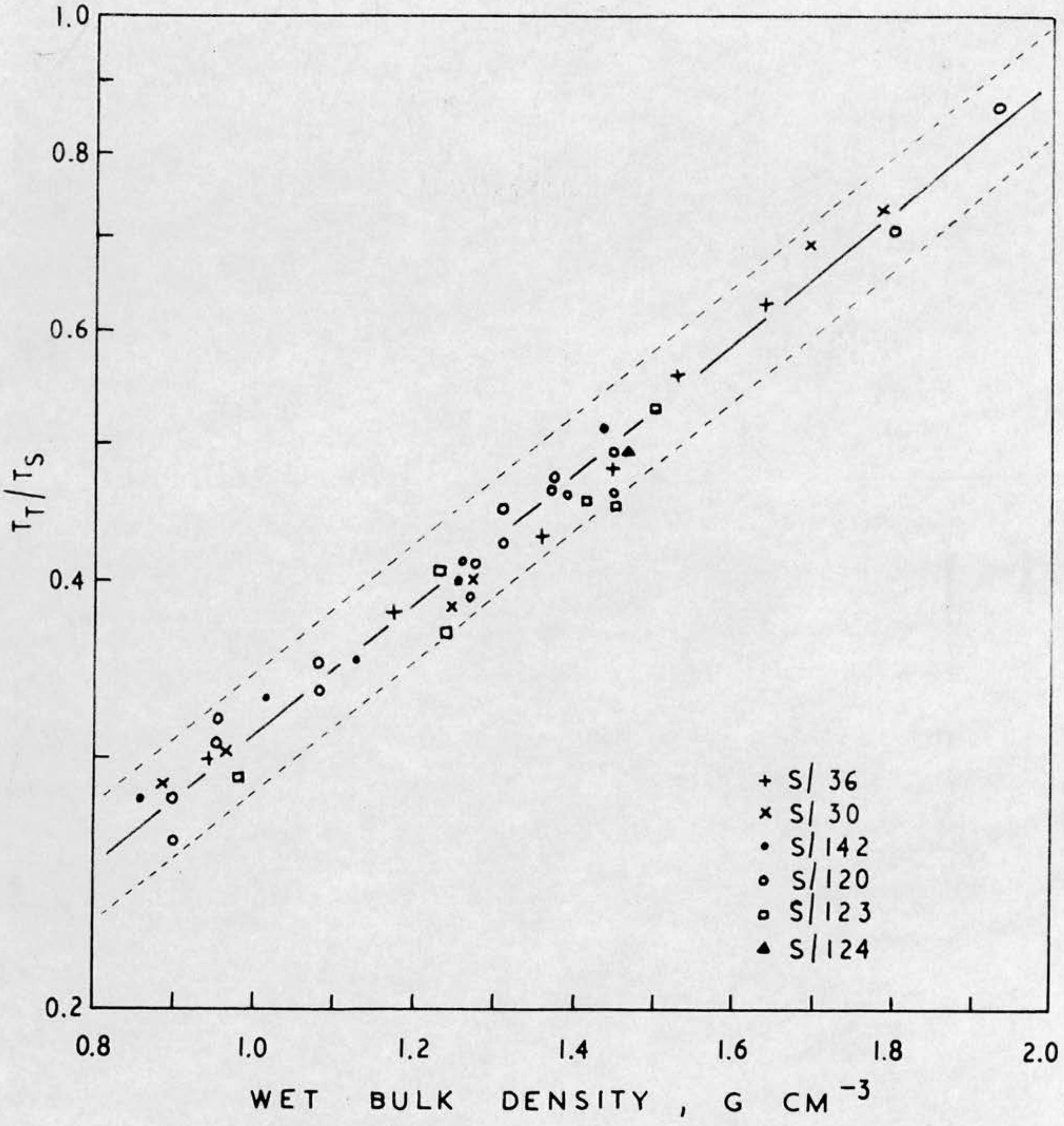

Fig. 9.11 The effect of wet bulk density on $\log_{10} T_t/T_s$ for six soils at various moisture contents contained in type A and B boxes with 95% confidence limits (MX146 detector, 30 mCi Cs-137 source)

TABLE 9.4a

Results of simple regression analysis of calibration tests with MX 146 detector and 30 mCi Cs-137 source

Container	Wooden Box Type A	Wooden Box Type A + B	Wooden Box Type B	Metal Box (Planar access)
No. Tests	8	41	19	27
Soils (No.)	S/120 (8)	S/30 (6) S/36 (6) S/142 (5) S/120 (18) S/123 (6)	S/30 (6) S/36 (6) S/142 (5) S/120 (2)	S/120 (10) S/124 (9)
A	- 0.9684	- 0.9625	- 0.9638	- 1.0049
S.E. (A)	0.0522	0.0150	0.0175	0.0247
B (D_{bw})	0.4550	0.4547	0.4591	0.5438
S.E. (B)	0.0424	0.0114	0.0127	0.0181
T (B)	10.72	39.75	36.02	30.14
R^2 x 100	95.05	97.59	98.71	97.32

TABLE 9.4b

Results of multiple regression analysis of calibration tests with MX 146 detector and 30 mCi Cs-137 source

Container	Wooden Box Type A + B	Wooden Box Type B
No. Tests	41	19
Soils (No.)	S/30 (6) S/36 (6) S/142 (5) S/120 (18) S/123 (6)	S/30 (6) S/36 (6) S/142 (5) S/120 (2)
A	- 0.9525	- 0.9450
S.E. (A)	0.0176	0.0185
B (D_{bw})	0.4441	0.4353
S.E. (B)	0.0130	0.0137
T (B)	34.07	31.87
B (Si + C)	- 0.000129	- 0.000196
S.E. (B)	0.000148	0.000142
T (B)	0.87	1.38
B (M)	0.000602	- 0.00129
S.E. (B)	0.000353	0.00040
T (B)	1.70	3.22
R^2 x 100	97.77	99.26

(d) Tests with 30 mCi Cs-137 source and samples in metal calibration boxes with planar access

These calibration tests were made in the same way as those described in (c) except that the probes were placed on the outside of a metal box to simulate the geometry with planar access. The dimensions of the box were 26.2 cm length (outside), 26.0 cm length (inside), 15.0 cm depth, 15.0 cm width. The probes were pressed against the sides of the box as in planar access tests in the field. Samples of soil-water mixtures were packed into the metal calibration boxes to give different bulk densities and measurements were taken at different depths as in (c). Standard counting times were obtained with the standard concrete-exposure test before and after measurements on each sample. The values for T_t/T_s obtained are plotted as a function of wet bulk density in Fig. 9.12. The corresponding regression constants and their standard errors are shown in Table 9.4a.

9.5 Precision of calibration

There seems to be no consistency in the literature concerning the reporting of the precision of calibration relations. Certain workers such as Harland and Urkan (1966) used a "root mean square density displacement from the best straight line" and obtained a value of 0.016 g cm^{-3} for a "single probe" transmission system. This appears to be equivalent to a confidence limit at a probability of 68%. A more usual technique is to calculate confidence limits for the estimated dependent variable after obtaining the linear regression coefficients. This was done for the three regressions in which the 30 mCi Cs-137 source was tested. 95% confidence limits are shown in Figs 9.10, 9.11 and 9.12. In addition 68% confidence

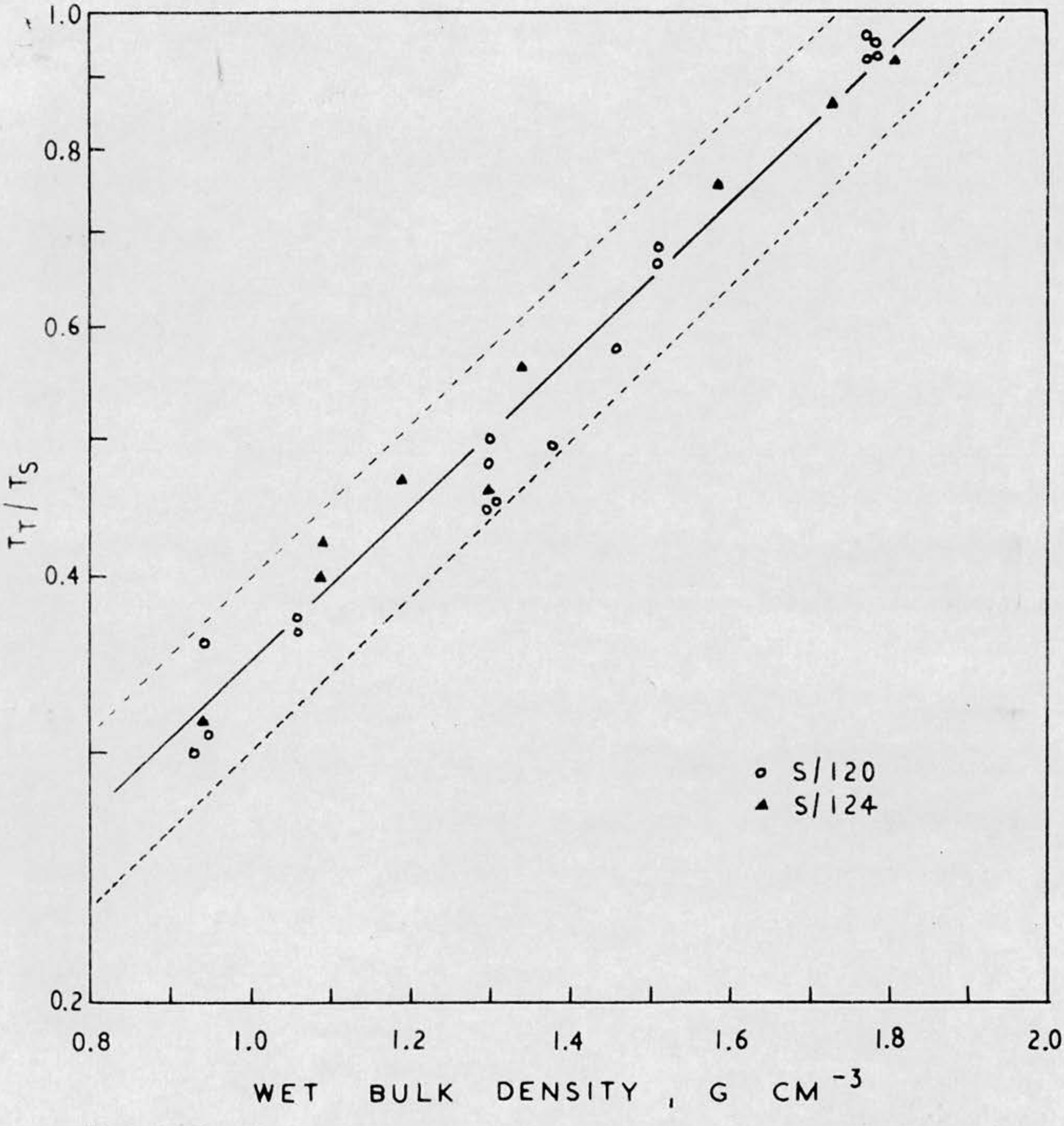

Fig. 9.12 The effect of wet bulk density on $\log_{10} T_t/T_s$ for two soils at various moisture contents using planar access boxes with 95% confidence limits (MX146 detector, 30 mCi Cs-137 source)

limits corresponding to $\hat{Y} \pm S_{\hat{Y}}$ were also calculated. Since the confidence limits for practical purposes are parallel to the regression line in this instance a single value for the possible variation in wet bulk density can be calculated from the confidence limits. The values for the 68% confidence limits were 0.04 g cm^{-3} for the results shown in Fig. 9.10 and Fig. 9.11 and 0.05 g cm^{-3} for Fig. 9.12. Calculations for these confidence limits are shown in Appendix 2.8.

CHAPTER 10

LABORATORY STUDIES WITH SCINTILLATION DETECTOR

10.1 Objective

The work described in this section was undertaken to examine to what extent improvements in performance could be obtained with a sodium iodide crystal scintillation detector in a non-collimated system. Particular attention was to be given to the problems of stability and vertical resolution. The former factor was suspected to be low under field conditions and to limit the application of this type of detector while the latter factor potentially offers a considerable advantage over a GM tube detector. It was therefore necessary to examine these factors critically and to balance the benefit of one against the disadvantage of the other.

10.2 Warm-up and ambient temperature effects

The functioning of the photomultiplier is a function of the e.h.t. voltage and it is important to establish the period required after switching on before reproducible results can be obtained. A simple way of checking this is to obtain repetitive readings from the time of switching on. The results of one such test are shown in Fig. 10.1. The warm-up period under these conditions was approximately 4 h. A somewhat disturbing feature was noticed. An irregular variation above and below the mean value occurred after the initial warm-up effect. This variation of count rate was greater than could be accounted for by random fluctuation of emission from the source. Some variation of temperature had occurred in the laboratory in this period and two further series of readings were obtained during which large fluctuations in laboratory air temperature were introduced by additional heating. These tests were made after an initial period of

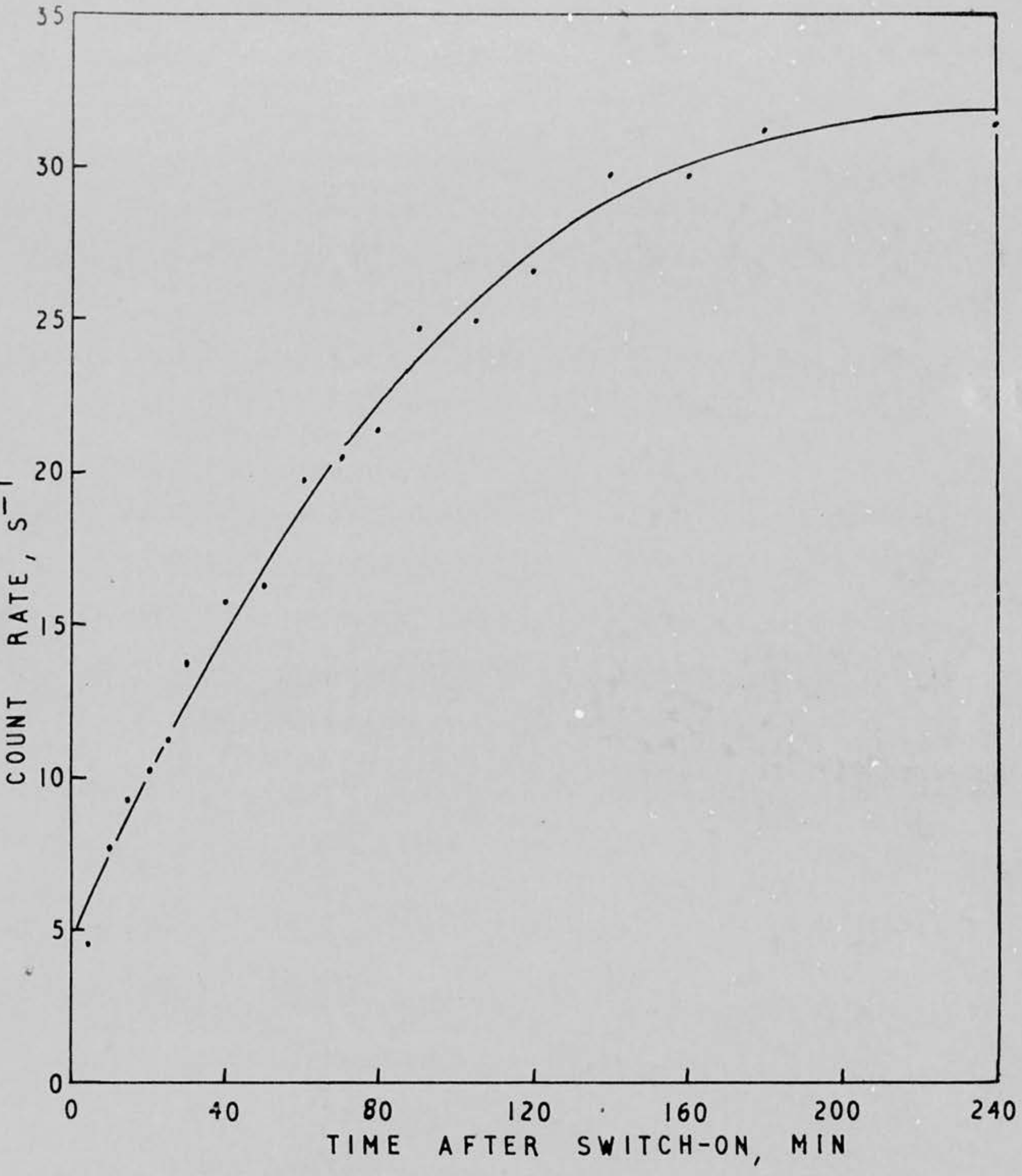

Fig. 10.1 The increase of count rate with time after switch-on (NaI detector)

5 h at uniform temperature. The results are shown in Figs 10.2 and 10.3. The results of the two runs were similar but there are some important differences in detail. Firstly, for the results shown in Fig. 10.2 some of the variation in individual count rate results can be attributed to a drift in threshold voltage which was found to occur during periods when the air temperature was changing rapidly. For the second run shown in Fig. 10.3 the threshold setting was watched carefully and corrections applied as soon as any deviation from 4.2 V could be detected.

The second run provides a more striking illustration of the effect of air temperature on count rate since the heating and cooling phases occurred more abruptly. The results are arranged in Fig. 10.3 to show the difference between the heating and cooling phases. The reason for this difference is not obvious but the following observations appear to be relevant.

(1) A steady rise in count rate occurred during the period 3 to 5 h after switching on. This suggests that the warm-up effect which, on the basis of the results shown in Fig. 10.1, had been thought to be complete within 4 h after switch-on, in fact was still continuing up to and presumably after 5 h. This difference in performance between runs could well be due to differences in air temperatures on the two days.

(2) If the warm-up effect found during the period 3 to 5 h after switch-on is extrapolated to 8 h after switch-on the line reaches the actual count obtained at this time. Since the temperature, by that time had dropped to the same value that it was during the 3 to 5 h after switch-on, it seems possible that a steady climb in count

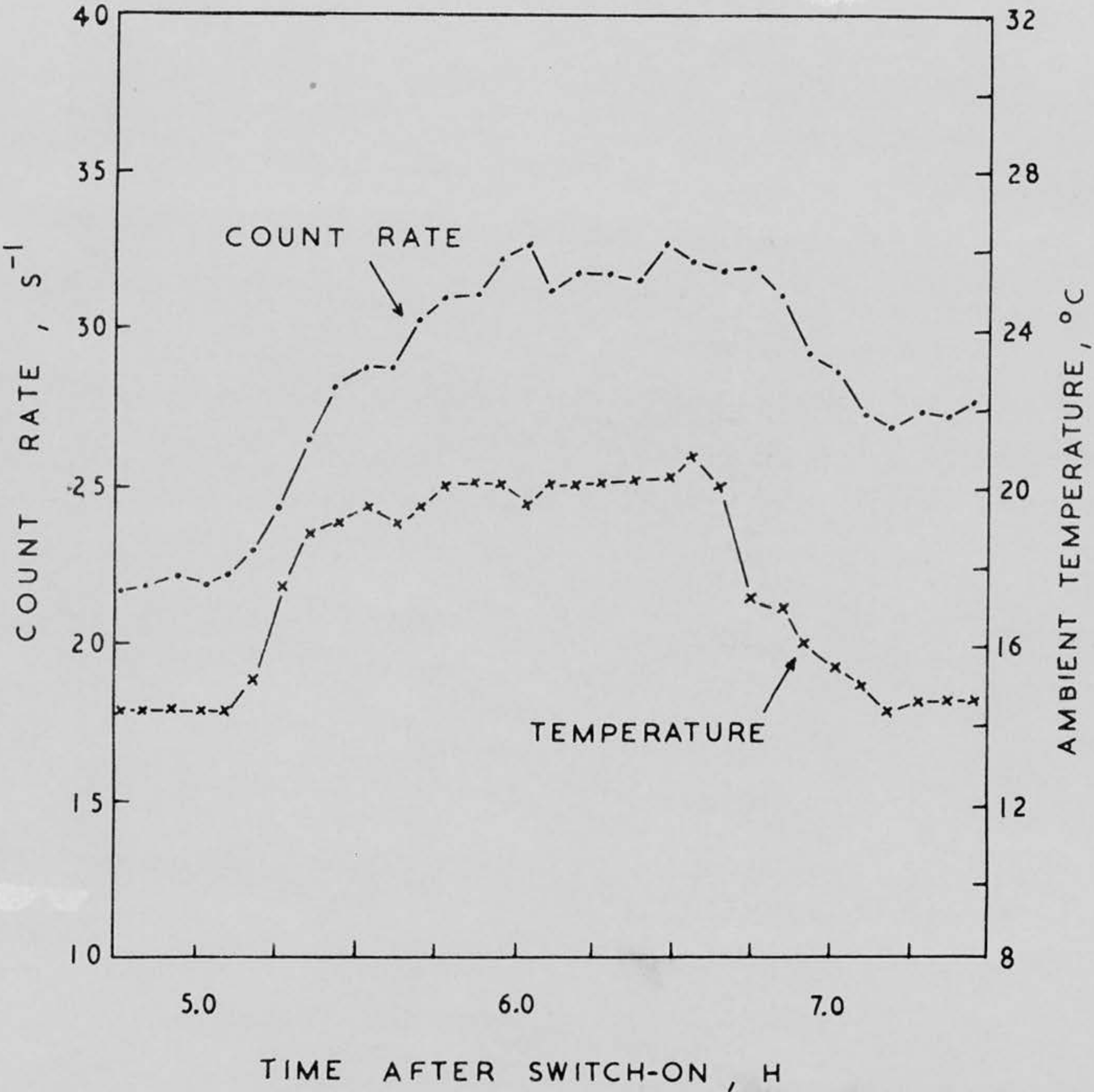

Fig. 10.2 The relation between count rate and ambient temperature at different times after switch-on (NaI detector)

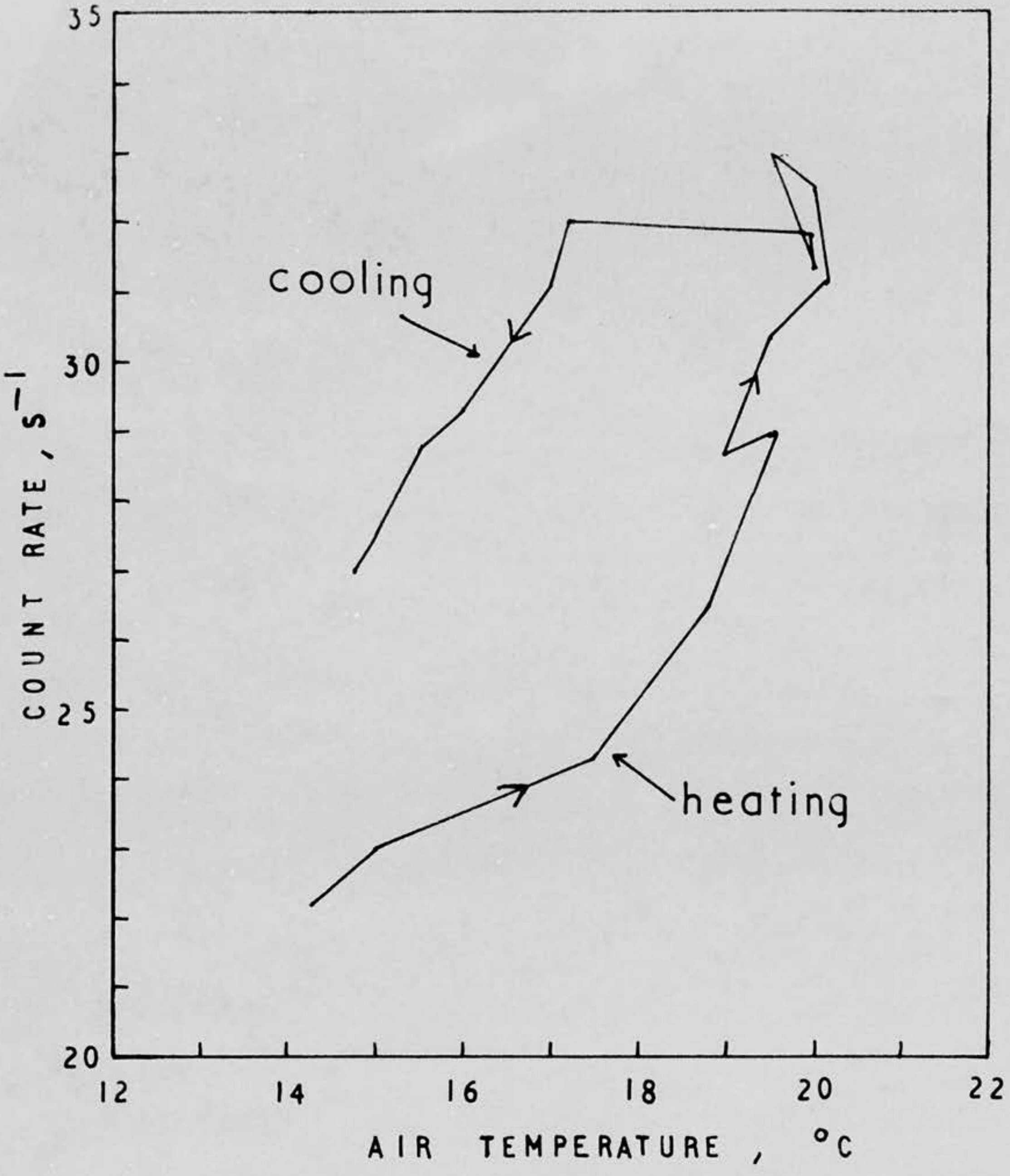

Fig. 10.3 The influence of heating and cooling of air surrounding NaI detector/photomultiplier assembly on count rate

rate would have occurred without any change in air temperature. This effect may be the explanation of the difference in count-rate behaviour during the warming and cooling phases as shown in Fig. 10.3.

(3) The following tentative hypotheses are put forward for confirmation:

(a) The length of time required to reach a stable count rate increases as the air temperature decreases,

(b) The stable count rate increases as air temperature increases,

(c) A rise in air temperature results in an immediate rise in count rate suggesting that the effect is more likely to be associated with the power supply or pulse-height analyser rather than with the PM tube since the thermal lagging effect of the evacuated PM tube would preclude any sudden response to changes in ambient temperature.

Numerous other tests were made in which the effect of temperature on various parts of the system were examined. It was found that the e.h.t. voltage, the threshold voltage and the detector/PM tube/pre-amplifier assembly were all, independently, sensitive to temperature and it was therefore concluded that in its present form the equipment was unsuited to operation under anything but isothermal laboratory conditions. The addition of a thermistor to the pre-amplifier was tried in an attempt to counterbalance temperature effects and a certain degree of improvement was obtained over a limited range. However the instability of the e.h.t. supply still appeared to represent a serious weakness in the equipment. A variation of approximately 40 V was measured when the ambient temperature varied in the range 0 - 20°C. The following sections 10.3, 10.4, and 10.5

describe work carried out in the laboratory under near-constant temperature conditions.

10.3 Vertical resolution

(a) Transmission parallel to liquid interfaces

The source and detector probes were lowered through a three phase system, air/kerosene/water. The count rate was determined at 1.25 cm increments of depth except in the vicinity of the interface when readings were obtained at 0.32 cm intervals. The results, shown in Fig. 10.4, demonstrate that the transition from the normal count rate in one medium to that in adjacent medium occurs in a vertical distance of between 0.63 and 1.27 cm. Since the vertical height of the detector and source are 0.63 cm and 0.51 cm respectively it appears that the vertical resolution of the method is approaching the theoretical limit and is within the expected performance of the instrument. These results were obtained using an aperture of 0.2 V set at the peak position of 6.7 V on the threshold scale. The sodium iodide detector was also used in the vertical resolution test considered in section 9.2 in which performance was compared with a small GM tube and a backscatter system.

10.4 Calibration tests with simple materials

(a) Steel (single setting)

Steel plates (0.635 cm thick) were arranged so that the transmission beam passed through them at right angles to the plane of the plates. By using different numbers of plates effective densities between 0.56 and 2.44 g cm^{-3} could be obtained. The pulse-height analyser was set so that only Cs-137 unattenuated gamma photons would be counted. The logarithm of the count rate was then plotted against density as shown in Fig. 10.5. The

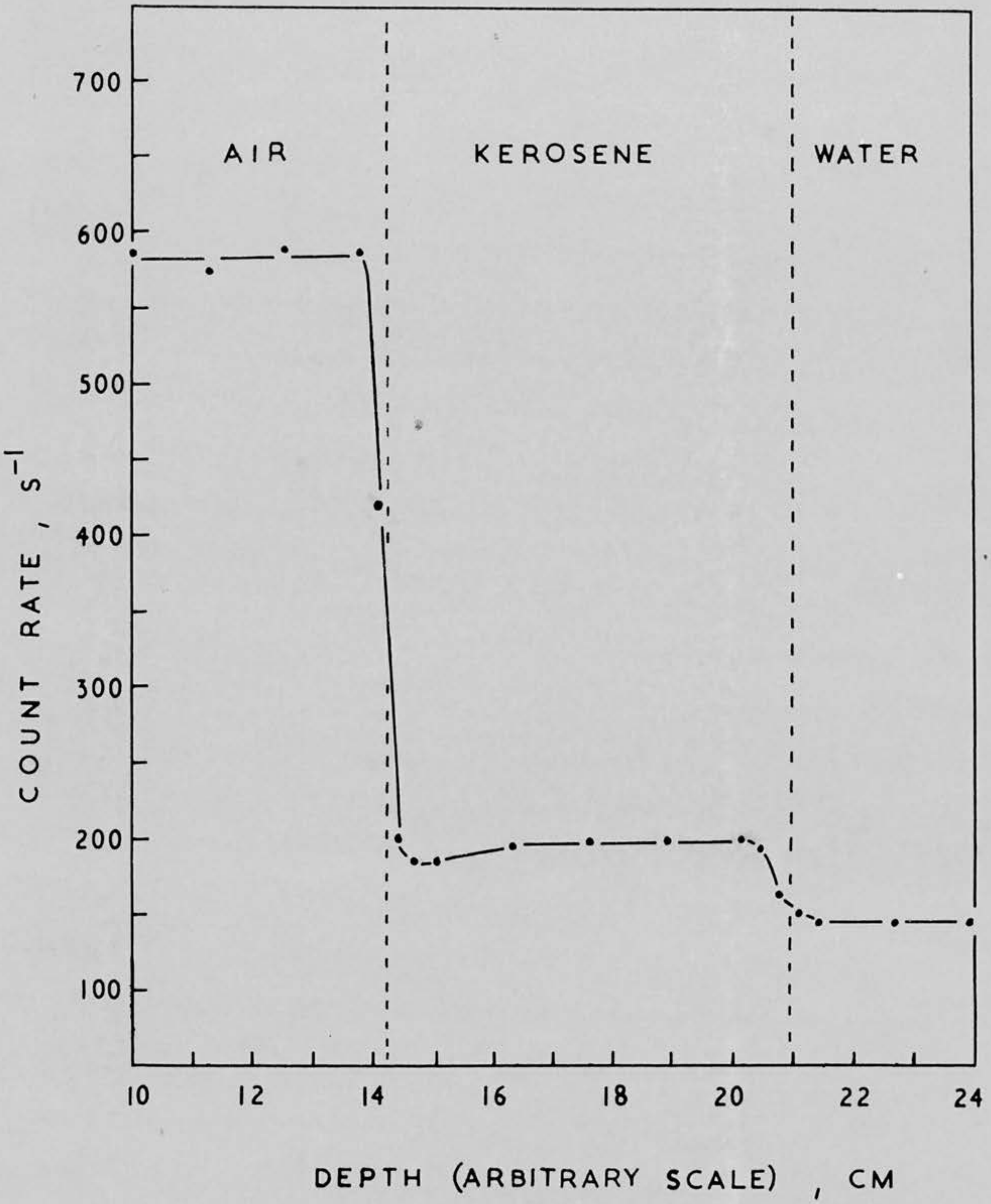

Fig. 10.4 The variation of count rate for gamma-ray transmission parallel to liquid interfaces (NaI detector, aperture 0.2V)

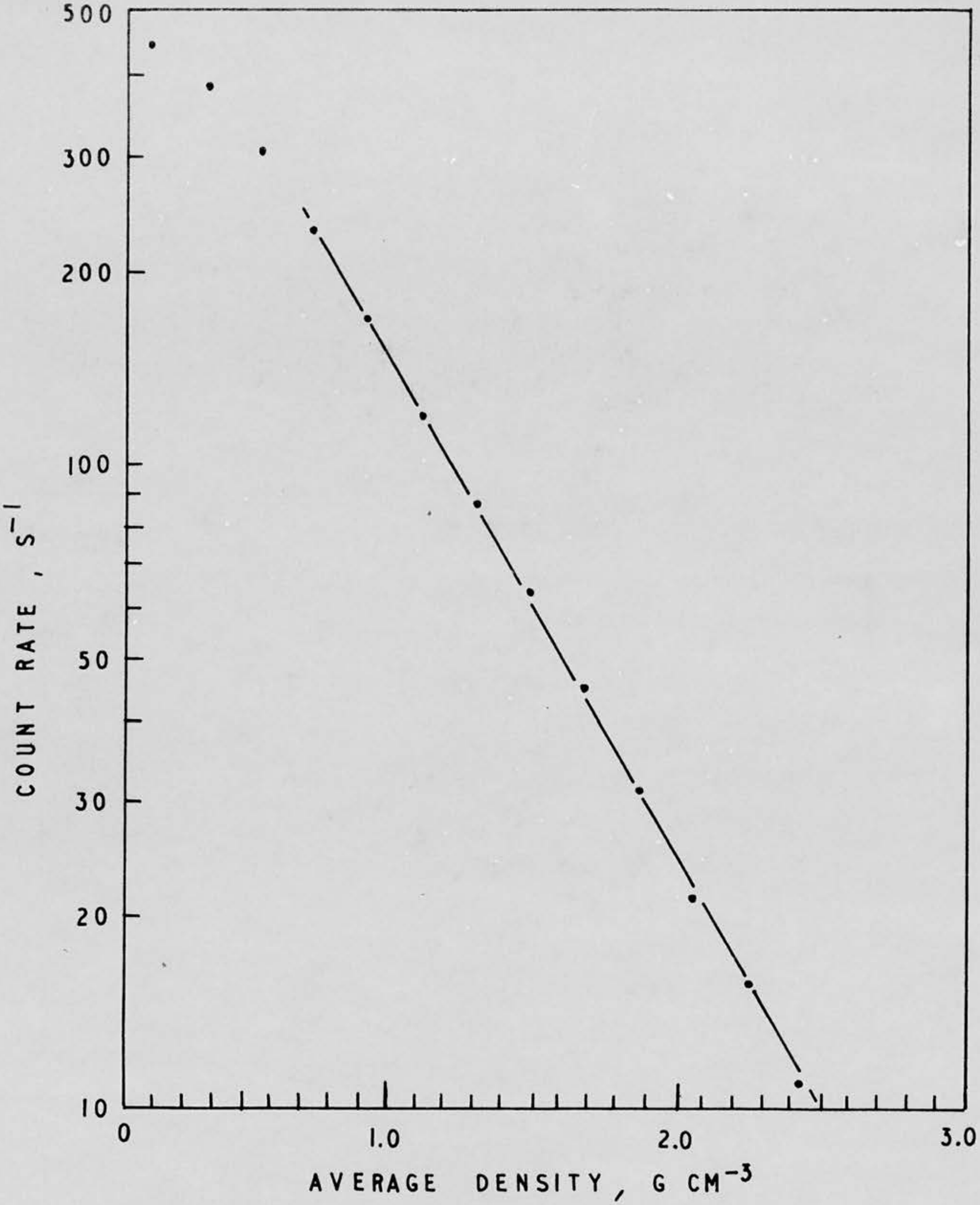

Fig 10.5 The relation between the effective density of steel and count rate (NaI detector)

straight line predicted by transmission theory was obtained within the density range from 0.7 to 2.4 g cm^{-3} corresponding to count rates of approximately 220 and 11 s^{-1} respectively. At count rates above about 250 s^{-1} there was a progressive falling away from the linear relationship established at lower count rates. This might be due to a limitation in pulse handling rate in the pulse-height analyser since a very much higher total count will be handled than that recorded by the scaler. However it was noticed with the calibration of the GM tube that a falling off of count rate occurred above about 250 s^{-1} so it may be that it is the counting rate of the scaler which is becoming limiting. Since the average density of soil material to be tested by this method will probably not be below 0.7 g cm^{-3} the fall of counting rate at low densities does not appear to represent a disadvantage.

(b) Steel: Effect of different discrimination settings on calibration relation

A further set of measurements was made using steel plates and comparisons made with different discriminator settings. The results are shown in Fig. 10.6. Linear regression analysis was used to determine the slope of each line after those data which were obviously departing from the linear relationship at low density values had been excluded. The results are shown in Table 10.1.

TABLE 10.1

Linear absorption coefficient values for steel related to threshold and aperture settings

Aperture V	Threshold V	Threshold to Peak Relation	Linear Absorption Coefficient cm^{-1}	I_o s^{-1}
0.2	4.15	Peak	0.484	367
Max	3.95	-0.2 V	0.495	1007
Max	4.15	Peak	0.496	799
Max	4.35	+0.2 V	0.518	529

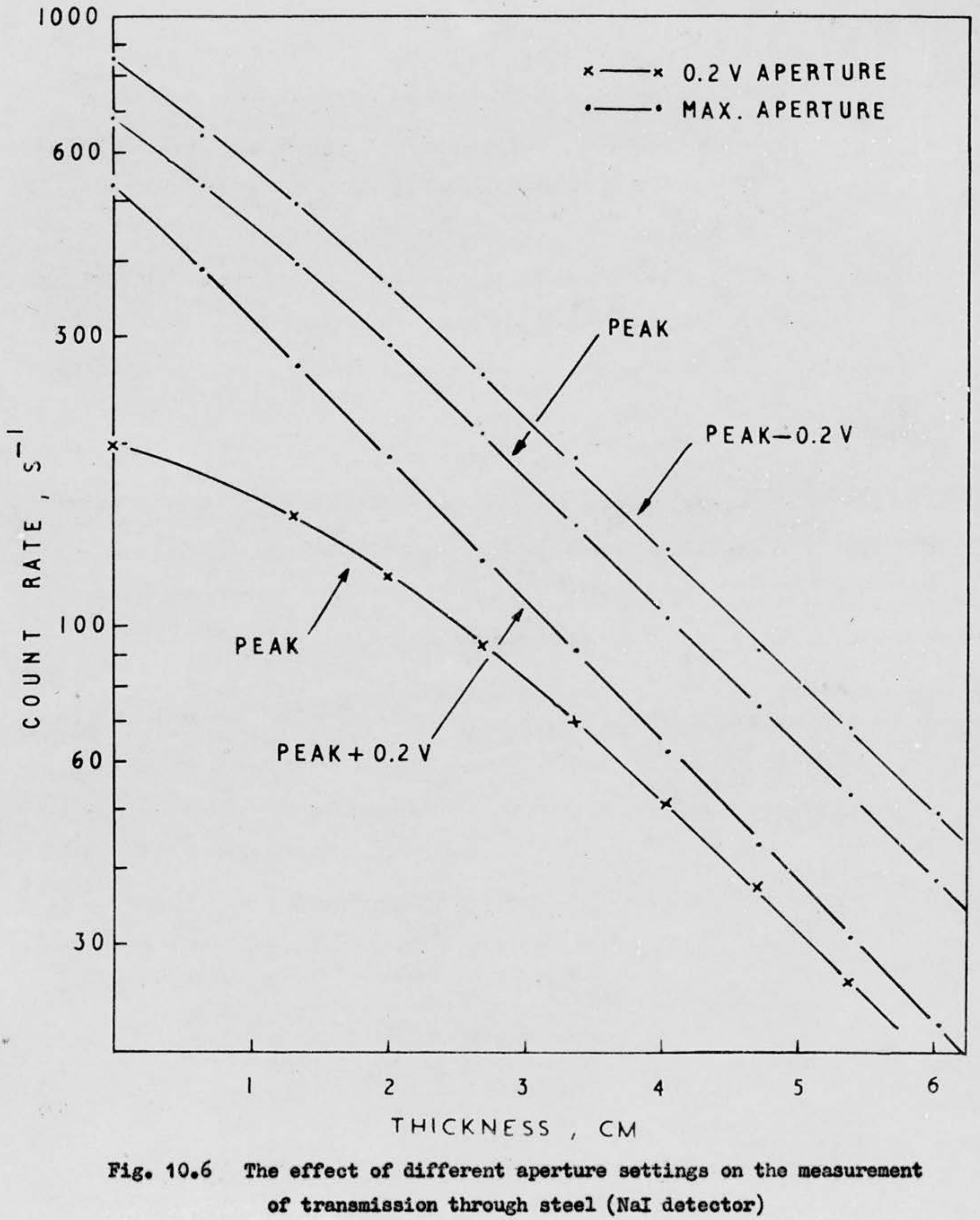

Fig. 10.6 The effect of different aperture settings on the measurement of transmission through steel (NaI detector)

The linear absorption values can be compared with that obtained by Grodstein (1957) by theoretical calculation for pure iron of approximately 0.577 cm^{-1} for Cs-137 radiation (0.66 MeV). The determined values are in fairly close agreement for the different settings and show an increase with increased threshold value. This is presumably due to an improved exclusion of slightly down-graded photons occurring in the photopeak. Owing to impurities in the steel a rigorous comparison between determined and theoretical coefficient value is not possible. The maximum permissible counting rate with a 0.2 V aperture would appear to be about 80 s^{-1} whereas counting rates up to 350 s^{-1} appear to be acceptable without loss when the maximum aperture is used.

(c) Glass: Effect of different discrimination settings on calibration relation

The same tests made with steel were repeated using glass 5 x 5 cm slides, after careful measurement of the thickness of each slide. The density of the glass was measured and found to be 2.506 g cm^{-3}. The results obtained with different operating settings are shown in Fig. 10.7. The linear absorption coefficients and count rate for zero sample thickness were calculated by regression analysis and are shown in Table 10.2.

TABLE 10.2

Linear absorption coefficient values for glass related to threshold and aperture settings

Aperture V	Threshold V	Threshold to Peak Relation	Linear Absorption Coefficient cm^{-1}	I_o s^{-1}	Date ref:
0.2	3.00	Peak	0.1637	195	15.11.65
Max	3.95	-0.2 V	0.1644	964	7. 2.66
Max	4.15	Peak	0.1644	751	7. 2.66
Max	4.35	+0.2 V	0.1694	486	7. 2.66

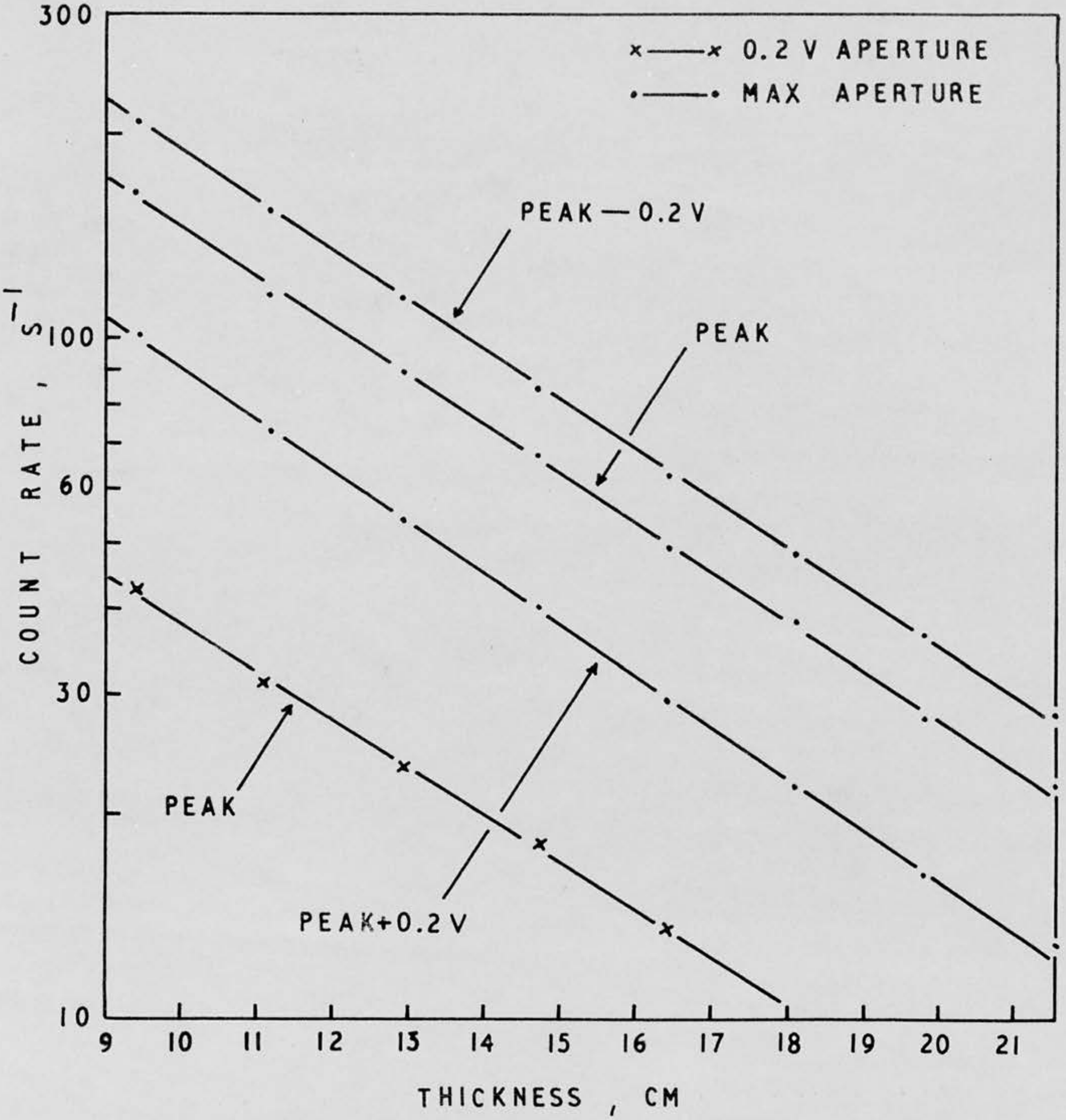

Fig. 10.7 The effect of different aperture settings on the measurement of transmission through glass (NaI detector)

The linear absorption coefficient values show good agreement, with the small variation following a similar pattern to that found with steel. The I_o values for glass are similar to but consistently lower than those for steel. For the maximum aperture settings, the differences are 43, 48 and 43 s^{-1} respectively suggesting a common effect lowering counting rates during the counting periods for glass. However the I_o values for the 0.2 V aperture readings differ markedly for the two materials. This is attributable to different performance conditions of the pulse height analyser with a considerable difference in amplifier gain as shown by the differences in peak threshold voltage on 15.11.65 and 7.2.66 respectively. This gain difference has had no effect on the linear absorption coefficients determined on the two dates.

No theoretical values for the linear absorption coefficient of glass are available for comparison with the above experimental values but it is of interest that

$$\frac{\mu \text{ steel}}{\mu \text{ glass}} \text{ (determined)} = \frac{\text{density steel}}{\text{density glass}} \text{ (determined)} = 3.1$$

(d) Water: Effect of different discrimination settings on calibration relation

A brass open-ended slotted tray with compartments made from 5 x 5 cm glass slide covers was used to measure the linear absorption coefficient of water. Twenty compartments were available each 1.184 cm in width and 20 000 counts were collected for each thickness of water. A variety of threshold and aperture settings were used in order to examine what effect these had on the determined linear absorption coefficient. The results obtained are shown in Fig. 10.8 and the calculated linear absorption

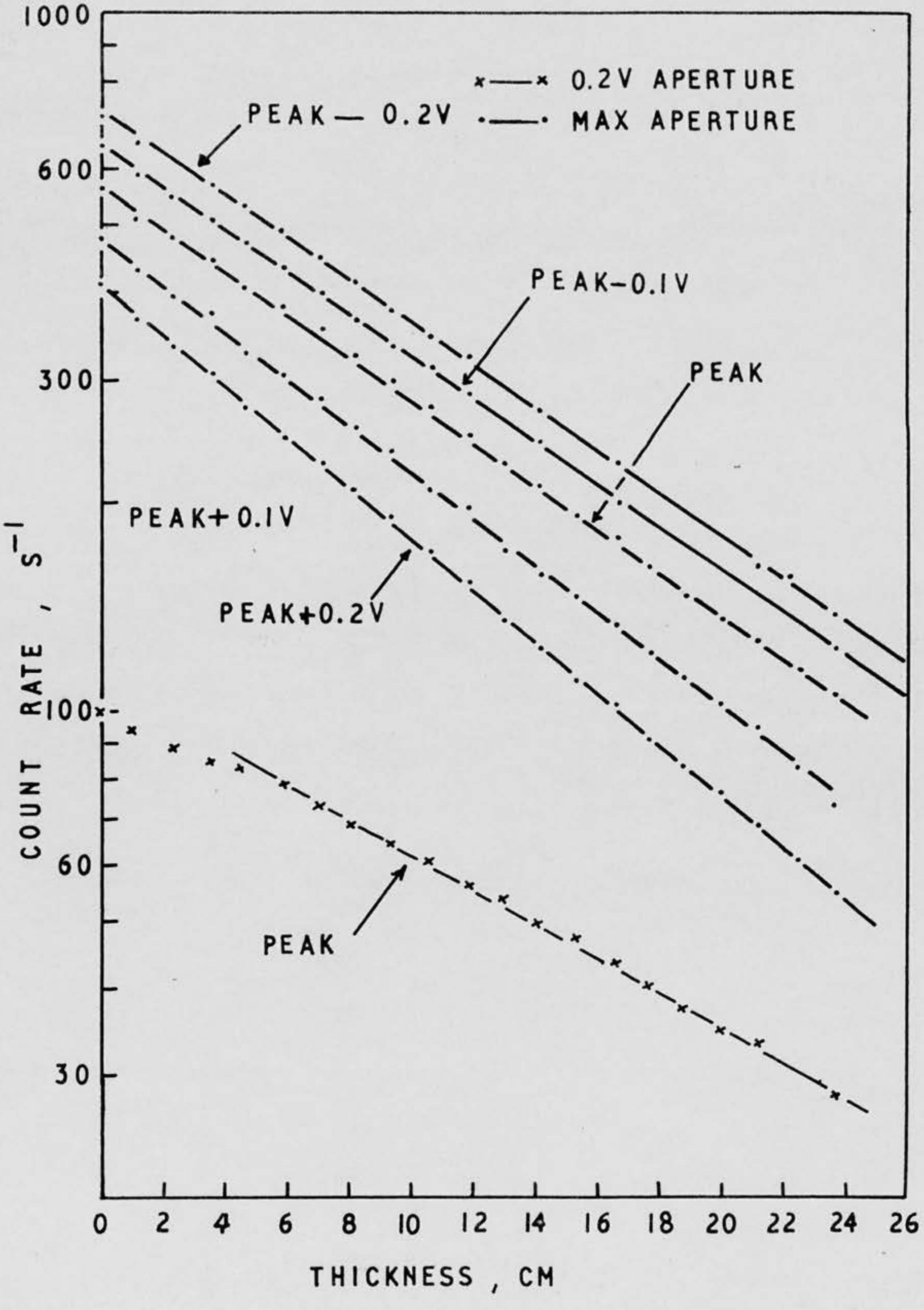

Fig. 10.8 The effect of different aperture settings on the measurement of transmission through water (NaI detector)

coefficient values are shown in Table 10.3.

TABLE 10.3

Linear absorption coefficient values for water related to threshold and aperture settings

Aperture V	Threshold V	Threshold to Peak Relation	Linear Absorption Coefficient cm^{-1}
0.2	4.4	+0.2 V	0.0564
Max	4.0	-0.2 V	0.0705
Max	4.1	-0.1 V	0.0702
Max	4.2	Peak	0.0713
Max	4.3	+0.1 V	0.0745
Max	4.4	+0.2 V	0.0842

The results obtained can be compared with those reported by other workers and summarised in Table 6.1. Because the density of water at normal temperature is virtually unity there is no significant difference between the linear-and mass-absorption coefficients for water. It appears that the selection of a threshold setting above the peak with a maximum aperture results in a progressive improvement in the linear absorption coefficient value, which at Peak + 0.2 V, very closely approaches the Grodstein (1957) value. This improvement is presumably due to the elimination of photons which have been only slightly reduced in energy and which were therefore being incorrectly included when the threshold was set at or below the peak value.

(e) Effect of aperture and threshold setting on sensitivity to change of sample density

A series of tests was made to investigate changes in sensitivity with a wide range of threshold setting relative to peak voltage at both 0.2 V and maximum aperture settings. Sensitivity was expressed as the ratio of the count rate for equal length samples of wood (density 0.82 g cm^{-3}) and magnesium (density 1.74 g cm^{-3}). The results are shown in Table 10.4.

TABLE 10.4

The effect of threshold setting on sensitivity to change in sample density at 0.2 V and maximum apertures

Threshold to Peak Relation V	0.2 V Aperture			Maximum Aperture		
	Count rate, s^{-1}		Sensitivity	Count rate, s^{-1}		Sensitivity
	Wood	Magnesium	$\frac{\text{Wood}}{\text{Magnesium}}$	Wood	Magnesium	$\frac{\text{Wood}}{\text{Magnesium}}$
- 0.8	85.3	16.9	5.05	521	86.5	6.02
- 0.7	78.9	14.6	5.40	475	80.8	5.88
- 0.6	77.2	13.6	5.68	461	74.6	6.18
- 0.5	75.9	12.5	6.07	435	68.5	6.35
- 0.4	79.4	12.4	6.40	406	61.7	6.58
- 0.3	80.4	12.2	6.57	379	56.6	6.70
- 0.2	93.3	14.3	6.51	349	52.2	6.68
- 0.1	104.2	16.0	6.49	315	46.8	6.73
Peak	108.0	18.0	6.02	286	42.2	6.77
+ 0.1	103.7	17.9	5.80	246	34.3	7.17
+ 0.2	84.4	14.8	5.72	196	27.9	7.01

The results show that, at all threshold settings tested, sensitivity was higher for a maximum aperture than for 0.2 V aperture. For a 0.2 V aperture the sensitivity was greatest (6.57) with a threshold setting at 0.3 V below the peak voltage whereas, for the maximum aperture, sensitivity was highest (7.17) at a threshold 0.1 above the peak. The use of maximum aperture can therefore be accepted for use with a mono-energetic photon source on grounds of both higher count rate and higher sensitivity. The most appropriate threshold would seem to be at or slightly above the peak voltage.

10.5 Calibration tests with soil-water mixtures

A fine grain sand (S/36) was used in these tests. Samples were prepared at approximately 5% and 14% water content by weight. The samples were packed into type A boxes with differing degrees of tamping to give a range of densities. 20 000 counts were collected at nine depths in each box and the mean wet bulk density was obtained by weighing the box before and after filling and dividing by its volume. A block of wood (density 0.82 g cm^{-3}) was used as a standard for these tests. Sample/wood standard count-rate ratios were calculated for each sample and the results are plotted in Fig. 10.9. Since no dependence on water content could be observed, a single value of mass-absorption coefficient for the soil-water mixtures was calculated by regression analysis. The computed value for μ was 0.0654 ± 0.0034 cm^2g^{-1}. The computed value of I_o was 820 ± 85 s^{-1}. This value of mass-absorption coefficient can be compared with those reported in the literature and assembled in Table 6.1 of Section 6.1.4.

The experimental value is within the range of results reported by Van Bavel <u>et al</u>. (1957) (0.0624 - 0.0676 cm^2g^{-1}) in which no collimation was used.

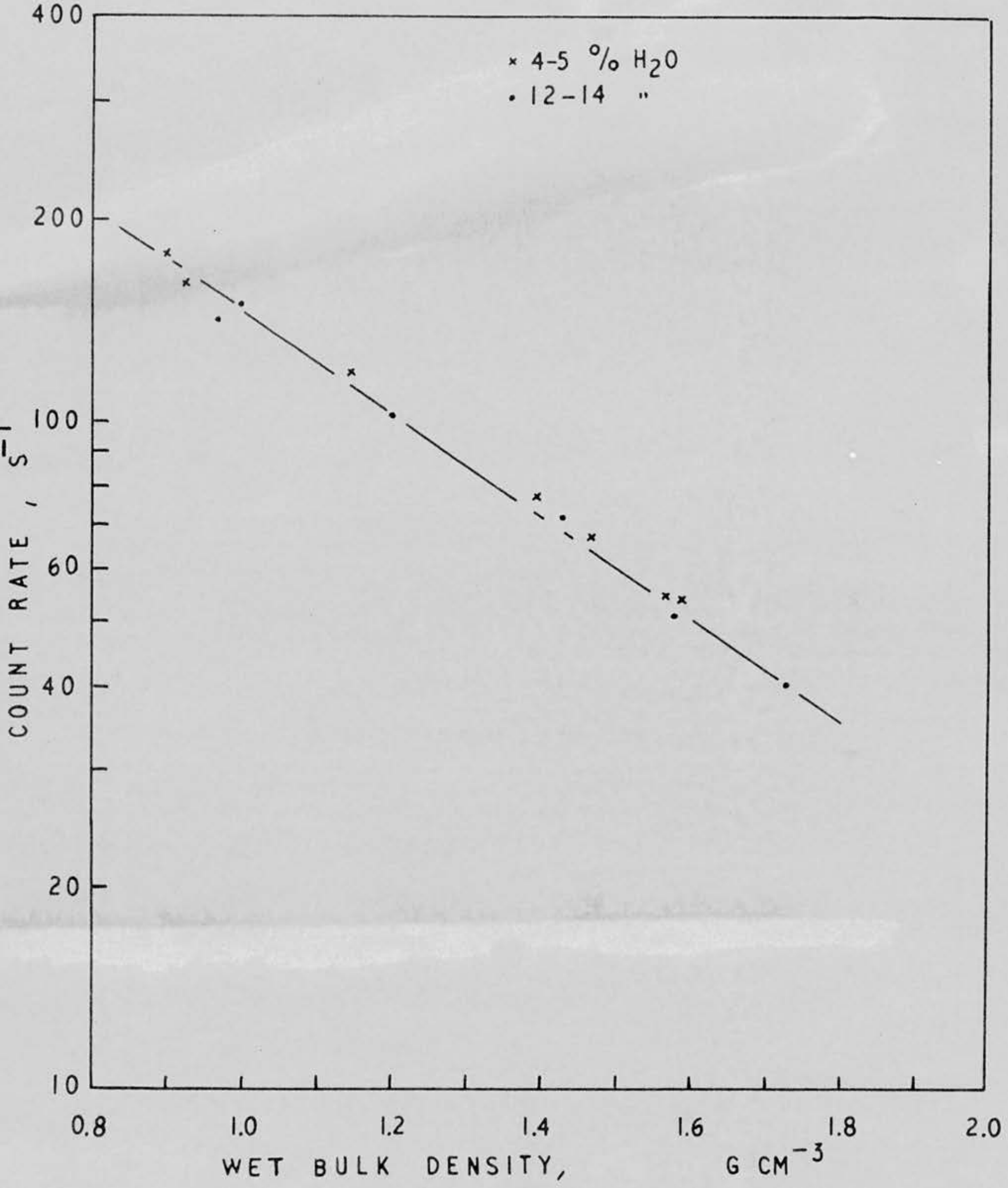

Fig. 10.9 The effect of wet bulk density of soil S/36 on count rate at two moisture contents (NaI detector, max. aperture at peak, 5 mCi Cs-137 source)

CHAPTER 11

FIELD STUDIES WITH GM DETECTOR

11.1 Stability under field conditions

In order to test the stability of performance of the counting equipment in the field a number of readings were obtained with a standard exposure. The standard exposure used in these tests was obtained by placing the probes with the active centre line 7.62 cm below the surface of a wooden box filled with an hydrated cement-sand mixture. The internal dimensions of the box were 10.2 cm wide x 12.7 cm deep x 40.6 cm long and two lengths of P.V.C. access tubing passed through the cement-sand mixture at 30.5 cm between centres. During tests the standard container was placed on a stool 43 cm above the ground surface in order to eliminate the possibility of variation in count rate due to differences in density of the material underlying the box.

Tests were made to examine the degree of variation obtained in the field using 64 standard exposure tests before and after soil-density measurements. 10 000 counts were collected in each case. The coefficient of variation should therefore be 1%. However a coefficient of variation of 1.73% was obtained and it was suspected that this increased degree of variation above the predicted level might have occurred as a result of disturbance in orientation of source and detector introduced by the movement of the equipment in the field. The influence of probe and control-frame movement on the standard exposure count variation was therefore tested. Repetitive measurements were made with and without intervening movement simulating the degree of disturbance and shock to which the equipment is subjected in the field. The measurements were repeated for 20 000, 10 000, 5 000 and 2 000 counts. The results are shown in Table 11.1. The effect of movement on variation was confirmed.

TABLE 11.1

The effect of control frame and probe movement and the number of counts collected on the precision of measurement of gamma-ray transmission with standard exposure

No. Counts	Movement	No. of Count periods	Time for count period			P	Coefficient of Variation		
			Mean s	Standard deviation s	Variance s^2		Measured %	Expected %	K
20 000	Yes	20	245.5	4.92	24.25	0.01	2.00	0.71	2.82
	No	20	242.0	1.72	2.94		0.71		1.00
10 000	Yes	16	121.0	2.17	4.73	0.01	1.80	1.00	1.80
	No	16	121.5	0.98	0.95		0.80		0.80
5 000	Yes	20	62.5	1.71	2.93	0.01	2.74	1.41	1.94
	No	20	59.9	0.83	0.69		1.38		0.98
2 000	Yes	20	24.9	0.57	0.33	0.05	2.30	2.24	1.03
	No	20	24.7	0.54	0.29		2.17		0.97

P = Probability that difference in variances is due to chance.

When movement between tests did not occur the K value, as defined in Eqn. (9.1), was very close to unity but, in those cases where movement occurred, the value is generally exceptionally high. It was suspected that the cause of the sensitivity to movement might be due to changes in the orientation of the source probe relative to the mid-line of the detector.

Changes were made in the source-probe location system and special precautions were taken to ensure that there was no backlash effect in the keyway. Following these changes a further set of 59 standard exposure tests, taken over a five-day period, was analysed. For the collection of 5000 counts the mean rate, s^{-1}, was 115.767 ± 0.088 (S.E.), the C.V. value was 1.56% and K was therefore 1.10. This represents a considerable improvement and it seems that this value is unlikely to be any further reduced under field conditions.

11.2 Usage tests with tubular access

These tests were undertaken to examine the potential of and problems associated with the method under field conditions. The initial object was to gather qualitative rather than quantitative information, so a number of contrasting field situations were examined with little or no replication at each site. Results for two replicated field experiments are considered in Section 11.5.

(a) Compaction under tractor wheels

A site in N.I.A.E.S.S. Field Station Section 3 was used for tests on the density changes in freshly-tilled soil as a result of the passage of a tractor wheel. Visual examination of the soil before compaction indicated a zone of high density between 20 and 28 cm depth. Disturbed samples, S/120, S/121 and

S/122 were taken from 0-15, 15-30 and 30-45 cm depths respectively and were used in the calibration test described in Section 9.4. Since no difference in calibration could be established for the three samples a common calibration relation was used.

The site was prepared by one passage of a rotary cultivator ('Rotavator'). A removable surface-level reference-datum bar was arranged across the site in such a way that it could be removed during the passage of the tractor and reset to exactly the same level afterwards. Access tubing was inserted at a position indicated by the reference-bar pointers for ease of relocation. Owing to the very loose nature of the tilled soil, placement of the drilling jig on the surface for the insertion of the access tubing caused some depression of the surface and this effect was subsequently confirmed by an increase of bulk density in the surface few centimetres as shown in Fig. 11.1. After insertion of the tubes the surface elevation was measured using the reference bar as a temporary elevation datum.

Gamma-ray transmission measurements were made at 2.5 cm intervals to a depth of 35 cm. The access tubing was then withdrawn and the holes carefully backfilled with soil and tamped frequently during filling. A Ferguson '35' tractor was then driven over the site so that the front and rear wheels passed twice along the line joining the positions of the two access tubes. Within the centre 10 cm of the wheel track there was an average depression of about 6.25 cm from the original surface. The line of maximum depression lay 5 cm to one side of the line joining the access tubing, due to the failure of the wheels to retrace the correct line exactly on the return passage. The floor of the depression was cleared of lug marks and a smooth surface prepared flush with the base of the lug depressions at a depth of

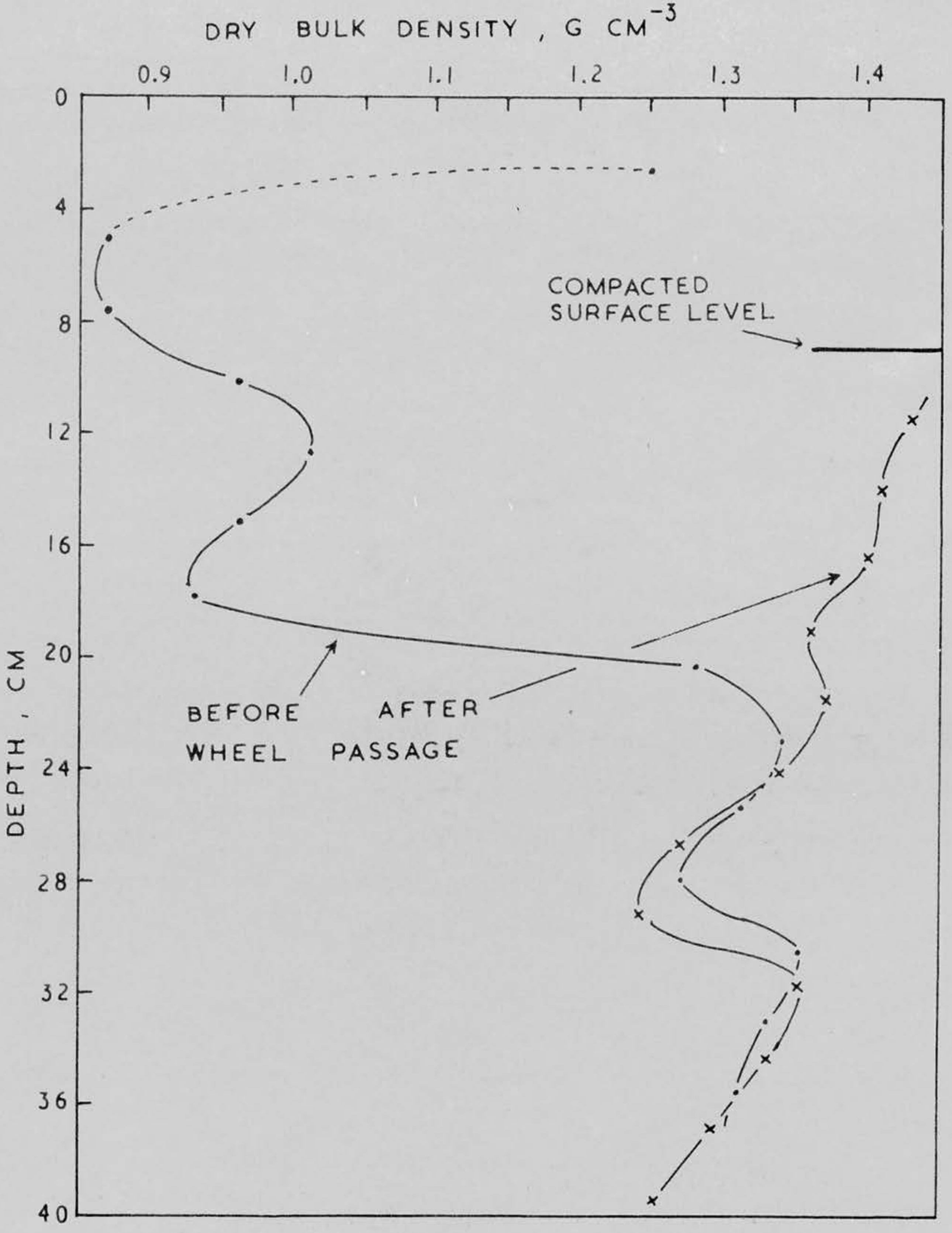

Fig. 11.1 Dry bulk density profiles before and after the passage of tractor wheels over loose soil (MX146 detector)

9 cm below the original surface. The access tubes were inserted after redrilling the holes in the same positions and gamma transmission measurements obtained as before. The long nose calipers were used to measure the distance between the access tubes and this was found to increase from 26.5 cm at 2.5 cm depth to 26.8 cm at 35 cm depth. The soil between the access tubing was then exposed by digging at one side and samples were removed in 2.5 cm increments of depth for moisture determinations by oven drying. The variation of moisture content with depth is shown in Fig. 11.2. The wet bulk density results were converted to dry bulk density values using the moisture content results for the corresponding depths. The variation of dry bulk density with depth before and after compaction were plotted with a common depth scale as shown in Fig. 11.1.

Comments on the results:

(1) Water content variation: The striking variation of water content values with depth shown in Fig. 11.2 confirms the necessity for a high degree of vertical resolution for this determination. Rainfall over the two weeks preceding these tests had been heavy and the results suggest that an impedance to drainage occurs at about 20 cm depth (uncompacted condition). Below this depth the water content falls away very sharply. The interpretation of moisture-content profiles must be very subjective if made without a series of measurements over a period of time owing to the highly transient nature of the water status of soils especially those of coarse texture as at this site.

(2) Dry bulk-density results: Good matching was found between the results for dry bulk density before and after compaction at depths below 23 cm (uncompacted condition). This depth appears to be the limit of influence by the compaction treatment for these conditions. The dry bulk density of

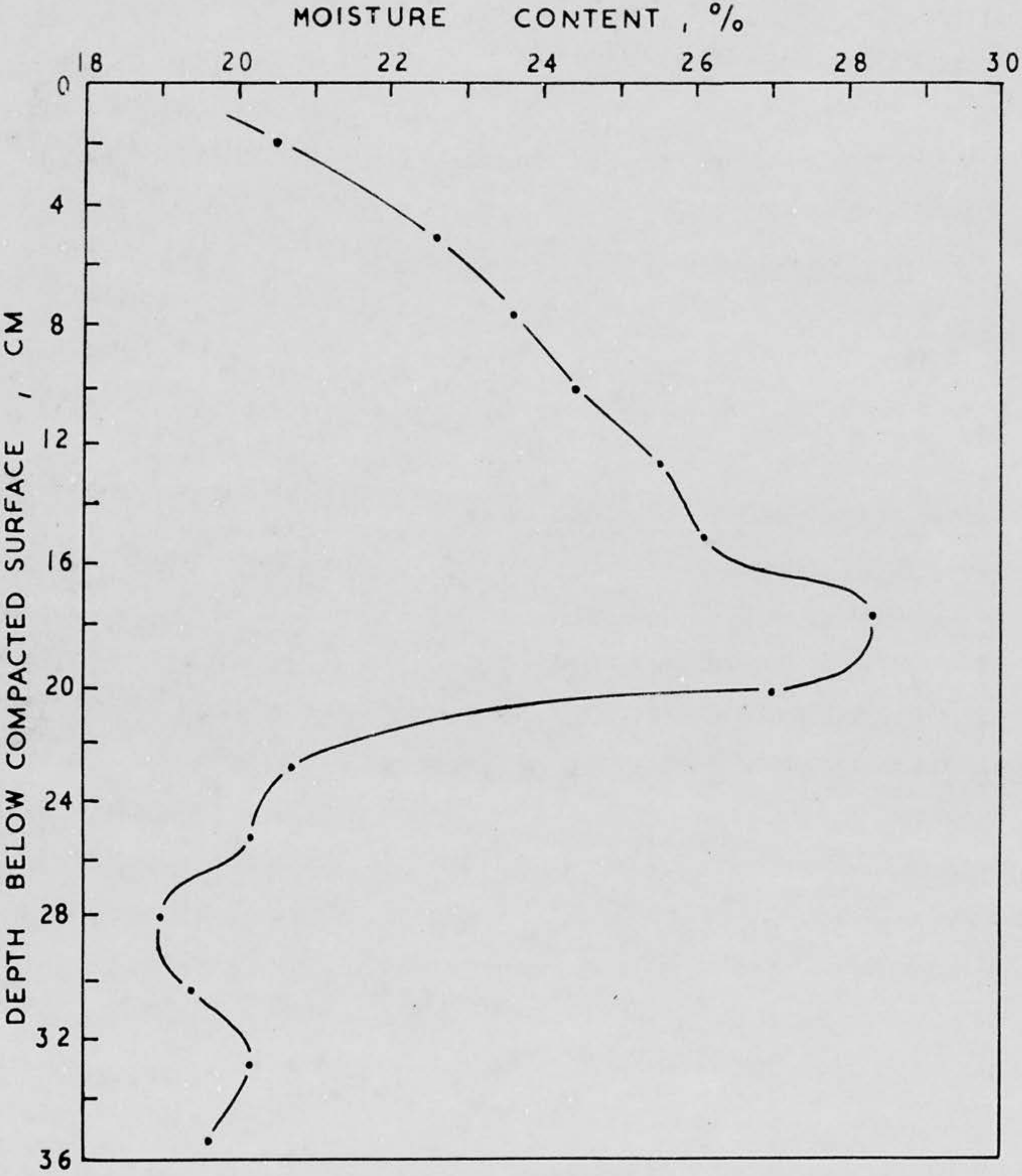

Fig. 11.2 The variation of soil moisture content with depth below compacted surface

the 0-15 cm zone has been increased from approximately 0.95 g cm^{-3} to approximately 1.4 g cm^{-3} by two passes of the front and rear wheels with a combined load of 730 kg. These dry bulk density values correspond to 56 and 83% of the maximum density found by the Proctor compaction test, (1.68 g cm^{-3}). However the optimum moisture determined for the laboratory test was 17.2% w/w whereas the moisture content of the 0-15 cm layer in the field was approximately 23% w/w at which moisture content the Proctor test gave a dry bulk density of 1.50 g cm^{-3}. The bulk density of the 0-15 cm layer after compaction therefore corresponds to 93% of the density which would have been achieved in the Proctor test at the corresponding moisture content.

A more detailed summary is given in Table 11.2 in which values are given for each 2.5 cm increment of depth.

TABLE 11.2

The relationship between dry bulk density values for different depths after field compaction compared with Proctor density values for corresponding moisture contents

Depth (after compaction) cm	% H_2O w/w	Field-Measured Dry Bulk Density g cm^{-3}	Proctor Dry Bulk Density for same moisture content g cm^{-3}	Relative Compaction* %
2.5	20.5	1.43	1.58	90
5.0	22.6	1.41	1.51	93
7.6	23.6	1.40	1.48	94
10.2	24.4	1.36	1.45	94
12.7	25.5	1.37	1.41	97
15.3	26.1	1.35	1.40	96

* Relative compaction is measured density as % of equivalent Proctor density for same moisture content.

(b) Compaction in raspberry cane nursery (tubular access)

An unusual growth pattern had been reported from a raspberry cane nursery at Millhill Farm, near Dundee. The effect is illustrated in Fig. 11.3. Sucker emergence was absent in bands about 25 cm wide on either side of the original planting row. Outside this band sucker emergence was normal. It was suspected that the passage of a heavy tractor-mounted crop sprayer several months previously might be associated with the effect. Access tubing was inserted within the zone in which there was no sucker emergence and within the zone of normal growth approximately 30 cm to one side. Fig. 11.5 shows the values for dry bulk density obtained at the two positions. There is a considerable difference of density and this suggests that the observed plant response is associated with soil changes resulting from the passage of heavily-loaded wheels.

(c) Compaction from tractor traffic through wheat field (tubular access)

N.I.A.E.S.S. Field Station Section 5 was ploughed and sown to wheat in the autumn of 1966. During the growing season of the crop, tractors, passing through the crop to neighbouring fields, established a temporary road as shown in Fig. 11.4. In order to examine the degree of compaction which had occurred as a result of this loading, density measurements were made at two positions within the undamaged wheat crop and at two positions 1 m away under the wheel tracks. The results are shown in Fig. 11.6 in which the results for the two pairs of positions have been averaged. The dry bulk density at a depth of 5 cm on the compacted soil was 1.56 g cm^{-3} compared with 1.13 g cm^{-3} at the same depth in the uncompacted soil.

(d) Soil compaction at grain harvest (tubular access)

Surface soil compaction occurs to a considerable extent at harvest time

Fig. 11.3 Inhibition of raspberry sucker emergence, thought to be associated with passage of loaded tractor wheels

Fig. 11.4 Site for study of effect of repetitive passage of tractor wheels

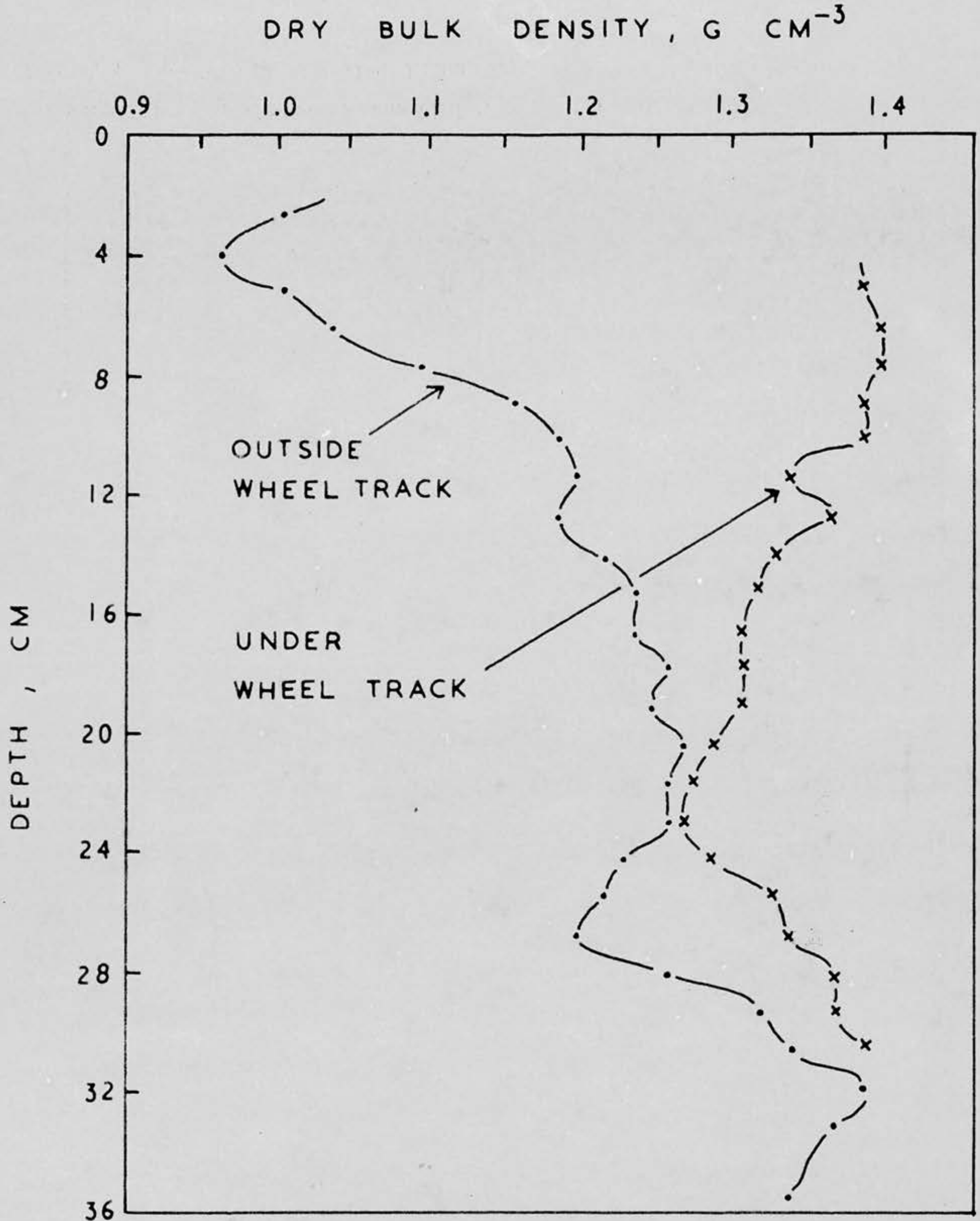

Fig. 11.5 Dry bulk density profiles in raspberry cane nursery in relation to track of tractor wheel (MX146 detector)

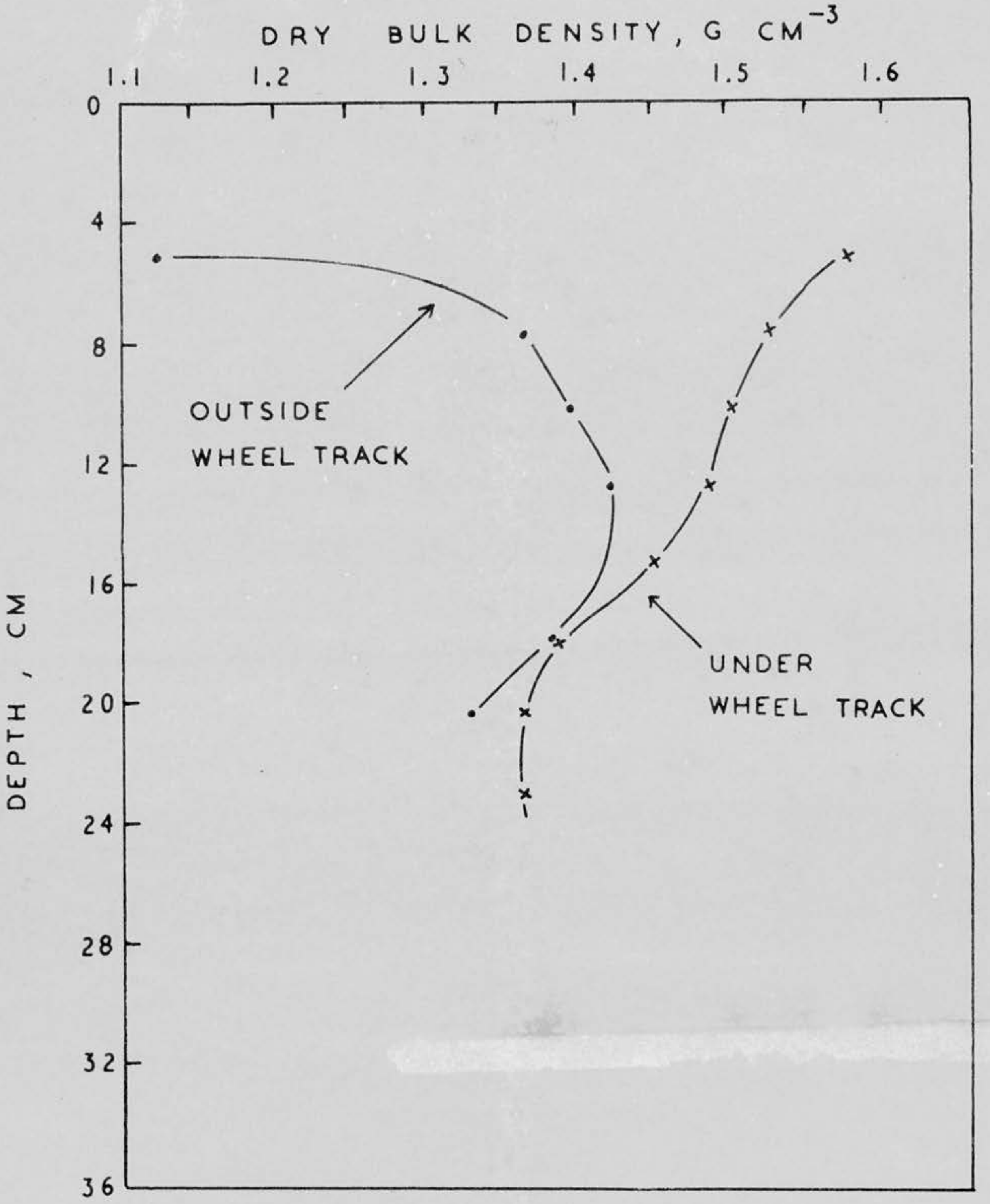

Fig. 11.6 Dry bulk density profiles in wheat crop (MX146 detector)

and Fig. 11.7 illustrates the change of bulk density as a result of the passage of a tractor and loaded grain trailer. The increase of density extends to a depth of about 12 cm. Combines and baling equipment will also contribute to compaction effects at harvest time. Zero-ploughing systems for continuous cereal production may result in a considerable increase in surface soil bulk density if the soil is in a readily-compactable state at the time of harvest traffic.

11.3 Usage tests with planar access

A second series of tests was made with planar access. This system is particularly suited to the detailed study of bulk-density distribution resulting from such tillage operations as ridging and ploughing in which banded patterns of bulk density can be expected parallel to the direction of working. It is also suited to the detailed study of the horizontal and vertical distribution of compaction under linear surface loading such as a tractor wheel.

(a) Density distribution in unploughed and ploughed soil (planar access)

Figs 11.8a and b show the results obtained in a section through unploughed grass ley and ploughed soil. Prior to ploughing, farmyard manure had been applied to the soil surface and the position of this material may be detected by the pockets of very high moisture content occurring in the ploughed soil shown in Fig. 11.8a. There is evidence in Fig. 11.8b of compaction occurring in the soil bearing the pressure on the landside of the plough. The very sharp increase of density at the depth of penetration of the plough is clearly demonstrated. 247 test readings for bulk density were made over the area of this section.

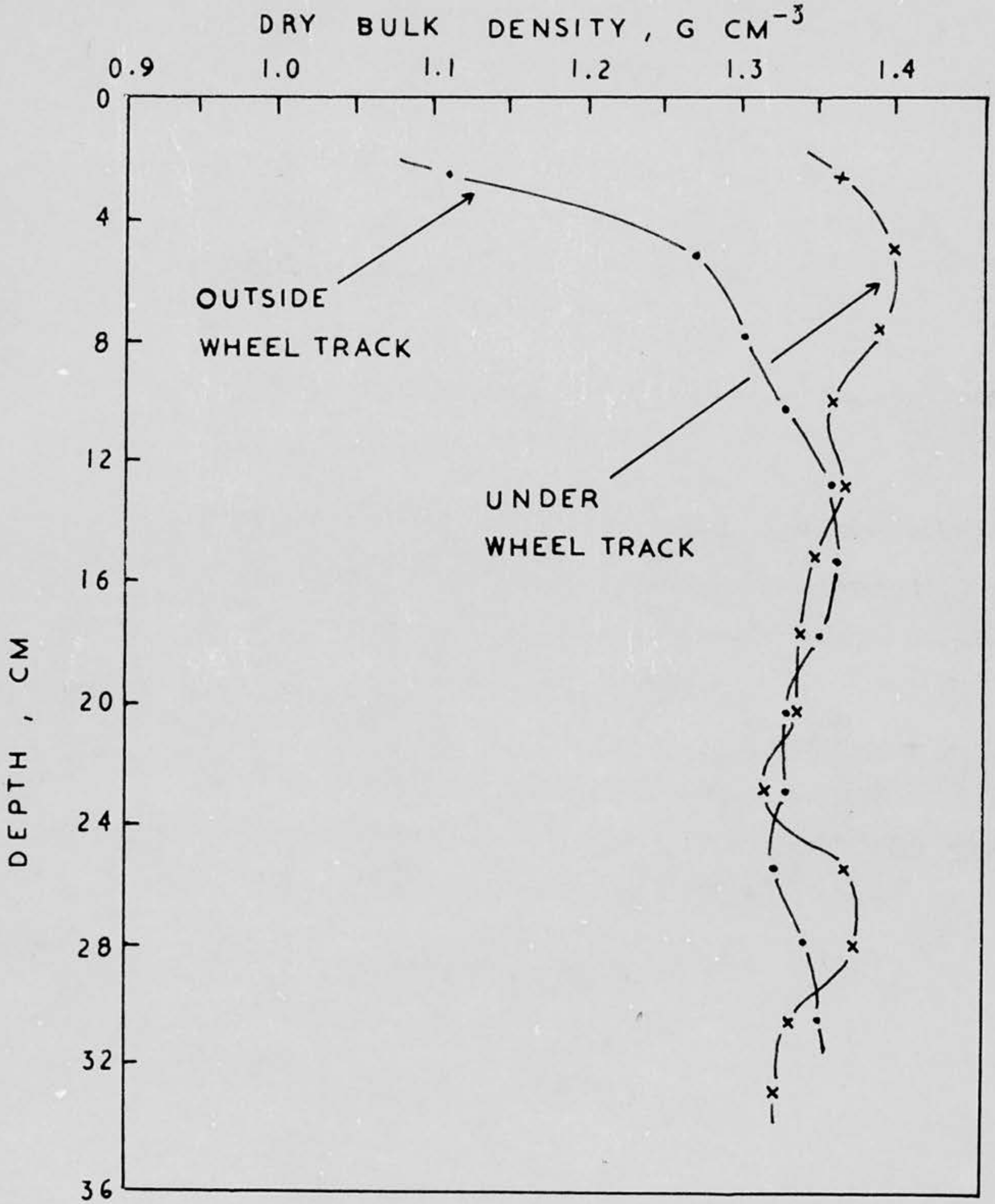

Fig. 11.7 Dry bulk density profiles in wheat stubble in relation to wheel track of grain trailer (MX146 detector)

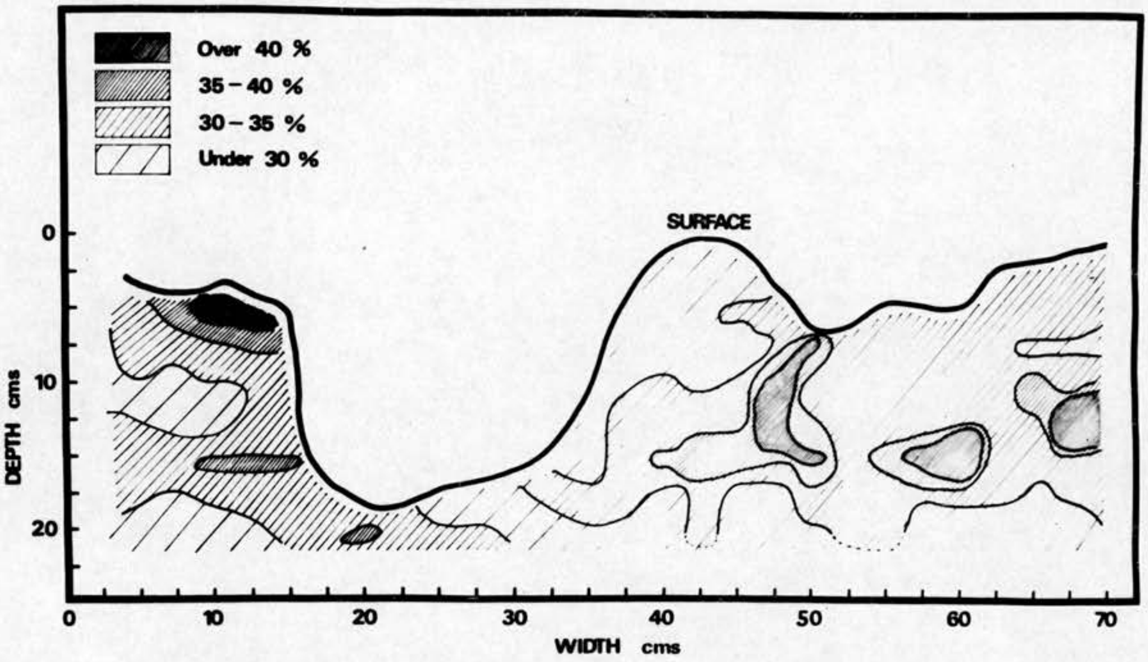

Fig. 11.8a The distribution of moisture content in a section through ploughed and unploughed soil

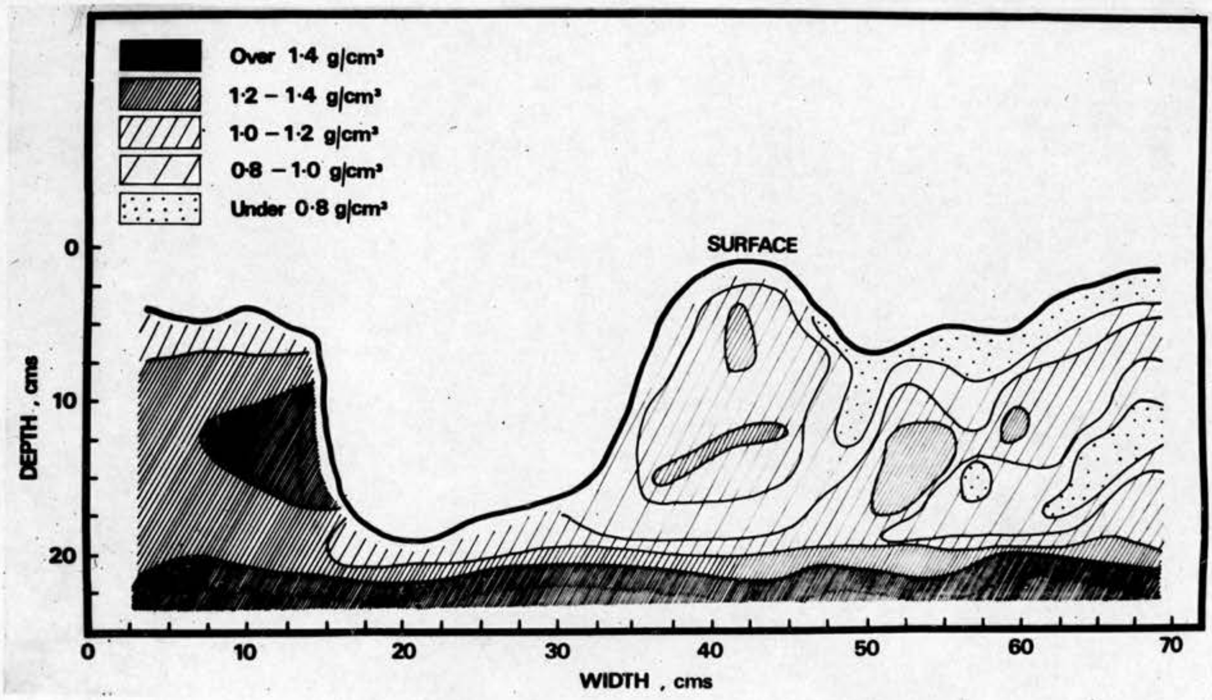

Fig. 11.8b The distribution of dry bulk density in a section through ploughed and unploughed soil

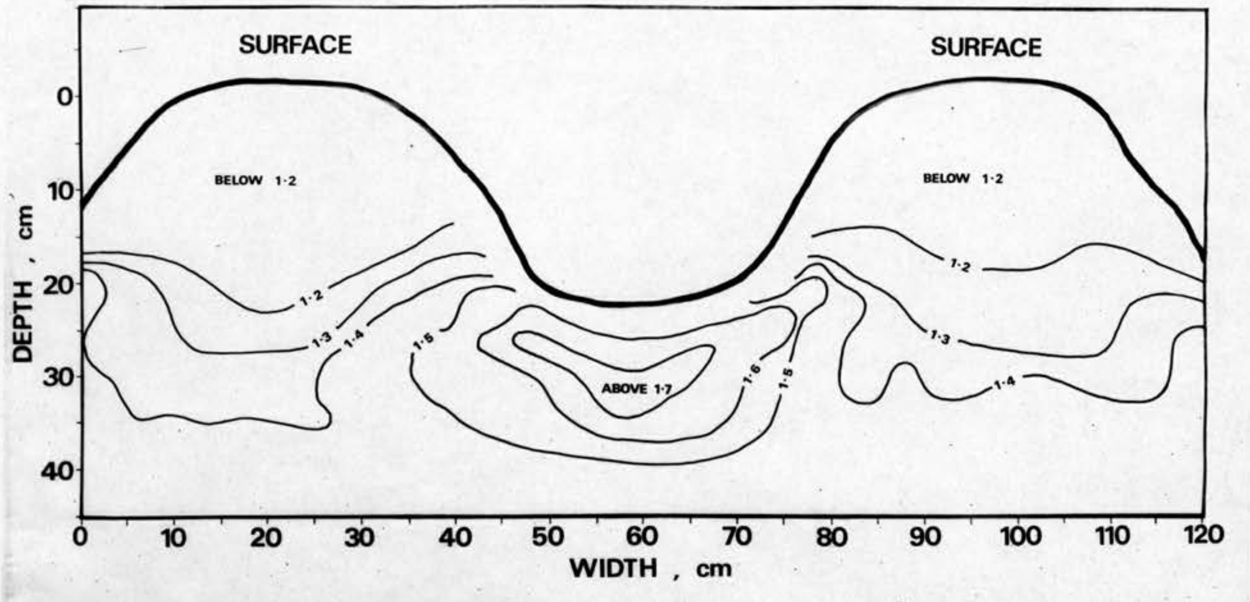

Fig. 11.9 The distribution of dry bulk density (g cm^{-3}) in a section through potato ridges and furrow at time of harvest

Fig. 11.10 The indication of wheel track compaction on the surface

(b) Density distribution in potato ridges and furrow (planar access)

Fig. 8.3 shows the installation of the alignment frame in potato ridges shortly before harvest after a tractor-mounted sprayer had been used to apply a defoliant. The distribution of dry bulk density (207 readings) obtained is shown in Fig. 11.9. Considerable compaction has occurred in the soil below the furrow and this extends into the sides of the adjoining ridge to a degree which could increase the quantity of clods lifted by the digger during harvest.

(c) Density distribution under tractor wheel (planar access)

A final test of the planar access method was made in a section of a wheel track of an unladen tractor passing over soil freshly loosened by rotary tillage as illustrated in Fig. 11.10. 320 test readings were obtained over the section and the bulk density contours drawn in by eye are shown in Fig. 11.11. The considerable horizontal and vertical penetration of the compaction effect is demonstrated, confirming the prediction of soil mechanics theory on the distribution of stress and strain under surface loading. Fig. 11.12 shows the results obtained when the dry bulk density data were submitted to trend surface analysis.

11.4 A sampling study in an uniformity trial

It was considered desirable to examine the performance of the equipment in an uniformity trial in the South Road Field prior to the start of an experiment in which four types of primary cultivation were to be compared. In particular it was necessary to determine the relationship between the number of sampling positions in each plot and the size of treatment difference which could be detected at a stated probability.

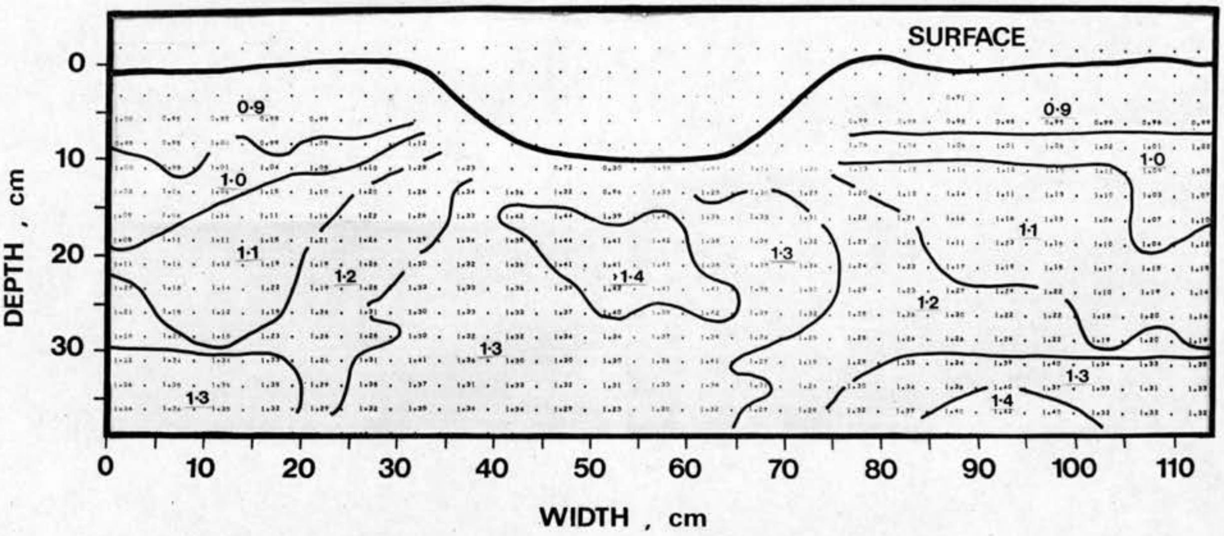

Fig. 11.11 The distribution of dry bulk density (g cm^{-3}) following tractor wheel compaction with contours fitted by eye

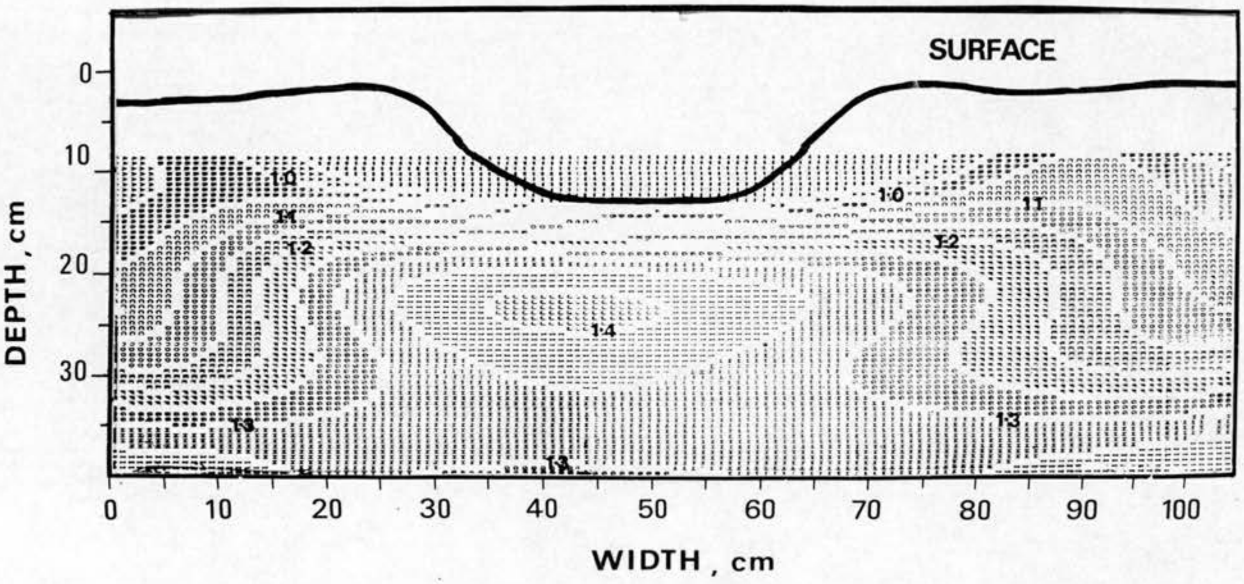

Fig. 11.12 The distribution of dry bulk density (g cm^{-3}) following tractor wheel compaction with contours fitted by 6-order trend surface analysis

The problems of sampling in a three dimensional medium such as soil, with variation expected in all directions, has not received much attention. A review of the statistical aspects of soil sampling techniques by Petersen and Calvin (1965) gives little assistance. Owing to the nature of the bulk density determination by gamma-ray transmission it is not practical to randomize the position of each measurement at each depth. A series of measurements at all depths has to be made at each sampling position.

The design of the experiment which was to follow the uniformity trial consisted of 4 cultivation treatments applied to whole-plots (162 ft x 40 ft) and 4 nitrogen fertilizer treatments applied to split plots (81 ft x 20 ft). There were 8 replications. Two areas, each 60 ft x 12 ft, were set out in each main plot for soil sampling, measurements of bulk density and moisture content were made at 5 cm intervals from 2.5 cm to 28 cm depth at 2 positions in each plot during late October and early November 1967. At that time no cultivation had taken place following the previous barley crop. Obvious ruts due to the passage of combine harvester, trailer and tractor wheels were avoided.

The individual results are set out in Appendix 4.11a. Three of the original results at 2.5 and 12.7 cm depths differed so greatly from the other values at these depths that 'missing plot' values have been substituted. For each depth the results were submitted to an analysis of variance using a specially prepared computer programme* and the results are shown in Appendix 4.11b. The results for "treatment" means, overall mean, standard error of "treatment" mean and coefficient of variation are shown in Table 11.3.

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* IAE 001/0003 Edit 14

Table 11.3

Summary of results for bulk density measurements in sampling study based on separate analysis of variance at each depth

Depth	"Treatment"				Mean	S.E. ("Treatment" mean)	C.V.
cm	Deep	Shallow	Chisel	Zero			%
2.5	1.214	1.226	1.203	1.290	1.233	0.030	10.8
7.6	1.292	1.256	1.225	1.301	1.268	0.030	9.5
12.7	1.224	1.214	1.198	1.261	1.224	0.029	10.6
17.8	1.180	1.172	1.164	1.230	1.186	0.021	7.1
22.9	1.204	1.192	1.154	1.208	1.190	0.033	11.0
27.9	1.389	1.371	1.367	1.400	1.382	0.040	11.7

Pooled standard error 0.031

There is a very marked increase of bulk density at a depth between 22.9 and 27.9 cm which is probably attributable to the depth of ploughing on previous occasions. The values for coefficient of variation compare favourably with values reported by De Boodt _et al._ (1967) for bulk density measurements using core sampling. There is only a small change of C.V. with depth. In order to examine whether any heterogeneity of variances exists for the different depths Bartlett's test was employed using a computer programme* for tests on sampling error and experimental error variances. A summary of the calculations is set out in Appendix 4.11c. In both cases the result for the calculated chi-squared value showed that no differences in variances at different depths could be established. In view of this, pooled estimates for experimental and sampling variance were used to calculate the effect of different numbers of sampling positions in each of the 32 whole plots. The details for these calculations are set out in Appendix 4.11d. It is shown that if two sample positions are used in each plot, differences in treatment means of 7% can be detected with a probability of 95%. If the number of positions per plot was increased to four

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* IAE 001/0027

the difference in treatment means detectable at the same probability can be reduced to 6%. It is concluded that two positions per plot gives a reasonably satisfactory precision since a difference of 7% in the determined mean bulk density (1.246 g cm^{-3}) would amount to 0.09 g cm^{-3}. A full analysis of the choice of numbers of samples per plot at each depth would require a comparison to be made between the cost of obtaining data and the value attached to the precision obtained. Until this has been done the present conclusions must be tentative.

It must be noted that these results are relevant only to sampling which specifically avoids wheel tracks. During the growth period the position of wheel tracks of tractors employed in previous cultivation operations will not be observed on the surface but the resultant bands of compaction may remain below the surface and contribute to horizontal variability.

11.5 The effect of autumn ploughing methods on dry bulk density at the time of emergence of spring-sown cereals

The gamma-ray transmission equipment was used to measure the effect of different methods of primary cultivation on the dry bulk density at the time of emergence of spring-sown cereals in two experiments by arrangement with Dr. J. Holmes and Mr. B. Rodger. Details of the experiments are shown in Table 11.4

TABLE 11.4

Details of experiments comparing the effect of different ploughing treatments

Location	Soil Series	Treatments	Depth of Ploughing cm	No. Reps	Crop
South Road Field, Bush Estate	Winton, sandy clay loam Macmerry, loam	Normal plouging		8	Barley
		– Deep (D)	28–33		
		– Shallow (S)	15–20		
		Chisel ploughing(C)	15–20		
		Zero ploughing (Z)	–		
Inchcoonans, Errol	Carey, silt	Normal ploughing (N)	24–26	6	Wheat
		Zero ploughing (Z)	–		

11.5.1 South Road Field experiment

The normal ploughing treatments were applied in November 1967 shortly after the density measurements had been made in the sampling study as reported in Section 11.4. Deep normal ploughing extended to a depth of 28-33 cm and shallow normal and chisel ploughing to a depth of 15-20 cm. Four passes of the chisel plough were made during the period 19/10/67 - 28/12/67 using an implement with tines 7.6 cm wide at 23 cm spacing. Plots which were to remain unploughed were sprayed with 'Paraquat' on 24/11/67. Ploughed plots were harrowed with spring-tine and straight-tine cultivators on 15/4/68 and barley was then drilled in all plots with a 'Fernhurst' Mark II Triple Disk direct drill. All plots were then harrowed and rolled. Gamma-ray transmission measurements were made and moisture content samples were obtained during the period 25/4/68 - 30/4/68 with readings at 7 depths (2.5 to 33.0 cm) at 2 positions per plot giving a total of 448 samples. Standard exposure tests were made before and after readings at each position. Dry bulk density values were calculated using the technique described in Section 8.5 and are shown in Appendix 4.12a. The results were initially subjected to a series of analyses of variance in which separate tests were made for each depth and these are shown in Appendix 4.12b.

Mean results for the 4 treatments at the 7 depths are tabulated in Table 11.5 and shown diagrammatically in Fig. 11.13. The experimental points have been joined by curves fitted by eye. These curves are thought to illustrate the likely change of density with depth but the interpolation between sampling depths is only approximate.

The experimental and sampling error variances for different depths shown in Appendix 4.12b were submitted to Bartlett's test for homogeneity and the results are shown in Appendix 4.12c. As in the uniformity trial the test showed that the

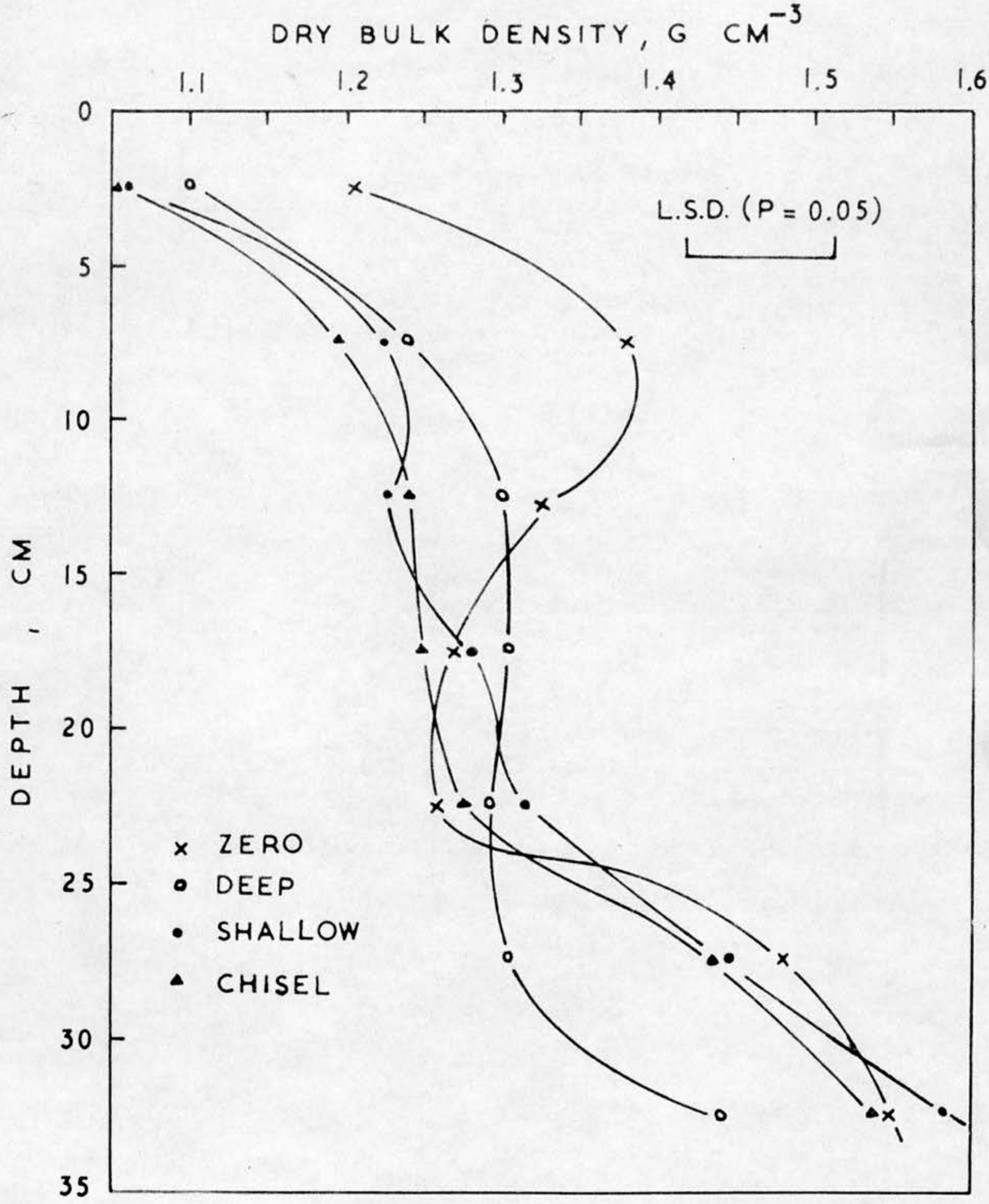

Fig. 11.13 The variation of dry bulk density with depth at the time of emergence of barley for deep and shallow normal ploughing, chisel and zero ploughing at South Road Field with L.S.D. value for comparison of treatments at any one depth (Each point represents the mean of 16 determinations)

TABLE 11.5

The effect of autumn-ploughing method on dry bulk density at the time of emergence of spring-sown barley at South Road Field (Separate analysis for each depth)

Depth	Dry Bulk Density, g cm^{-3}				S.E.	L.S.D.	C.V.
cm	Deep Ploughing	Shallow Ploughing	Chisel Ploughing	Zero Ploughing	(Treatment mean)	(P=0.05)	%
	mean of 16 determinations						
2.5	1.100	1.060	1.056	1.206	0.025	0.073	8.9
7.6	1.242	1.226	1.197	1.379	0.025	0.075	8.1
12.7	1.300	1.223	1.243	1.327	0.029	0.086	9.2
17.8	1.304	1.281	1.252	1.275	0.030	0.088	9.4
22.9	1.296	1.313	1.278	1.264	0.026	0.077	8.2
27.9	1.308	1.443	1.442	1.485	0.037	0.110	10.5
33.0	1.442	1.582	1.542	1.540	0.043	0.126	11.3

Pooled S.E. (Treatment mean) 0.032

experimental error variances were homogeneous at a probability of $P = 0.05$ and it would therefore be appropriate to combine all the data in an analysis of variance using a split-plot design with ploughing methods as main-plot treatment and depths of sampling as sub-plot treatment. Sub-plot treatments were arranged systematically without randomization so a normal split-plot analysis could not be used. Cochran and Cox (1957) have given an analysis procedure for this situation and the results obtained with this technique are shown in Appendix 4.12d. There was no difference in dry bulk density for different ploughing treatments over all depths but there was a highly significant ($P = 0.005$) interaction between ploughing treatments and depths. The standard error for the difference between two ploughing treatment means at any one depth was found to 0.045 g cm^{-3} and the L.S.D. value at a probability of $P = 0.05$ was found to be 0.09 g cm^{-3}. This value has been indicated diagrammatically in Fig. 11.13. The dry bulk density values for the zero ploughing treatment at 2.5 and 7.6 cm depth are greater than for the three ploughing treatments. At depths between 12.7 and

22.9 cm inclusive there is no difference in dry bulk density for the four treatments whereas at depth 27.9 cm the dry bulk density following deep ploughing was significantly less than that for the other treatments.

11.5.2 Inchcoonans experiment

The Inchcoonans experiment was conducted in a similar manner to that at South Road Field. Wheat was drilled in spring with a 'Sisis Contravator' direct drill and this was followed with a chain harrow at right angles to the line of seeding. Gamma-ray measurements for bulk density were made and moisture content samples obtained on 21-23/5/68 at 2 positions in each plot at the same 7 depths as in Section 11.5.1 giving a total of 168 readings. The results obtained are tabulated in Appendix 4.13a. Analysis of variance tests were made for the data at each depth separately and the results are tabulated in Table 11.6 and shown in Appendix 4.13b. Mean dry bulk density values for the two treatments at different depths are shown graphically in Fig. 11.14. The experimental error and sampling error variances at different depths were tested for homogeneity by Bartlett's test and the results are shown in Appendix 4.13c. It was found that the probability of the chi-squared values being attributable to chance was less than 2.5% and less than 0.05% for the experimental and sampling errors respectively. It was therefore concluded that the variances at different depths were heterogeneous. Inspection of the values showed that a marked change of magnitude of these variances occurred at a depth between 22.9 and 27.9 cm. Since this corresponds approximately to the depth of ploughing it was concluded that soil variability was considerably greater above the ploughing depth than below it.

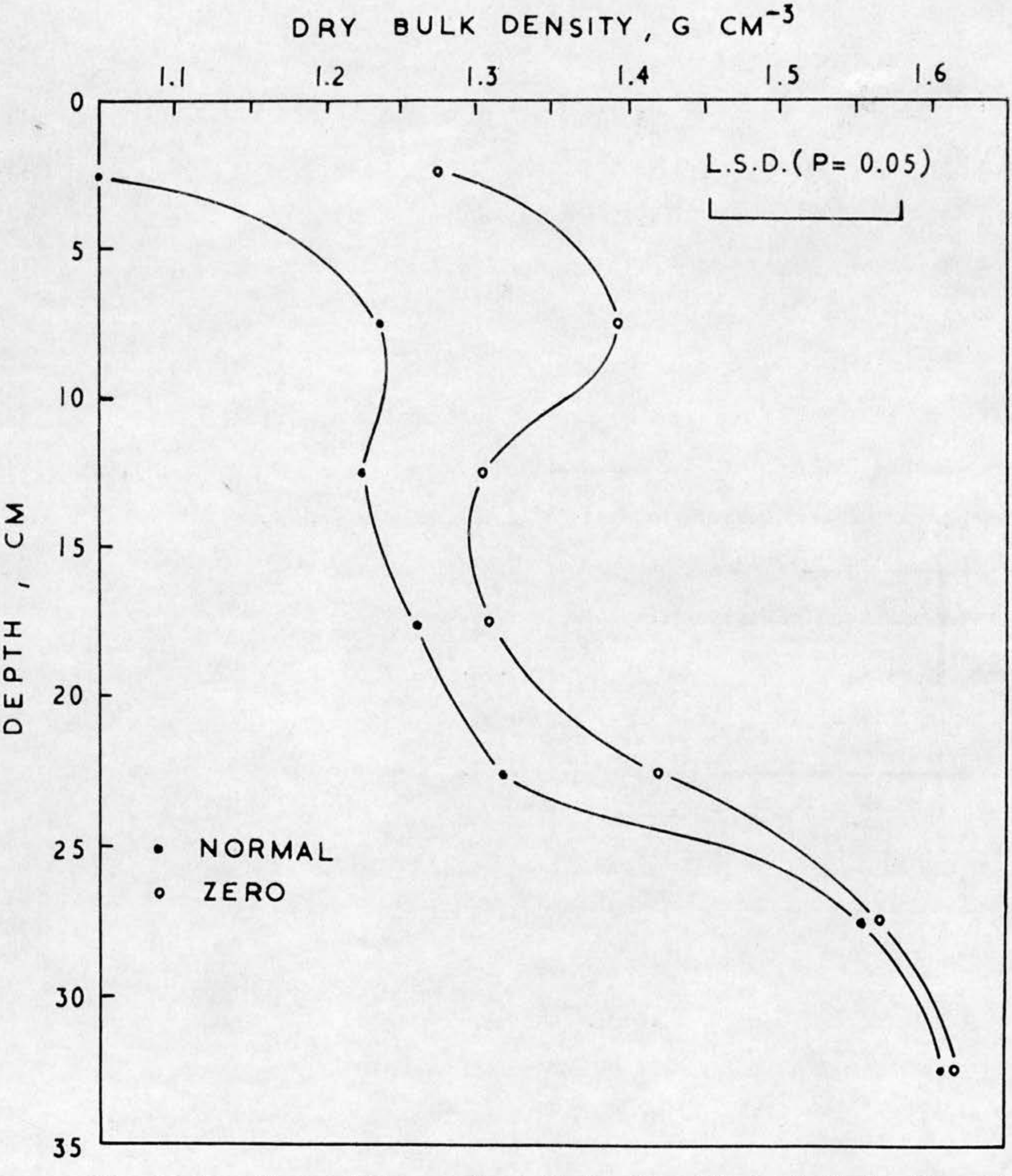

Fig. 11.14 The variation of dry bulk density with depth at the time of emergence of wheat for normal and zero ploughing treatments at Inchcoonans with L.S.D. value for comparison of treatments at any one depth (Each point represents the mean of 12 determinations)

TABLE 11.6

The effect of autumn-ploughing method on dry bulk density at the time of emergence of spring-sown wheat at Inchcoonans (Separate analysis for each depth)

Depth cm	Dry Bulk Density, g cm^{-3}				
	Normal Ploughing (mean of 12 determinations)	Zero Ploughing (mean of 12 determinations)	S.E. (Treatment mean)	L.S.D. (P=0.05)	C.V. %
2.5	1.048	1.277	0.044	0.129	13.1
7.6	1.235	1.393	0.030	0.090	8.0
12.7	1.224	1.301	0.033	0.097	9.0
17.8	1.260	1.308	0.052	0.153	14.0
22.9	1.318	1.421	0.043	0.127	10.9
27.9	1.553	1.566	0.016	0.047	3.5
33.0	1.603	1.610	0.007	0.022	1.6

S.E. (Pooled, Treatment mean) (2.5-22.9 cm) 0.041
(27.9-33.0 cm) 0.013

The pooled standard error for a treatment mean was found to be 0.041 g cm^{-3} for the 2.5 - 22.9 cm depths and 0.013 g cm^{-3} for the 27.9 and 33.0 cm depths.

An analysis of variance of the pooled data for the 2.5 - 22.9 cm depths was carried out according to the technique described in Section 11.5.1 and the results are shown in Appendix 4.13d.

The variation of dry bulk density with depth shows a distribution for the two treatments similar to that found for normal (shallow) and zero ploughing at South Road Field. Zero ploughing treatment results in significantly greater (P=0.05) dry bulk density for the 2.5 and 7.6 cm depths. Differences below these depths are less than the L.S.D. value but mean dry bulk density values following zero ploughing remain higher than following normal ploughing to a depth of 22.9 cm. There is virtually no difference between the treatment means at 27.9 and 33.0 cm depth.

CHAPTER 12

DISCUSSION AND CONCLUSIONS

12.1 Studies with GM detector

The tests made with a small GM detector showed that the gamma-ray transmission method provides a useful method for the measurement of changes of soil bulk density in field studies of tillage and traffic. Both tubular and planar access techniques are of value. The former system is suited to field experiments, particularly those of long duration, in which large numbers of readings are required with a minimum of disturbance. For situations in which very intensive study is required of bulk density changes occuring as a result of linear compactive or disruptive effects, such as wheel traffic or ploughing, the use of planar access is preferable. The amount of disturbance is necessarily greater however. Difficulty can be expected with both access systems in stony soils. The measurement of sample thickness and source-detector separation seems to overcome one of the disadvantages of the gamma-ray transmission method. Insertion of the plates for planar access has to be undertaken slowly and carefully in order to avoid excessive outward flexing of the plates even when the cutting edge has been strengthened with an angle member.

The small active dimensions of the GM detector used makes possible a satisfactory degree of vertical resolution for most purposes. However the resolution obtained is inadequate for detailed studies of bulk density within the surface 0-5 cm depth or close to very abrupt changes of bulk density within the soil mass. The small size and low detection efficiency of this detector makes it necessary to use at least 30 mCi Cs-137. Use of a source of this activity requires care and attention to shielding. Dose rates could be as high as 300 mrad h^{-1} at the surface of the unshielded source probe. However, in practice, when under the supervision of trained personnel the dose rate at any part of the operator's body should not exceed 10 mrad h^{-1} and this will be experienced only for a few minutes at the most in a normal days work. Exposure levels could be considerably reduced by the use of remote control equipment, especially for planar access. In this way the operator need never be near the equipment while the source probe is out of its shield. The use of depleted uranium for all shielding would also reduce the exposure levels since the shielding action of this material is approximately twice that of lead for equal thickness.

Highly significant and interesting variation in gamma-ray background count rate was established for different soils and at different depths. However the count rates measured were never high enough to represent a significant source of error in transmission measurements.

The use of a digital computer has been an important component of this study both in giving assistance with standard statistical operations and the computation of bulk density results for non-standard geometry which would otherwise have been extremely tedious. The use of a line-printer to obtain a two dimensional co-ordinate print-out of bulk density results similarly resulted in a great saving in time. The use of high order polynomial trend surface analysis permits smoothed contours of bulk density to be drawn without human bias. Care is needed in the selection of a suitable order of polynomial since the achievement of a high correlation coefficient per se does not necessarily indicate the most satisfactory results. Excessive accentuation may be given to regions of high and low bulk density.

Gamma-ray transmission is as well suited to the measurement of air-filled porosity as to dry bulk density provided the particle density is known. For certain situations the air-filled porosity may be a better estimate of compactive or disruptive changes in soil than dry bulk density.

Stability of the equipment in the field was basically within the limits set by the random disintegration rate of the isotope. However this could be achieved only as a result of strict attention to alignment of the source probe. The use of a standard exposure is essential in order to guard against misalignment or faults in the counting equipment.

Linear relationships were established between mass thickness and count rate for glass, steel and soil-water mixtures using 5 mCi and 30 mCi Cs-137 sources provided the count rate did not exceed the limits set by the dead time of the detector and scaler. In the case of the 30 mCi Cs-137 source this limit was reached at bulk densities below about 0.5 g cm^{-3}. No differences in regression coefficient could be established for different soils or different moisture contents. For calibration tests with four soils with moisture contents varying from 1% to 40% $^{w}/w$, 98% of the variation in sample : standard ratio could be accounted for by a linear relationship with wet bulk density. These results suggest that for this equipment differences in the absorption coefficient for soil and water are insignificant and that the 'build-up' effect can be assumed to be of no practical importance over the range of bulk density studied. The reason for these results probably lies in the partial elimination of low energy photons owing to the filtering action of the stainless steel tubing surrounding the detector. This tubing together with the wall of the detector accounts for a total thickness of 1500 mg cm^{-2}.

The scatter in the calibration relationships with soil-water mixtures was attributed to the inherent difficulties of making up standard samples in which the portion "seen" by the gamma-ray transmission equipment is of equal density to the whole sample. It is difficult to prepare samples of soil at comparatively high values of moisture content and bulk density values to the degree of internal uniformity which is required if satisfactory calibrations are to be obtained. The standard deviation of a predicted bulk density was about 0.04 and 0.05 g cm^{-3} for tubular and planar access samples respectively. It is probable that these values could be reduced by greater attention to uniformity in the preparation of samples for calibration tests. However the natural variation of bulk density in field soils is such that a very high degree of precision in calibration is not required.

12.2 Studies with scintillation detector

As a result of the detailed studies on the stability problems associated with the use of a sodium iodide detector it is considered that its use in the field is unsatisfactory without a stabilizing system capable of providing compensation for the thermal sensitivity which was found in all parts of the equipment. Provision for overcoming the thermal sensitivity of the e.h.t. supply and pulse height analyser would seem to be equally important as that for the detector-photomultiplier assembly. A pronounced warm-up effect under isothermal conditions was also demonstrated. A system such as that described by Williams, Snelling and Pickup (1966) would appear to be capable of eliminating errors introduced by warm-up and ambient temperature instability.

The vertical resolution obtained with a sodium iodide detector has been shown to be very satisfactory. Provided the photon energy level does not exceed that of Cs-137 the use of a crystal as thin as 0.635 cm is acceptable although at higher photon energies efficiency of detection in such a thin crystal would be very low. In spite of the very small active cross section, satisfactory count rates were obtained with a 5 mCi Cs-137 source provided a very narrow setting of the double discrimination aperture was not required. Below equivalent bulk densities of about 0.5 g cm^{-3} (corresponding to a count rate of about 300 s^{-1} with a setting of 0.2V at the peak) the count losses became appreciable. Tests with maximum aperture setting for steel, glass and water however showed notable advantages over the use of a double discriminator. The $\log_{10}$ count rate could be increased by about 45% by using a maximum aperture instead of a 0.2V aperture. Much higher count rates could be used with maximum aperture without any evidence of count loss through coincidence. Determined values for the linear absorption coefficients for these materials showed that an increase could be obtained with aperture settings in the order (1) 0.2V at peak, (2) maximum aperture at peak - 0.2V, (3) maximum aperture at peak and (4) maximum aperture at peak + 0.2V. There seems to be no advantage in using a double discriminator setting and several advantages in using maximum aperture setting. In order to take full advantage of the high counting rate which is practicable with this system, attention must be given to the provision of high speed components particularly in the pulse height analyser. In the equipment used in this work the circuit employed monostables with dead times of 20 and 35 µs. It would be preferable to reduce these values to about 1 µs.

12.3 Field studies

It is clear from the preliminary usage tests that very marked changes in dry bulk density occur in soils as a result of compactive and disruptive processes in field soils. The quantitative prediction of these effects must await the development of theory as considered in Chapters 3 and 4. In the meantime however the accurate measurement of these changes in dry bulk density under a wide range of soils, implements and traffic is essential if the processes involved are to be understood. Increases of dry bulk density by as much as 40% may result from the passage of an unladen tractor rear wheel running over loose soil. A smaller but nevertheless important increase results from similar loading on soils in a firmer condition such as studied in the raspberry cane nursery and under wheat stubble. The depth to which an increase of dry bulk density could be detected was related to the firmness of the soil at the time of compaction. After rotary cultivation compaction from tractor wheels could be detected to 20 cm whereas under wheat stubble, differences were found only to 10 cm.

The horizontal distribution of compactive changes are illustrated by the results obtained with planar access. In the case of the section through potato ridges at the time of harvest the passage of a tractor wheel has caused a notable increase of dry bulk density in the sides of the ridge as well as below the furrow. This effect could influence the efficiency of subsequent potato lifting operations since the greater mechanical strength of these compacted parts will increase the draught of a lifting share as well as the number of clods which will survive the agitation received on the first elevator.

Planar access studies in a plane at right angles to the line of passage of a tractor wheel over loose soil showed the concentric pattern of bulk density contours which soil mechanics theory predicts but which have rarely been demonstrated in field soils. Owing to local irregularities the contour pattern obtained after fitting by eye tends to conceal some of the basic symmetry of the bulk density distribution. The use of trend surface analysis however permits the fitting of smoothed contours in which the contribution of local irregularities is very much reduced. The use of trend surface analysis however would not be appropriate for data in which a very irregular distribution of bulk density is to be expected such as in a cross-section of ploughed and unploughed soil. Owing to the very steep gradients of bulk density over certain parts of this section any attempt to smooth the contours would tend to conceal important information. Interpretation of sections as complex as that obtained for the ploughed and unploughed soil must be made with caution and preferably be based on a number of replicated tests. Of particular importance is the influence of bulk density variation present in the sample before the treatment was applied. This is well shown by the continuation of the 'plough pan' under the unploughed soil in Fig. 11.9b. This is probably the result of previous ploughing operations. It may be impossible to demonstrate the influence of furrow bottom wheel compaction during ploughing operations if an intense 'plough pan' is already present. Caution is also required in the interpretation of the high bulk density zone close to the vertical side of the furrow. While this may be due to compactive changes introduced as a result of pressure on the land side of the plough, the effect would have to be confirmed by replicated tests in soils of known initial bulk density.

The use of the tubular access system in a field uniformity trial provided important information prior to the study of ploughing treatments on subsequent changes in bulk density. No difference in experimental or sampling error could be found for depths in the range 2.5 to 27.9 cm. This suggested that both the performance of the instrument and the variability of the soil did not change over this range. The test also lead to the conclusion that the use of two sampling positions per plot for the 32 plot experiment at South Road field would permit the detection of a 7% difference in treatment means at a probability of 95%. When 7 depths were measured at each position it was found possible to obtain the 448 readings of gamma-ray transmission and the moisture samples in a three day period.

Dry bulk density values were obtained at two sites at the time of emergence of spring sown cereals following the application of different ploughing treatments in the previous autumn. At both sites the zero ploughing treatment had resulted in bulk density values in the 0-12 cm zone approximately 20% higher than those following normal ploughing. It is likely that this effect will be accentuated by compactive changes resulting from harvest traffic and that a cumulative increase of bulk density will occur in the zero ploughing treatments in future years. At the South Road field the effect of deep ploughing in autumn could be shown to result in a value of bulk density in the 25-32 cm depth approximately 10% lower than following shallow, chisel or zero ploughing treatments. Future sampling at both these experiments will have to be so arranged that the effect of wheel traffic at harvest can be distinguished from changes resulting from the different ploughing treatments.

12.4 Conclusions

Equipment

(1) Two systems of gamma-ray transmission equipment have been used to measure the changes in bulk density of soils. A Geiger:Müller detector with a 30 mCi Cs-137 source was found to be a satisfactory system for field studies with a high degree of stability. A linear calibration relationship between wet bulk density and count rate was established and found to be independent of soil type and moisture content. The use of a sodium iodide scintillation detector provided a much finer degree of resolution in layered media and a reduction of about $^1/6$ in the required

source activity. However without the provision of a reliable stabilisation system the use of this detector under field conditions appears to be unsatisfactory.

(2) Two methods of insertion of source and detector probes in field soils were tested. Tubular access was suitable for formal field experimentation when soil disturbance must be minimal. Planar access permitted horizontal and vertical scanning and was therefore more suited to detailed studies at a limited number of sites. The access tubes or plates were not always parallel and therefore the sample thickness was measured at each position of transmission measurement.

Measurements

(3) Changes in bulk density of up to 40% were demonstrated in field soils as a result of the passage of tractor wheels and implements. These density changes were large enough to cause important changes in mechanical properties and physical fertility of the soil. The depth of compaction during the passage of tractor wheels exceeded the depth of penetration of most secondary cultivation implements. Thus harvest and seed-bed traffic may cause a cumulative increase of bulk density if ploughing is not practiced.

(4) Soil compaction studies must take into account the previous history of the soil. Residual plough pans were found in the field soils tested. In order to study compactive changes below the depth of ploughing it is first necessary to destroy residual pans or work in soil tanks. In all field studies considerable horizontal variation of bulk density can be expected as a result of previous passage of

implements and wheels.

(5) Gamma-ray background count rate in field soils was found to vary at different depths and between different sites, probably due to natural radioactive elements. However this was not a serious error in bulk density measurements because the background count was always very low compared with the transmission count rate.

(6) Experimental error variances at different depths were not homogeneous at one site, values above plough depth being approximately ten times those below plough depth. However, at another site of contrasting soil type, no such effect could be found. Therefore tests for homogeneity must be made before pooling results from different depths at any site.

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APPENDIX 1: DATA RELEVANT TO CHAPTER 8

Appendix 1.1 Background levels for materials in laboratory (See Table 8.3)

Material	Wet Bulk Density g cm^{-3}	counts per 1000 S				
		replication				mean
		I	II	III	IV	
Soil S/30	1.45	1579	1600	1617	1581	1594
Soil S/30	1.83	1501	1513	1514	1521	1512
Water	1.00	1332	1297	1377	1319	1331
Sand S/36	1.55	1481	1513	1469	1480	1486
Sand S/36	1.70	1372	1391	1377	1373	1378
Air	0.0	1654	1683	1708	1726	1693

Analysis of Variance

Source	D.F.	S.S.	M.S.	F
Material	5	358 733	71 746	151.4***
Reps	3	1716	572	1.21
Error	15	7111	474	
Total	23	367 560		

Appendix 1.2 127-channel pulse height analyser results for sample S/82 at position P/26 at 120-135 cm depth (See Fig. 8.7)

Counts per 16384 s period after subtraction of background										
	Channel Number									
	00	01	02	03	04	05	06	07	08	09
00	-	9795	10299	10726	11066	10729	9249	6899	5863	5303
10	5238	5141	4413	3484	2702	2515	2223	2218	2184	2046
20	2065	1941	1975	2167	2368	2667	2723	2456	1849	1585
30	1259	1207	1158	1173	1280	1157	1187	1150	1012	1065
40	1037	1105	1248	1430	1479	1331	1279	1178	1030	894
50	0804	0737	0770	0760	0747	0845	0810	0740	0676	0674
60	0627	0615	0575	0502	0500	0434	0396	0387	0373	0408
70	0580	0800	1068	1301	1495	1500	1330	1083	0784	0558
80	0408	0306	0223	0217	0239	0171	0216	0184	0153	0186
90	0222	0199	0202	0182	0190	0163	0131	0124	0127	0110
100	0107	0196	0093	0094	0072	0119	0057	0094	0116	0125
110	0126	0113	0132	0118	0098	0099	0117	0116	0129	0121
120	0107	0109	0091	0098	0068	0064	0065	0059	-	-

Appendix 2: DATA RELEVANT TO CHAPTER 9

Appendix 2.1 The influence of type of detector and number of counts collected on precision of measurement (See Table 9.2)

Detector System S-D Separation, cm Material Discriminator (Aperture & Threshold)	MX120 Backscatter 23.2 Water -	NaI Trans. 33.0 Air 0.2V & 5.1V (Peak)	MX120 Backscatter 35.9 Water -	MX 146 Trans. 30.5 Lead -
Count Rate s^{-1}	369.86	82.22	87.08	63.86
	370.13	80.85	87.75	65.65
	369.73	81.48	87.63	66.55
	367.18	81.60	86.88	65.83
	365.89	82.06	87.37	65.39
	366.72	82.06	86.99	65.45
	366.45	83.80	87.29	65.52
	361.83	82.00	87.71	64.25
	370.20	81.07	86.96	63.94
	370.79	81.86	86.76	65.57
	366.53	79.42	88.52	64.51
	372.56	80.79	85.51	63.64
	368.19	81.65	89.09	65.17
	370.72	80.86	88.32	65.16
	366.98	80.32	88.02	63.43
	373.06	80.13	88.76	65.93
	363.47	80.97	88.85	64.83
	369.84	79.98	89.44	65.20
	366.07	78.26	87.62	65.33
	366.27	81.92	85.72	66.21
$\bar{\bar{R}}$, s^{-1}	368.12	81.11	87.61	65.71
$\bar{\bar{T}}$, s	54.32	100.00	228.30	76.09
$\bar{N}$, counts	141.42	8111.5	20000	5000
S_R, s^{-1}	2.885	1.597	1.075	0.872
S_N, counts	156.45	126.37	236.7	66.37
$K = S_N/N^{\frac{1}{2}}$	1.106	1.40	1.67	0.94
χ^2	23.34	37.37	53.24	16.74

Appendix 2.1 (Continued)

Detector	MX 146	MX 146	MX 146	MX 146	MX 146
System	Trans.	Trans.	Trans.	Trans.	Trans.
S-D Separation, cm	30.5	30.5	16.5	16.5	16.5
Material	Lead	Lead	Air	Air	Air
Discriminator (Aperture & Threshold)	-	-	-	-	-
Count Rate s^{-1}	66.23	64.18	402.58	403.23	405.02
	64.54	64.34	405.84	406.17	406.09
	65.31	63.91	407.17	411.35	407.41
	66.25	64.14	400.96	404.53	404.61
	65.73	64.17	404.86	405.19	405.43
	65.36	64.07	417.01	405.68	399.28
	64.75	64.21	401.28	401.61	405.27
	64.39	64.00	411.18	403.55	406.75
	64.81	64.09	401.93	407.17	399.28
	64.96	63.89	399.04	405.19	406.17
	65.50	64.26	401.28	400.64	408.16
	64.57	62.90	411.52	405.35	409.75
	65.19	63.64	403.55	404.86	406.75
	64.19	63.99	400.96	404.53	404.86
	64.85	62.91	405.52	402.58	405.10
	64.45	63.09	394.64	401.77	405.02
	64.92	63.70	411.86	404.37	403.88
	65.12	64.04	410.51	403.06	404.29
	65.12	64.19	403.88	392.00	405.43
	64.92	63.11	410.51	405.19	404.53
$\bar{R}$, s^{-1}	65.06	63.84	405.30	403.90	405.15
$\bar{T}$, s	153.71	313.27	12.34	24.76	49.36
N, counts	10000	20000	5000	10000	20000
S_R, s^{-1}	0.559	0.464	5.446	3.617	2.456
S_N, counts	85.98	145.39	67.20	89.55	121.23
$K = S_N/N^{\frac{1}{2}}$	0.86	1.03	0.95	0.90	0.86
χ^2	14.04	20.08	17.16	15.24	13.96

Appendix 2.2 The change of count rate with angular displacement of gamma-ray transmission probe (See Fig 9.2).

Detector : MX146
S-D separation : 30.5 cm
Source : 5.0 mCi Cs-137

Angular Displacement from midline, degrees	Count Rate s^{-1} mean of 4
+ 30	112.91
+ 25	135.74
+ 20	128.55
+ 15	154.74
+ 10	212.74
+ 5	257.29
0	270.05
- 5	276.04
- 10	266.13
- 15	230.66
- 20	168.05
- 25	133.48
- 30	121.78

Appendix 2.3 The relation between count rate and equivalent density of steel plates (See Fig. 9.7).

Calibration : 30 mCi Cs-137 Source, MX 146 detector.
Material : Steel, Density 7.78 g cm^{-3}, thickness of plates 0.683

No. of plates	Equivalent Density g cm^{-3}	Count Rate s^{-1}
4	0.810	437.4
5	1.012	365.8
6	1.214	310.2
7	1.418	254.3
8	1.620	214.1
9	1.822	176.3
10	2.025	146.7
11	2.227	121.6
12	2.430	99.4
13	2.633	84.2
14	2.835	71.4
15	3.037	60.0
16	3.239	50.7

Appendix 2.4 The effect of mass thickness of soil (S/116) on count rate at two moisture contents in open ended cylinders (See Fig.9.8)

Nominal moisture content %	Mass Thickness g cm^{-2}	Count Rate s^{-1}	Actual moisture content % $^{w}/_{w}$
20	13.92	111.0	18.6
"	10.61	135.2	19.6
"	13.25	112.6	19.6
"	8.98	144.5	19.4
"	16.24	94.6	19.7
"	19.64	76.4	19.5
"	19.65	75.2	19.5
"	21.34	67.1	19.3
"	21.65	65.7	18.7
"	23.30	62.6	18.5
11	16.87	88.4	10.7
"	18.52	81.7	10.8
"	19.39	76.4	11.2
"	19.62	75.9	11.2
"	20.19	72.8	11.0
"	22.04	64.5	11.0
"	12.96	114.8	10.7
"	9.28	144.9	10.8
"	22.70	66.9	10.6
"	26.53	53.8	11.8
"	13.92	110.0	12.0
"	10.06	137.7	11.2

Appendix 2.5 The effect of wet bulk density on count rate for five soils (MX 146 detector, 5 mCi Cs-137 source) (See Fig. 9.9)

Soil Lab No.	Count Rate s^{-1}	Wet bulk Density g cm^{-3}	Moisture Content % $^{w}/_{w}$	Silt & Clay %
S/120	23.44	1.661	20.4	29
S/120	65.53	0.907	20.6	29
S/120	29.73	1.457	20.4	29
S/120	40.36	1.274	20.7	29
S/121	31.11	1.477	21.8	27
S/121	20.98	1.727	21.6	27
S/121	66.06	0.946	22.2	27
S/121	40.69	1.270	21.8	27
S/122	32.29	1.449	16.2	16
S/122	24.85	1.614	15.9	16
S/122	68.31	0.918	15.7	16
S/122	38.02	1.303	13.3	16
S/34	66.33	0.916	20.7	63
S/34	49.94	1.321	20.5	63
S/34	34.24	1.478	20.2	63
S/34	19.00	1.846	20.6	63
S/124	76.77	0.809	30.8	42
S/124	58.58	0.982	29.8	42
S/124	23.51	1.665	30.0	42

Appendix 2.6 **The effect of wet bulk density on $\log_{10} T_t/T_s$ for four soils at various moisture contents contained in Type A and B boxes (MX 146 detector, 30 mCi Cs-137 source (See Figs 9.10 and 9.11).**

Container	Soil Lab No	T_t/T_s	Wet Bulk Density g cm^{-3}	Moisture Content % $^w/_w$	Silt & Clay %
A	S/120	0.461	1.391	18	29
A	S/120	0.461	1.448	18	29
A	S/120	0.388	1.270	17	29
A	S/120	0.471	1.368	20	29
A	S/120	0.306	0.955	19	29
A	S/120	0.335	1.081	1	29
A	S/120	0.453	1.307	0.1	29
A	S/120	0.262	0.900	0.1	29
A	S/120	0.283	0.900	0.1	29
A	S/120	0.425	1.307	0.1	29
A	S/120	0.349	1.081	1.0	29
A	S/120	0.412	1.270	17	29
A	S/120	0.495	1.448	18	29
A	S/120	0.468	1.368	20	29
A	S/120	0.320	0.955	19	29
A	S/124	0.499	1.460	26	42
A	S/123	0.409	1.226	5	55
A	S/123	0.530	1.498	6	55
A	S/123	0.456	1.447	7	55
A	S/123	0.458	1.416	22	55
A	S/123	0.366	1.242	22	55
A	S/123	0.290	0.980	22	55
B	S/36	0.560	1.530	9	9
B	S/36	0.480	1.450	1	9
B	S/36	0.300	0.950	8	9
B	S/36	0.630	1.640	16	9
B	S/36	0.380	1.180	15	9
B	S/36	0.430	1.360	1	9
B	S/30	0.396	1.280	2	27
B	S/30	0.690	1.700	26	27
B	S/30	0.733	1.790	32	27
B	S/30	0.310	0.960	16	27
B	S/30	0.286	0.890	6	27
B	S/30	0.378	1.250	2	27
B	S/142	0.350	1.130	4	90
B	S/142	0.330	1.020	23	90
B	S/142	0.280	0.860	19	90
B	S/142	0.400	1.260	30	90
B	S/142	0.515	1.440	40	90
B	S/120	0.705	1.801	27	29
B	S/120	0.867	1.933	23	29

	Fig. 9.10	Fig. 9.11
Type of Box	B	A and B
n	19	41
ΣX	25.424	52.742
$\bar{X}$	1.338	1.286
Σx^2	1.9644	2.9127

Appendix 2.7 The effect of wet bulk density on $\log_{10} T_t/T_s$ for two soils at various moisture contents using planar access boxes (MX 146 detector, 30 mCi Cs-137) (See Fig. 9.12).

Soil Lab Sample No.	T_t/T_s	Wet Bulk Density g cm^{-3}	Moisture Content % $^w/_w$	Silt + Clay %
S/124	0.460	1.300	15.5	42
S/124	0.365	1.730	20.6	42
S/124	0.315	0.939	20.5	42
S/124	0.423	1.090	10.0	42
S/124	0.399	1.090	10.5	42
S/124	0.469	1.190	15.2	42
S/124	0.562	1.340	20.5	42
S/124	0.756	1.586	14.3	42
S/124	0.924	1.810	13.8	42
S/120	0.578	1.462	18.3	29
S/120	0.966	1.782	19.1	29
S/120	0.337	0.940	19.2	29
S/120	0.503	1.301	20.0	29
S/120	0.667	1.511	17.4	29
S/120	0.447	1.297	17.4	29
S/120	0.374	1.060	1.3	29
S/120	0.966	1.776	25.3	29
S/120	0.300	0.933	0.1	29
S/120	0.494	1.384	0.4	29
S/120	0.930	1.782	19.1	29
S/120	0.361	0.940	19.2	29
S/120	0.484	1.301	20.0	29
S/120	0.685	1.511	17.4	29
S/120	0.450	1.297	17.4	29
S/120	0.377	1.060	1.3	29
S/120	0.939	1.776	25.3	29
S/120	0.311	0.933	0.1	29

ΣX 36.121 n = 27

$\bar{X}$ 1.338 Σx^2 2.4043

Appendix 2.8a Calculation of confidence limits for regression relation for data tabulated in Appendix 2.6 (Type B box) (See Fig. 9.10 and Table 9.4a)

Given: n 19 $1/n$ 0.05263 $1 + 1/n$ 1.0526

Σx^2 1.9644 S_B 0.0127

$\bar{X}$ 1.338 $S_B(\Sigma x^2)^{\frac{1}{2}}$ 0.017797

$t_{(.05)(17)}$ 2.110   B 0.4591   A -0.9638

Log_{10} Form

X_o	$1 + 1/n + \frac{(X_o-\bar{X})^2}{\Sigma x^2}$	$S_{\hat{Y}}$	$t_{(.05)(17)} S_{\hat{Y}}$	$\hat{Y}$	$\hat{Y} - tS_{\hat{Y}}$	$\hat{Y} + tS_{\hat{Y}}$
0.80	1.19990	0.019495	0.04112	-0.5965	-0.6376	-0.5554
1.20	1.06229	0.018339	0.03869	-0.4129	-0.4516	-0.3742
1.60	1.08754	0.018555	0.03914	-0.2292	-0.2683	-0.1901
2.00	1.27570	0.020103	0.04241	-0.0456	-0.0880	-0.0032

Anti-log_{10} Form

X_o	$\hat{Y}$	$\hat{Y} - tS_{\hat{Y}}$	$\hat{Y} + tS_{\hat{Y}}$
0.8	0.253	0.230	0.278
1.2	0.386	0.354	0.422
1.6	0.590	0.539	0.646
2.0	0.900	0.815	0.992

Appendix 2.8b Calculation of confidence limits for regression relation for data tabulated in Appendix 2.6 (Type A and B boxes (See Fig. 9.11 and Table 9.4a)

Given: n 41 $1/n$ 0.02439 $1 + 1/n$ 1.02439

Σx^2 2.9127 S_B 0.0114

$\bar{X}$ 1.286 $S_B(\Sigma x^2)^{\frac{1}{2}}$ 0.01946

$t_{(0.05)(39)}$ 2.021 B 0.4547 A -0.9625

Log$_{10}$ Form

X_o	$1 + 1/n + \frac{(X_o-\bar{X})^2}{\Sigma x^2}$	$S_{\hat{Y}}$	$t_{(.05)(39)} S_{\hat{Y}}$	$\hat{Y}$	$\hat{Y} - tS_{\hat{Y}}$	$\hat{Y} + tS_{\hat{Y}}$
0.80	1.10548	0.02046	0.04135	-0.5987	-0.6400	-0.5574
1.20	1.02693	0.01972	0.03985	-0.4169	-0.4567	-0.3771
1.60	1.05824	0.02002	0.04046	-0.2350	-0.2755	-0.1945
2.00	1.19939	0.02131	0.04307	-0.0531	-0.0962	-0.0100

Anti-log$_{10}$ Form

X_o	$\hat{Y}$	$\hat{Y} - tS_{\hat{Y}}$	$\hat{Y} + tS_{\hat{Y}}$
0.8	0.252	0.229	0.277
1.2	0.383	0.349	0.420
1.6	0.582	0.530	0.639
2.0	0.885	0.801	0.977

Appendix 2.8c Calculation of confidence limits for regression relation for data tabulated in Appendix 2.7 (Metal box) (See Fig. 9.12 and Table 9.4a)

Given: n 27 $1/n$ 0.03704 $1 + 1/n$ 1.03704

Σx^2 2.4043 S_B 0.0181

$\bar{X}$ 1.338 $S_B(\Sigma x^2)^{\frac{1}{2}}$ 0.028064

$t_{(0.05)(25)}$ 2.060 B 0.5438 A -1.0049

Log_{10} Form

X_o	$1 + 1/n + \frac{(X_o - \bar{X})^2}{\Sigma x^2}$	$S_{\hat{Y}}$	$t_{(.05)(25)}\ S_{\hat{Y}}$	$\hat{Y}$	$\hat{Y} - tS_{\hat{Y}}$	$\hat{Y} + tS_{\hat{Y}}$
0.8	1.1574	0.03018	0.06217	-0.5699	-0.6321	-0.5077
1.20	1.0449	0.02869	0.05910	-0.3523	-0.4114	-0.2932
1.60	1.0656	0.02896	0.05966	-0.1348	-0.1945	-0.0751
2.00	1.2193	0.03098	0.06382	+0.0827	+0.1465	+0.0189

Anti-log_{10} Form

X_o	$\hat{Y}$	$\hat{Y} - tS_{\hat{Y}}$	$\hat{Y} + tS_{\hat{Y}}$
0.8	0.269	0.233	0.310
1.20	0.444	0.388	0.509
1.60	0.733	0.639	0.841
2.00	1.210	1.402	1.044

APPENDIX 3: DATA RELEVANT TO CHAPTER 10

Appendix 3.1 Experimental data obtained in tests on the relation between the effective density of steel and count rate (See Fig. 10.5).

Count rate s^{-1}	Effective Density of Steel $g\ cm^{-3}$
524.3	0.0
444.9	0.19
383.8	0.38
301.9	0.56
229.0	0.75
168.1	0.94
119.8	1.13
87.2	1.32
63.6	1.50
45.0	1.69
31.2	1.88
21.3	2.07
15.6	2.26
11.0	2.44

Appendix 3.2 Experimental data obtained in tests on the effect of aperture and threshold setting on the relation between the thickness of steel and count rate (See Fig. 10.6).

Relation to Peak	Peak	Peak	Peak + 0.2V	Peak - 0.2V
Threshold	4.15 V	4.15 V	4.35 V	3.95 V
Aperture	0.2 V	Max	Max	Max
Thickness cm	Count Rate s^{-1}	Count Rate s^{-1}	Count Rate s^{-1}	Count Rate s^{-1}
0.00	199.4	681.0	-	845.7
0.683	174.4	528.0	-	640.8
1.366	151.6	394.5	269.2	491.8
2.049	120.1	290.6	190.1	362.2
2.732	91.9	207.2	128.3	260.0
3.416	69.3	147.2	90.1	187.9
4.099	51.0	103.3	61.9	134.2
4.783	37.1	73.8	43.3	91.2
5.466	25.6	52.6	30.5	68.1
6.149	-	38.1	21.9	49.3
6.883	-	27.0	16.1	33.6

Note : Data above the dashed lines _ _ _ _ were excluded from the regression analysis owing to non-linearity resulting from excessive count rate.

Appendix 3.3 Experimental data obtained in tests on the effect of aperture and threshold on the relation between the thickness of glass and count rate (See Fig. 10.7).

Nominal Threshold	Peak	Peak	Peak + 0.2V	Peak - 0.2V
Actual Threshold	4.15	4.15	4.35 V	3.95 V
Aperture	0.2	Max	Max	Max
Thickness, cm	Count rate, s^{-1}			
0	-	738.5	559.3	915.7
9.41	42.7	164.4	100.4	208.6
11.16	31.0	115.4	73.2	153.4
12.91	23.1	89.3	53.4	114.8
14.66	17.9	66.9	40.4	84.2
16.41	13.4	49.3	29.3	62.5
18.21	-	38.3	21.9	48.1
19.93	-	27.5	16.2	36.3
21.66	-	21.8	12.9	28.0

Note: Data above the dashed lines _ _ _ _ were excluded from the regression analysis owing to non-linearity resulting from excessive count rate.

Appendix 3.4 Experimental data obtained in tests on the effect of aperture and threshold setting on the relation between the thickness of water and count rate (See Fig. 10.8)

Nominal Threshold, V	Peak	Peak + 0.2V	Peak + 0.1V	Peak	Peak - 0.1V	Peak - 0.2V
Actual Threshold, V	4.20	4.40	4.30	4.20	4.10	4.00
Aperture , V	0.2	Max.	Max.	Max.	Max.	Max.
Thickness, cm	Count rate, s^{-1}					
0.00	100	409	474	564	643	709
1.18	94	366	430	509	582	657
2.37	89	332	395	480	549	611
3.55	85	303	372	444	506	570
4.74	82	273	328	402	471	532
5.92	79	247	302	381	434	489
7.10	73	229	281	353	399	450
8.28	69	208	256	326	367	415
9.47	64	190	236	298	334	378
10.65	60	170	207	275	314	346
11.84	56	154	197	250	286	325
13.02	54	135	170	229	-	-
14.20	50	123	159	211	245	272
15.39	47	112	147	192	-	-
16.57	44	102	134	178	199	228
17.75	40	90	121	162	-	-
18.94	37	84	113	146	-	-
20.12	35	77	105	136	-	-
21.31	33	69	95	127	146	162
22.49	-	62	82	115	-	-
23.67	28	55	73	107	123	138

Appendix 3.5 Experimental data obtained in tests on the relation between wet bulk density of soil S/36 and count rates at 4-5 and 11-13% moisture content (See Fig. 10.9)

Count rate s^{-1}	Wet Bulk Density $g\ cm^{-3}$	Moisture Content % $^{w}/_{w}$
179.8	0.899	4.5
160.9	0.926	4.4
118.1	1.145	4.7
77.7	1.395	5.2
67.2	1.474	4.9
54.6	1.572	4.6
53.7	1.590	5.1
142.9	0.970	13.4
151.1	1.003	11.4
102.4	1.202	12.6
72.0	1.428	12.3
51.3	1.585	13.1
40.4	1.727	14.1

APPENDIX 4: DATA RELEVANT TO CHAPTER 11

Appendix 4.1 Results for 64 standard exposure tests obtained in the field prior to improvement in source-detector alignment (See Section 11.1).

MX 146 detector: Time for 10,000 counts, s			
140.19	140.96	140.96	139.52
136.09	136.09	135.53	135.53
139.90	138.40	141.16	137.76
140.13	141.94	142.66	142.66
144.17	139.78	141.16	142.19
140.66	140.66	140.01	140.01
139.56	138.55	139.06	136.13
136.84	136.84	136.38	136.38
138.46	137.03	140.96	133.24
136.42	136.42	138.66	138.66
139.28	138.50	139.63	139.56
138.18	138.18	140.94	140.94
141.02	135.16	144.53	144.50
138.28	138.26	143.27	143.27
139.87	140.19	138.81	141.79
139.52	136.54	139.26	138.76

Appendix 4.2 The effect of control frame and probe movement and the number of counts collected on the precision of measurement of gamma-ray transmission with standard exposure (See Table 11.1).

No. of Counts collected	Time for collection of counts, s							
	20,000		10,000		5,000		2,000	
movement	Yes	No	Yes	No	Yes	No	Yes	No
	259.41	240.54	124.79	121.67	62.73	61.39	25.78	24.63
	251.18	241.46	120.73	120.62	62.31	59.47	25.13	24.87
	242.24	243.77	119.47	122.80	62.13	61.09	24.97	25.02
	248.57	244.41	121.03	123.17	60.59	60.50	24.94	25.08
	249.24	241.77	118.68	120.08	61.93	60.29	24.87	25.67
	251.30	242.18	123.53	121.22	62.50	59.69	25.60	24.11
	241.71	244.29	120.58	120.52	63.00	60.12	25.08	24.41
	240.73	242.94	121.33	120.76	61.54	58.97	25.71	24.85
	244.71	238.36	123.45	121.62	62.53	60.01	25.48	24.51
	238.80	241.98	121.39	120.71	60.60	60.97	24.17	24.72
	249.76	242.63	119.16	122.27	63.30	60.14	24.27	25.08
	246.67	242.25	118.26	122.58	61.35	60.05	24.82	24.09
	246.14	242.85	121.42	120.79	64.37	60.10	25.49	24.79
	244.00	242.53	117.87	120.76	64.49	59.13	25.23	25.38
	242.26	242.53	120.27	122.37	65.32	59.57	25.01	23.97
	244.88	244.67	124.82	122.61	61.76	58.95	24.90	24.85
	242.64	240.31	-	-	63.41	59.89	23.79	25.25
	241.47	239.28	-	-	65.98	57.78	24.26	23.34
	241.91	239.61	-	-	60.30	59.71	24.11	24.78
	241.71	242.59	-	-	59.19	60.50	24.45	24.46

Appendix 4.3 Results for 59 standard exposure tests obtained in the field after improvement in source-detector alignment (See Section 11.1)

MX 146 detector: Time for 5000 counts, s

43.53	43.91	43.94	44.16	43.26
42.67	44.20	42.68	43.93	41.85
43.08	42.76	43.78	44.25	43.23
42.89	43.87	43.21	42.99	42.78
43.21	43.16	43.09	42.75	43.96
43.86	42.98	44.15	43.99	42.18
43.55	42.60	43.70	42.89	42.98
44.76	43.73	43.76	41.80	42.33
42.59	44.39	42.69	43.22	42.57
43.12	43.31	42.96	43.50	43.04
42.86	42.58	43.63	42.57	41.81
42.17	42.37	42.89	43.40	-

Appendix 4.4 Experimental data obtained before and after passage of tractor wheels over loose soil (See Fig. 11.1 and Fig. 11.2).

After 'rotavation' before passage of tractor wheel

Depth below surface cm	Count Rate s^{-1}	Micrometer Reading in.	Moisture Content % $^{w}/w$	Wet Bulk Density $g\ cm^{-3}$	Dry Bulk Density $g\ cm^{-3}$
2.5	29.27	1.452	20.5	1.51	1.25
5.0	54.75	1.449	21.4	1.06	0.87
7.6	54.58	1.444	22.6	1.07	0.87
10.1	45.86	1.439	23.2	1.18	0.96
12.7	42.13	1.438	24.0	1.25	1.01
15.2	45.43	1.435	24.2	1.19	0.96
17.8	47.31	1.435	25.0	1.16	0.93
20.3	24.80	1.434	25.8	1.61	1.28
22.8	22.28	1.433	26.0	1.69	1.34
25.4	22.90	1.430	27.4	1.67	1.31
27.9	24.29	1.427	28.2	1.63	1.27
30.4	23.53	1.426	22.3	1.65	1.35
33.0	25.62	1.423	20.3	1.60	1.33
35.5	26.30	1.421	19.6	1.57	1.31
Surface level with respect to datum 10,3 in.					
After passage of tractor wheel					
2.5	21.65	-	20.5	1.72	1.43
5.0	21.31	-	22.6	1.73	1.41
7.6	21.38	-	23.6	1.73	1.40
10.1	22.50	-	24.2	1.69	1.36
12.7	21.50	-	25.5	1.72	1.37
15.2	22.69	-	26.1	1.69	1.34
17.8	24.48	-	28.3	1.63	1.27
20.3	26.65	-	27.0	1.57	1.24
22.8	24.38	-	20.7	1.63	1.35
25.4	25.27	-	20.2	1.60	1.33
27.9	27.78	-	19.1	1.54	1.29
30.4	29.52	-	19.5	1.49	1.25
33.0	31.48	-	20.2	1.45	1.21
35.5	32.57	-	19.6	1.43	1.19

Appendix 4.5 Experimental data obtained in raspberry cane nursery (Fig.11.4)

(A) In line of satisfactory sucker growth

Depth below Surface cm	Count Rate s^{-1}	Moisture Content % $^w/_w$	Wet Bulk Density g cm^{-3}	Dry Bulk Density g cm^{-3}
2.5	214.5	20.0	1.20	1.00
3.8	222.0	20.1	1.16	0.96
5.0	212.0	20.1	1.20	1.00
6.3	203.3	20.2	1.24	1.03
7.6	188.7	20.5	1.31	1.09
8.9	169.9	20.8	1.39	1.15
10.1	161.0	20.9	1.43	1.18
11.4	159.1	21.0	1.44	1.19
12.7	157.0	21.6	1.44	1.18
14.0	150.0	22.3	1.48	1.21
15.2	139.8	23.2	1.52	1.23
16.5	136.4	24.2	1.53	1.23
17.7	131.1	24.8	1.56	1.25
19.0	133.1	25.3	1.55	1.24
20.3	129.5	24.5	1.57	1.26
21.6	133.6	23.8	1.55	1.25
22.8	132.5	24.1	1.55	1.25
24.1	140.9	24.5	1.52	1.22
25.4	137.0	26.5	1.53	1.21
26.7	135.4	28.4	1.53	1.19
27.9	128.4	25.7	1.57	1.25
29.2	121.2	23.0	1.61	1.31
30.4	118.4	21.4	1.62	1.33
31.7	112.2	19.8	1.65	1.38
33.0	116.6	20.2	1.63	1.36
35.5	120.2	20.6	1.61	1.33

(B) In line of zero sucker emergence

Depth below Surface cm	Count Rate s^{-1}	Moisture Content % $^w/_w$	Wet Bulk Density g cm^{-3}	Dry Bulk Density g cm^{-3}
2.5	102.2	23.0	1.70	1.38
3.8	104.4	21.3	1.69	1.39
5.0	105.4	21.0	1.68	1.39
6.3	109.9	20.7	1.66	1.38
7.6	106.1	20.7	1.67	1.38
8.9	119.2	20.8	1.61	1.33
10.1	112.4	21.3	1.65	1.36
11.4	119.2	21.7	1.61	1.32
12.7	122.9	22.3	1.60	1.31
14.0	120.8	23.0	1.60	1.30
15.2	118.7	23.5	1.61	1.30
16.5	118.8	24.0	1.61	1.30
17.7	122.0	24.5	1.60	1.28
19.0	125.9	25.1	1.59	1.27
20.3	129.2	24.7	1.57	1.26
21.6	124.6	24.3	1.59	1.28
22.8	119.5	23.6	1.63	1.32
24.1	116.2	23.0	1.63	1.33
25.4	108.3	22.0	1.66	1.36
26.7	110.9	21.0	1.65	1.36
27.9	107.3	20.5	1.67	1.38

Appendix 4.6 Experimental data obtained under wheat crop (Fig. 11.6)

		Under wheel tracks			Away from wheel tracks			
Depth cm	T_t/T_s	Wet Bulk Density g cm^{-3}	Moisture Content % $^w/_w$	Dry Bulk Density g cm^{-3}	T_t/T_s	Wet Bulk Density g cm^{-3}	Moisture Content % $^w/_w$	Dry Bulk Density g cm^{-3}
Site A								
5.0	0.884	1.82	14.9	1.581	0.330	1.12	17.5	0.95
7.6	0.882	1.82	16.2	1.566	0.641	1.58	17.1	1.34
10.1	0.848	1.80	17.3	1.533	0.723	1.68	17.7	1.42
12.7	0.850	1.80	17.3	1.536	0.678	1.63	16.7	1.39
15.2	0.821	1.77	18.6	1.491	0.643	1.58	16.8	1.34
17.8	0.801	1.75	18.8	1.473	0.707	1.66	17.0	1.41
20.3	0.737	1.70	17.5	1.445	0.630	1.57	15.8	1.34
22.8	0.750	1.71	18.3	1.444				
Site B								
5.6	0.869	1.81	16.1	1.559	0.558	1.51	15.1	1.31
7.6	0.794	1.74	17.8	1.477	0.596	1.56	14.3	1.37
10.1	0.753	1.71	18.4	1.444	0.569	1.53	13.6	1.35
12.7	0.740	1.70	19.9	1.418	0.617	1.60	12.3	1.42
15.2	0.691	1.65	18.7	1.384	0.539	1.50	12.1	1.34
17.8	0.597	1.55	19.3	1.297	0.576	1.55	13.2	1.37
20.3	0.581	1.52	18.5	1.281	0.515	1.48	13.8	1.30
22.8	0.534	1.46	14.6	1.272	0.579	1.55	13.3	1.37

Appendix 4.7 Experimental data obtained under wheat stubble (Fig. 11.7).

		Under wheel tracks			Away from wheel tracks			
Depth cm	T_t/T_s	Wet Bulk Density g cm^{-3}	Moisture Content % $^w/_w$	Dry Bulk Density g cm^{-3}	T_t/T_s	Wet Bulk Density g cm^{-3}	Moisture Content % $^w/_w$	Dry Bulk Density g cm^{-3}
2.5	0.813	1.72	26.4	1.36	0.482	1.38	24.9	1.10
5.0	0.853	1.74	24.7	1.40	0.604	1.58	24.3	1.27
7.6	0.823	1.72	24.1	1.39	0.656	1.62	24.6	1.30
10.1	0.772	1.70	25.4	1.36	0.694	1.65	24.7	1.32
12.7	0.765	1.69	24.0	1.36	0.768	1.70	25.2	1.36
15.2	0.739	1.68	24.7	1.35	0.785	1.70	25.4	1.36
17.8	0.738	1.68	25.5	1.34	0.749	1.69	25.3	1.35
20.3	0.719	1.67	25.6	1.33	0.713	1.66	24.9	1.33
22.8	0.712	1.64	24.8	1.31	0.711	1.66	25.5	1.32
25.4	0.749	1.69	23.7	1.37	0.692	1.65	25.4	1.32
27.9	0.710	1.66	20.9	1.37	0.711	1.66	24.0	1.34
30.4	0.652	1.62	22.2	1.33	0.685	1.65	22.5	1.35
33.0	0.632	1.60	21.3	1.32	-	-	-	-

Appendix 4.8 Experimental data obtained in potato ridge and furrow (Fig. 11.8)

Row Index	Depth Index	T_t/T_s	Wet Bulk Density g cm^{-3}	Moisture Content % $^w/_w$	Dry Bulk Density g cm^{-3}	Row Index	Depth Index	T_t/T_s	Wet Bulk Density g cm^{-3}	Moisture Content % $^w/_w$	Dry Bulk Density g cm^{-3}
2	9	0.628	1.44	22	1.18	12	13	0.744	1.58	20	1.32
	11	0.880	1.73	22	1.42		14	0.953	1.79	24	1.44
	13	0.782	1.63	23	1.33		15	0.968	1.81	27	1.43
	14	0.862	1.71	24	1.38		16	0.848	1.70	28	1.33
	15	0.955	1.79	26	1.47	14	5	0.545	1.32	20	1.10
	16	0.965	1.80	28	1.41		7	0.517	1.28	22	1.05
4	7	0.534	1.31	22	1.07		9	0.616	1.43	20	1.19
	9	0.574	1.37	21	1.13		10	0.680	1.51	21	1.25
	11	0.783	1.62	22	1.33		10.5	0.696	1.53	21	1.26
	13	0.772	1.61	24	1.30		11	0.815	1.66	21	1.37
	14	0.705	1.54	26	1.22		12	0.863	1.71	21	1.41
	15	0.887	1.72	29	1.33		12.5	0.852	1.70	21	1.40
	16	0.839	1.69	28	1.32		13	0.840	1.69	21	1.40
6	5	0.513	1.27	21	1.05		14	0.959	1.80	22	1.48
	7	0.524	1.29	20	1.08		15	0.953	1.79	25	1.43
	9	0.592	1.39	21	1.15		16	0.816	1.66	26	1.32
	11	0.721	1.56	24	1.26	16	7	0.526	1.29	19	1.08
	13	0.751	1.59	27	1.25		9	0.651	1.47	20	1.23
	14	0.799	1.65	26	1.31		10	0.764	1.60	22	1.31
	15	0.864	1.71	25	1.37		10.5	0.829	1.68	23	1.37
	16	0.844	1.69	28	1.32		11	0.955	1.79	24	1.44
8	5	0.666	1.49	22	1.22		12	0.955	1.79	22	1.47
	7	0.517	1.28	22	1.05		12.5	0.955	1.79	21	1.48
	9	0.526	1.29	21	1.07		13	0.982	1.82	21	1.50
	11	0.628	1.44	23	1.17		14	0.968	1.81	27	1.43
	13	0.716	1.55	24	1.25		15	1.091	1.91	26	1.52
	14	0.792	1.64	26	1.30		16	1.007	1.84	22	1.51
	15	0.731	1.57	27	1.24	18	9	0.618	1.43	20	1.19
	16	0.747	1.59	28	1.24		10	0.777	1.62	22	1.33
10	5	0.586	1.39	22	1.14		10.5	0.845	1.69	23	1.37
	7	0.518	1.28	22	1.05		11	1.042	1.87	23	1.52
	9	0.480	1.21	27	0.95		12	1.036	1.86	23	1.51
	11	0.603	1.41	25	1.13		12.5	0.843	1.69	21	1.40
	13	0.716	1.55	23	1.26		13	1.118	1.93	21	1.60
	14	0.843	1.69	25	1.35		14	1.053	1.88	25	1.50
	15	0.783	1.63	25	1.30		15	1.099	1.92	23	1.56
	16	0.679	1.51	28	1.18		16	1.118	1.93	22	1.58
12	5	0.494	1.24	22	1.02	20	11	0.651	1.47	22	1.20
	7	0.468	1.19	24	0.96		12	1.247	2.02	24	1.63
	9	0.531	1.30	26	1.03		12.5	1.255	2.03	23	1.65
	10	0.607	1.41	23	1.15		13	1.275	2.04	22	1.67
	10.5	0.630	1.44	22	1.18		14	1.233	2.01	22	1.65
	11	0.692	1.52	21	1.26		15	1.125	1.94	22	1.59
	12	0.682	1.51	21	1.25		16	1.116	1.93	24	1.56
						22	12.5	1.231	2.01	24	1.62

Appendix 4.8 (continued)

Row Index	Depth Index	T_t/T_s	Wet Bulk Density g cm^{-3}	Moisture Content % $^w/_w$	Dry Bulk Density g cm^{-3}
22	13	1.277	2.04	24	1.65
	14	1.372	2.10	25	1.68
	15	1.275	2.04	24	1.65
	16	1.251	2.03	26	1.61
24	12.5	1.050	1.88	25	1.50
	13	1.236	2.01	26	1.60
	14	1.278	2.04	26	1.62
	15	1.325	2.07	25	1.66
	16	1.304	2.06	24	1.66
26	12	0.976	1.81	24	1.46
	12.5	1.161	1.96	25	1.57
	13	1.251	2.03	25	1.62
	14	1.283	2.05	25	1.68
	15	1.299	2.06	24	1.66
	16	1.239	2.01	24	1.62
28	12	1.170	1.97	24	1.59
	12.5	1.273	2.04	24	1.65
	13	1.292	2.05	24	1.65
	14	1.266	2.04	23	1.64
	15	1.225	2.01	22	1.65
	16	1.271	2.04	24	1.65
30	11	0.710	1.54	24	1.24
	12	1.249	2.02	24	1.63
	12.5	1.232	2.01	23	1.64
	13	1.201	1.99	23	1.62
	14	1.084	1.90	23	1.55
	15	1.068	1.89	22	1.55
	16	1.084	1.90	24	1.53
32	9	0.723	1.56	21	1.29
	10	0.918	1.76	22	1.44
	10.5	1.013	1.84	23	1.50
	11	1.122	1.93	24	1.56
	12	1.010	1.85	24	1.49
	12.5	1.006	1.84	24	1.48
	13	0.981	1.82	24	1.47
	14	0.948	1.79	24	1.44
	15	0.889	1.73	24	1.40
	16	0.980	1.82	24	1.47
34	5	0.475	1.20	20	1.00
	7	0.553	1.34	20	1.12
	9	0.678	1.51	21	1.25
	10	0.735	1.57	22	1.29
	10.5	0.796	1.64	22	1.34
	11	0.911	1.75	22	1.43
	12	0.932	1.77	24	1.43
34	12.5	0.897	1.74	25	1.39
	13	0.860	1.71	25	1.37
	14	0.884	1.73	25	1.38
	15	0.890	1.74	26	1.38
	16	0.943	1.78	25	1.42
36	5	0.446	1.15	20	0.96
	7	0.555	1.34	20	1.12
	9	0.631	1.45	21	1.20
	11	0.788	1.63	22	1.34
	12	0.753	1.59	24	1.28
	13	0.752	1.59	25	1.27
	14	0.875	1.72	23	1.40
	15	0.967	1.81	21	1.50
	16	0.988	1.82	25	1.46
38	5	0.457	1.17	20	0.96
	7	0.523	1.29	21	1.07
	9	0.561	1.33	21	1.10
	11	0.753	1.59	21	1.31
	12	0.751	1.59	25	1.27
	13	0.731	1.57	28	1.23
	14	0.770	1.62	26	1.28
	15	0.901	1.74	25	1.39
	16	1.032	1.86	25	1.49
40	5	0.478	1.21	20	1.01
	7	0.578	1.37	21	1.13
	9	0.555	1.34	21	1.11
	11	0.783	1.63	21	1.35
	12	0.732	1.57	25	1.26
	13	0.797	1.64	28	1.28
	14	0.743	1.58	26	1.25
	15	0.951	1.79	25	1.43
	16	0.968	1.81	25	1.45
42	5	0.462	1.18	19	0.99
	7	0.556	1.34	20	1.12
	9	0.602	1.41	19	1.18
	11	0.778	1.62	20	1.35
	13	0.745	1.58	27	1.24
	14	0.795	1.64	26	1.30
	15	0.929	1.77	23	1.44
	16	1.010	1.85	25	1.48
44	5	0.477	1.21	20	1.01
	7	0.462	1.18	20	0.98
	9	0.643	1.46	21	1.31
	11	0.743	1.58	21	1.31
	13	0.748	1.59	25	1.27

Appendix 4.8 (continued)

Row Index	Depth Index	T_t/T_s	Wet bulk Density $g\ cm^{-3}$	Moisture Content $\%\ ^w/_w$	Dry Bulk Density $g\ cm^{-3}$
44	14	0.771	1.61	27	1.28
	15	0.723	1.56	26	1.24
	16	1.036	1.86	26	1.48
46	9	0.593	1.39	21	1.15
	11	0.827	1.67	21	1.38
	13	0.817	1.66	22	1.36
	14	0.875	1.72	25	1.38
	15	0.815	1.66	28	1.30
	16	0.954	1.79	27	1.41
48	11	0.703	1.54	21	1.27
	13	0.885	1.73	23	1.41
	14	0.939	1.78	24	1.44
	15	0.887	1.73	24	1.40
	16	0.983	1.82	26	1.44
50	14	0.835	1.68	22	1.38
	15	0.905	1.75	23	1.42
	16	0.961	1.80	24	1.45

Appendix 4.9 Experimental data obtained in cross section of ploughed soil (Figs 11.9a and b)

Row Index	Depth Index	T_t/T_s	Wet bulk Density g cm^{-3}	Moisture Content % w/w	Dry Bulk Density g cm^{-3}
2	4	0.605	1.45	31.7	1.10
	5	0.881	1.74	31.4	1.32
	6	0.878	1.74	31.0	1.33
	7	0.828	1.70	30.2	1.31
	8	0.849	1.72	29.3	1.33
	9	0.892	1.75	29.9	1.35
	10	0.771	1.64	30.5	1.26
	11	0.807	1.68	30.8	1.28
	12	0.847	1.72	31.0	1.31
	13	0.808	1.68	30.8	1.28
	14	0.817	1.69	30.5	1.29
	15	0.892	1.75	29.0	1.36
	16	1.002	1.84	26.5	1.45
4	4	0.672	1.53	36.5	1.12
	5	0.962	1.81	33.5	1.36
	6	0.930	1.78	30.6	1.36
	7	0.932	1.78	39.8	1.37
	8	0.939	1.79	28.9	1.40
	9	0.959	1.81	29.0	1.40
	10	0.933	1.78	29.1	1.38
	11	0.923	1.77	31.9	1.29
	12	0.913	1.77	34.6	1.31
	13	0.852	1.72	31.3	1.31
	14	0.887	1.75	27.9	1.37
	15	0.940	1.79	27.2	1.41
	16	0.986	1.83	26.5	1.45
6	4	0.727	1.60	42.4	1.12
	5	0.924	1.77	37.1	1.29
	6	0.947	1.80	31.8	1.37
	7	0.884	1.74	30.7	1.33
	8	0.961	1.81	29.5	1.40
	9	0.955	1.80	29.1	1.39
	10	0.972	1.82	28.7	1.41
	11	0.962	1.81	32.7	1.36
	12	0.978	1.82	36.7	1.33
	13	0.941	1.79	34.0	1.34
	14	0.861	1.72	32.7	1.29
	15	0.912	1.77	29.9	1.36
	16	0.982	1.82	27.1	1.43
7	4	0.694	1.55	42.4	1.09
	5	0.923	1.77	37.1	1.29
	6	0.952	1.80	31.8	1.37
	7	0.958	1.81	30.7	1.38
	8	0.982	1.82	29.5	1.41
	9	1.030	1.85	29.1	1.43
7	10	1.040	1.86	28.7	1.44
	11	1.049	1.86	32.7	1.40
	12	0.999	1.84	36.7	1.35
	13	0.938	1.79	34.0	1.34
	14	0.903	1.76	32.7	1.33
	15	0.949	1.80	29.9	1.39
	16	1.057	1.87	27.1	1.47
10	11	0.453	1.22	32.7	0.92
	12	0.797	1.67	36.7	1.22
	13	0.986	1.83	34.0	1.37
	14	0.936	1.79	32.4	1.35
	15	0.920	1.77	31.3	1.35
	15½	0.985	1.82	30.7	1.39
	16	1.106	1.89	30.1	1.45
12	15	0.582	1.42	33.4	1.06
	16	1.053	1.86	34.4	1.38
14	15	0.611	1.46	34.2	1.09
	16	1.049	1.86	36.2	1.36
16	15	0.581	1.42	32.0	1.08
	16	1.045	1.86	35.0	1.38
18	15	0.672	1.53	29.0	1.19
	16	1.054	1.86	31.8	1.41
20	15	0.679	1.54	28.0	1.20
	16	1.003	1.84	30.3	1.41
22	15	0.779	1.65	23.0	1.34
	16	1.002	1.85	25.3	1.47
24	15	0.750	1.61	26.5	1.27
	16	1.031	1.85	28.5	1.44
26	13	0.389	1.10	28.0	0.86
	14	0.458	1.24	30.3	0.95
	15	0.881	1.74	30.0	1.33
	16	0.998	1.84	29.6	1.42
28	6	0.479	1.27	29.2	0.98
	7	0.651	1.50	29.6	1.16
	8	0.621	1.47	29.9	1.13
	9	0.661	1.52	30.9	1.16
	10	0.685	1.54	31.9	1.17
	11	0.818	1.69	32.6	1.28
	12	0.707	1.57	33.2	1.18
	13	0.509	1.31	32.0	0.99
	14	0.467	1.25	30.8	0.96
	15	0.691	1.55	29.2	1.20
	16	0.926	1.78	27.5	1.40
30	2	0.489	1.29	29.5	0.99
	3	0.519	1.32	29.5	1.02

Appendix 4.9 (continued)

Row Index	Depth Index	T_t/T_s	Wet bulk Density g cm^{-3}	Moisture Content % w/w	Dry Bulk Density g cm^{-3}
30	4	0.582	1.41	29.5	1.10
	5	0.650	1.50	29.6	1.16
	6	0.600	1.44	29.6	1.11
	7	0.599	1.44	29.9	1.11
	8	0.557	1.39	30.2	1.07
	9	0.554	1.38	30.4	1.06
	10	0.724	1.58	30.6	1.21
	11	0.713	1.57	34.6	1.17
	12	0.661	1.52	38.5	1.10
	13	0.482	1.27	34.2	0.95
	14	0.415	1.14	29.8	0.88
	15	0.667	1.53	28.4	1.19
	16	0.925	1.77	27.0	1.39
32	2	0.689	1.55	28.9	1.20
	3	0.660	1.52	28.0	1.19
	4	0.695	1.56	27.1	1.23
	5	0.721	1.58	27.8	1.24
	6	0.619	1.47	28.5	1.14
	7	0.615	1.47	29.0	1.14
	8	0.605	1.44	29.5	1.11
	9	0.738	1.60	30.4	1.23
	10	0.648	1.50	31.2	1.14
	11	0.618	1.47	35.6	1.08
	12	0.563	1.39	39.9	0.99
	13	0.473	1.25	35.2	0.92
	14	0.45	1.22	30.5	0.94
	15	0.64	1.49	30.7	1.14
	16	0.96	1.81	30.8	1.38
34	2	0.585	1.42	27.9	1.11
	3	0.615	1.46	29.2	1.13
	4	0.616	1.47	30.4	1.13
	5	0.628	1.48	29.3	1.14
	6	0.604	1.30	28.2	1.01
	7	0.559	1.39	29.4	1.07
	8	0.602	1.44	30.6	1.10
	9	0.715	1.57	30.4	1.20
	10	0.693	1.55	30.2	1.19
	11	0.600	1.44	34.6	1.07
	12	0.475	1.27	38.9	0.91
	13	0.436	1.20	34.3	0.89
	14	0.505	1.30	29.7	1.00
	15	0.714	1.57	29.2	1.21
	16	0.906	1.77	28.7	1.38
36	3	0.296	0.90	27.6	0.71
	4	0.454	1.22	30.8	0.93
	5	0.568	1.40	30.3	1.07
	6	0.531	1.35	29.7	1.04
36	7	0.471	1.25	35.8	0.92
	8	0.475	1.25	41.8	0.88
	9	0.453	1.22	44.0	0.85
	10	0.468	1.25	46.2	0.86
	11	0.474	1.25	41.1	0.89
	12	0.475	1.25	36.0	0.92
	13	0.547	1.38	32.8	1.04
	14	0.614	1.46	29.5	1.13
	15	0.78	1.65	29.7	1.27
	16	0.987	1.83	29.8	1.41
38	7	0.305	0.91	37.5	0.66
	8	0.303	0.90	32.7	0.68
	9	0.358	1.04	33.9	0.78
	10	0.503	1.30	35.1	0.96
	11	0.627	1.48	38.2	1.07
	12	0.645	1.49	41.2	1.06
	13	0.698	1.56	36.8	1.14
	14	0.628	1.48	32.4	1.12
	15	0.748	1.61	30.8	1.23
	16	0.815	1.68	29.1	1.30
40	6	0.485	1.27	30.1	0.98
	7	0.598	1.44	31.0	1.10
	8	0.646	1.50	31.8	1.14
	9	0.732	1.60	32.4	1.21
	10	0.783	1.65	32.9	1.24
	11	0.976	1.82	33.0	1.37
	12	0.921	1.77	33.1	1.33
	13	0.755	1.63	32.6	1.23
	14	0.465	1.24	32.0	0.94
	15	0.784	1.65	32.1	1.25
	16	0.940	1.79	32.1	1.36
42	5	0.349	1.02	30.0	0.78
	6	0.383	1.08	32.8	0.81
	7	0.474	1.25	32.5	0.94
	8	0.674	1.53	32.2	1.16
	9	0.795	1.66	32.0	1.26
	10	0.848	1.72	31.8	1.30
	11	0.875	1.73	34.0	1.29
	12	0.734	1.60	36.1	1.18
	13	0.385	1.09	33.9	0.81
	14	0.280	0.84	31.7	0.64
	15	0.713	1.57	32.1	1.19
	16	0.972	1.82	32.1	1.38
44	5	0.362	1.04	31.5	0.79
	6	0.321	0.94	31.8	0.71
	7	0.386	1.10	31.0	0.84
	8	0.403	1.12	30.2	0.86

Appendix 4.9 (continued)

Row Index	Depth Index	T_t/T_s	Wet Bulk Density $g\ cm^{-3}$	Moisture Content % $^w/_w$	Dry Bulk Density $g\ cm^{-3}$
44	9	0.49	1.29	31.0	0.98
	10	0.510	1.31	31.7	1.00
	11	0.372	1.06	35.9	0.78
	12	0.363	1.04	40.0	0.74
	13	0.439	1.20	36.0	0.88
	14	0.450	1.22	32.0	0.92
	15	0.724	1.59	29.3	1.23
	16	1.032	1.85	26.6	1.46
46	5	0.358	1.04	33.2	0.78
	6	1.514	1.31	32.3	0.99
	7	0.555	1.38	33.1	1.04
	8	0.731	1.60	33.8	1.20
	9	0.745	1.60	32.6	1.21
	10	6.673	1.53	31.3	1.16
	11	0.581	1.42	48.3	0.96
	12	0.522	1.32	65.2	0.80
	13	0.444	1.20	48.1	0.81
	14	0.461	1.24	31.0	0.95
	15	0.69	1.55	29.0	1.20
	16	1.040	1.86	27.0	1.46
48	4	0.312	0.92	32.3	0.69
	5	0.463	1.24	31.9	0.94
	6	0.574	1.40	31.5	1.06
	7	0.644	1.49	32.1	1.13
	8	0.678	1.54	32.6	1.16
	9	0.638	1.49	31.4	1.13
	10	0.553	1.38	30.1	1.06
	11	0.498	1.30	31.8	0.99
	12	0.388	1.10	33.4	0.83
	13	0.352	1.02	31.9	0.77
	14	0.485	1.27	30.4	0.97
	15	0.660	1.52	29.1	1.18
	16	0.959	1.81	27.8	1.42
50	3	0.359	1.04	31.5	0.79
	4	0.444	1.20	31.9	0.91
	5	0.589	1.43	30.9	1.09
	6	0.602	1.44	29.9	1.11
	7	0.669	1.53	33.7	1.11
	8	0.655	1.51	36.6	1.10
	9	0.448	1.22	35.4	0.90
	10	0.297	0.89	34.2	0.66
	11	0.282	0.84	34.3	0.62
	12	0.342	0.99	34.4	0.74
	13	0.462	1.24	31.6	0.94
50	14	0.496	1.30	28.8	1.01
	15	0.684	1.54	27.8	1.20
	16	0.977	1.82	26.8	1.44
52	2	0.337	0.99	32.6	0.75
	3	0.470	1.25	32.2	0.95
	4	0.586	1.43	31.7	1.09
	5	0.644	1.49	30.7	1.14
	6	0.475	1.26	29.7	0.97
	7	0.448	1.22	31.7	0.93
	8	0.347	1.02	33.7	0.76
	9	0.387	1.10	40.6	0.78
	10	0.392	1.10	47.5	0.75
	11	0.563	1.39	40.5	0.99
	12	0.651	1.50	33.4	1.12
	13	0.611	1.46	32.5	1.10
	14	0.669	1.53	31.6	1.16
	15	0.661	1.52	28.7	1.18
	16	0.889	1.75	25.8	1.39

Appendix 4.11a Dry bulk density results obtained in uniformity trial at South Road Field, Oct - Nov 1967 (See Table 11.3)

* S = 'Shallow ploughing', D = 'Deep ploughing', C = 'Chisel ploughing', Z = 'Zero ploughing'

Depth cm	Rep	'S1'	'S2'	'D1'	'D2'	'C1'	'C2'	'Z1'	'Z2'
2.5	1	1.219	1.182	1.188	1.322	1.349	1.063	1.195	1.221
	2	1.351	1.357	1.338	1.087	1.267	1.006	1.254	1.269
	3	1.366	1.155	1.075	1.373	1.064	1.224	1.093	1.230
	4	1.084	1.210	1.150	1.139	1.368	1.287	1.256	1.340
	5	1.405	1.204	1.380	1.115	1.315	1.319	1.301	1.301
	6	0.999	1.123	1.250	1.203	1.114	1.114	1.427	1.329
	7	1.310	1.251	1.038	1.259	1.123	1.061	1.263	1.236
	8	1.142	1.253	1.329	1.182	1.310	1.126	1.480	1.318
7.6	1	1.156	1.185	1.351	1.357	1.333	1.017	1.233	1.278
	2	1.315	1.217	1.364	1.318	1.320	1.175	1.350	1.280
	3	1.234	1.051	1.072	1.357	1.181	1.171	1.043	1.280
	4	1.008	1.241	1.136	1.204	1.354	1.367	1.240	1.357
	5	1.508	1.436	1.457	1.273	1.216	1.328	1.433	1.335
	6	1.208	1.320	1.451	1.189	1.003	1.048	1.413	1.391
	7	1.368	1.345	1.011	1.425	1.343	1.202	1.223	1.308
	8	1.288	1.214	1.350	1.358	1.335	1.213	1.304	1.344
12.7	1	1.066	1.110	1.320	1.373	1.309	0.984	1.132	1.202
	2	1.260	1.173	1.189	1.127	1.305	1.039	1.274	1.206
	3	1.219	1.065	1.102	1.279	1.194	1.136	1.042	1.252
	4	0.987	1.226	1.155	1.166	1.302	1.224	1.195	1.323
	5	1.315	1.427	1.289	1.065	1.138	1.283	1.330	1.313
	6	1.221	1.345	1.337	1.026	1.215	1.002	1.375	1.320
	7	1.327	1.335	0.985	1.383	1.270	1.239	1.347	1.236
	8	1.271	1.074	1.392	1.392	1.337	1.183	1.236	1.388
17.8	1	1.052	1.066	1.257	1.252	1.189	1.141	1.158	1.204
	2	1.273	1.139	1.169	1.039	1.229	1.058	1.300	1.178
	3	1.155	1.069	1.045	1.146	1.102	1.122	1.082	1.294
	4	0.977	1.236	1.111	1.206	1.279	1.173	1.061	1.254
	5	1.223	1.361	1.160	1.165	1.049	1.263	1.229	1.209
	6	1.120	1.333	1.292	1.121	1.178	1.082	1.330	1.324
	7	1.307	1.189	1.048	1.342	1.114	1.189	1.254	1.273
	8	1.207	1.052	1.159	1.373	1.292	1.163	1.205	1.327
22.9	1	1.072	1.056	1.234	1.148	1.136	1.014	1.263	1.276
	2	1.200	1.155	1.144	1.107	1.243	1.070	1.126	1.246
	3	1.222	1.052	1.126	1.302	1.095	1.303	0.980	1.215
	4	1.056	1.168	1.066	1.172	1.331	1.153	1.120	1.332
	5	1.464	1.515	1.192	1.379	1.135	1.149	1.173	1.172
	6	1.080	1.202	1.332	1.208	1.070	0.992	1.365	1.304
	7	1.280	1.196	1.101	1.194	1.180	1.203	1.141	1.262
	8	1.118	1.233	1.230	1.331	1.266	1.130	1.147	1.206
27.9	1	1.113	1.128	1.318	1.312	1.308	1.289	1.250	1.291
	2	1.412	1.335	1.250	1.169	1.318	1.247	1.266	1.324
	3	1.537	1.387	1.481	1.528	1.481	1.478	1.455	1.293
	4	1.309	1.379	1.241	1.347	1.538	1.288	1.319	1.448
	5	1.654	1.625	1.365	1.474	1.436	1.358	1.279	1.351
	6	1.293	1.292	1.548	1.428	1.104	1.228	1.681	1.412
	7	1.394	1.526	1.335	1.380	1.348	1.381	1.361	1.429
	8	1.189	1.360	1.541	1.507	1.591	1.486	1.595	1.654

* Treatments not yet applied

Appendix 4.11b Analyses of variance for bulk density results for different depths in uniformity trial, South Road Field Oct - Nov 1968 (See Table 9.3)

Depth cm	Source of Variation	D.F.	SS	MS	F	Sig. of F value
2.5	Reps	7	0.074			
	Treatments	3	0.068	0.0226	1.70	n.s
	Expt. error	21	0.279	0.0133		
	Sampling error	30*	0.365	0.0121		
	Total	61*	0.786			
7.6	Reps	7	0.190			
	Treatments	3	0.058	0.019	1.32	n.s.
	Expt. error	21	0.306	0.015		
	Sampling error	32	0.375	0.012		
	Total	63	0.929			
12.7	Reps	7	0.114			
	Treatments	3	0.034	0.011	0.86	n.s.
	Expt. error	21	0.279	0.013		
	Sampling error	31*	0.443	0.014		
	Total	62*	0.870			
17.8	Reps	7	0.069			
	Treatments	3	0.042	0.014	2.01	n.s.
	Expt. error	21	0.148	0.007		
	Sampling error	32	0.314	0.010		
	Total	63	0.573			
22.9	Reps	7	0.085			
	Treatments	3	0.029	0.010	0.56	n.s.
	Expt. error	21	0.361	0.017		
	Sampling error	32	0.242	0.008		
	Total	63	0.716			
27.9	Reps	7	0.377			
	Treatments	3	0.012	0.004	0.15	n.s.
	Expt. error	21	0.548	0.026		
	Sampling error	32	0.183	0.006		
	Total	63	1.119			

* Reduced on account of missing plot(s)

Appendix 4.11c Bartlett's test for homogeneous experimental and sampling variances, bulk density tests at different depths in uniformity trial, South Road Field (See Table 11.3)

Depth	Experimental Error		Sampling Error	
cm	Variance	D.F.	Variance	D.F.
2.5	0.0133	21	0.0121	30
7.6	0.0151	21	0.0120	32
12.7	0.0130	21	0.0140	31
17.8	0.0070	21	0.0100	32
22.9	0.0170	21	0.0080	32
27.9	0.0260	21	0.0060	32
χ^2(calculated)		8.79	7.22	
χ^2(tabulated) (D.F. = 5, P = 0.05)		11.07	11.07	
Pooled Variance		0.0152	0.0103	
Pooled S.E.		0.0308		

Appendix 4.11d Calculations of effect of varying number of samples per plot on experimental precision

The pooled experimental error variance, 0.0152, is an estimate of

$$\hat{\sigma}_s^2 + n\,\hat{\sigma}_e^2$$

where $\hat{\sigma}_s^2$ is the pooled sampling error variance of which $S_s^2 = 0.0103$ is an estimate and n is the number of samples per plot for each depth, in this case n = 2.

∴ S_e^2 is found to be 0.0024. Given an overall mean density $\bar{\bar{X}} = 1.246$ and r = 8 replications these values may be substituted in the relation

$$t_{(.05)(21)} = \frac{\bar{\bar{X}}_1 - \bar{\bar{X}}_2}{S_{\bar{x}_1 - \bar{x}_2}} = \frac{\bar{\bar{X}}_1 - \bar{\bar{X}}_2}{\sqrt{2}\sqrt{\dfrac{S_s^2 + n\,S_e^2}{8\,n}}} = 2.08$$

where $\bar{\bar{X}}_1$ and $\bar{\bar{X}}_2$ are two treatment means. A given difference between $\bar{\bar{X}}_1$ and $\bar{\bar{X}}_2$ can be expressed as a proportion, p_1 of $\bar{\bar{X}}$, therefore

$$\bar{\bar{X}}_1 - \bar{\bar{X}}_2 = p\,\bar{\bar{X}} = 1.246\ p$$

$$p^2(1.246)^2 = (2.08)^2\ 2\left(\frac{S_s^2}{8n} + \frac{S_e^2}{8}\right)$$

$$1.554\ p^2 = \frac{4.3264}{8}\ 2\left(\frac{0.0103}{n} + 0.0024\right)$$

$$1.554\ p^2 = 1.082\left(\frac{0.0103}{n} + 0.0024\right)$$

$$1.436\ p^2 = \frac{0.0103}{n} + 0.0024$$

Appendix 4.11d (continued)

This equation can be used to calculate the value of p for different values of n and results for n = 1 to 4 are shown below.

Samples per plot at a given depth n	% differences in treatment means detectable at probability of 95% 100 p
4	5.9
3	6.4
2	7.2
1	9.4

Appendix 4.12a Dry bulk density results obtained at time of emergence in field experiment on ploughing methods at South Road Field (See Fig. 11.13 and Table 11.5)

D = Deep ploughing, S = Shallow ploughing, C = Chisel ploughing,
Z = Zero ploughing

Depth	Rep.	Dry bulk density, g cm^{-3}							
cm		D1	D2	S1	S2	C1	C2	Z1	Z2
2.5	1	1.078	1.069	1.113	1.089	1.302	1.074	1.240	1.224
	2	1.073	1.097	0.993	1.104	1.105	0.929	1.001	1.285
	3	1.142	1.270	0.962	1.049	0.901	0.993	1.247	1.121
	4	1.055	1.202	0.950	0.977	1.085	1.119	1.099	1.183
	5	1.366	1.113	1.120	1.102	1.008	1.163	1.361	1.224
	6	1.108	0.938	1.068	1.078	1.006	0.875	1.287	1.225
	7	1.048	1.074	1.016	1.079	1.067	1.050	1.105	1.346
	8	0.885	1.081	1.147	1.106	1.162	1.053	1.108	1.239
7.5	1	1.179	1.064	1.276	1.286	1.352	1.154	1.242	1.361
	2	1.189	1.213	1.076	1.187	1.189	1.049	1.284	1.351
	3	1.142	1.288	1.040	1.133	1.290	1.156	1.408	1.297
	4	1.350	1.244	1.044	1.241	1.274	1.158	1.312	1.288
	5	1.348	1.336	1.084	1.333	1.204	1.252	1.429	1.453
	6	1.275	1.212	1.179	1.358	1.012	1.149	1.447	1.476
	7	1.134	1.259	1.351	1.397	1.191	1.279	1.436	1.499
	8	1.191	1.451	1.235	1.392	1.256	1.192	1.363	1.412
12.7	1	1.360	1.095	1.327	1.346	1.354	1.245	1.085	1.209
	2	1.354	1.309	1.132	1.237	1.315	0.893	1.159	1.330
	3	1.289	1.232	0.998	1.049	1.177	1.272	1.339	1.320
	4	1.150	1.233	1.031	1.210	1.268	1.253	1.323	1.263
	5	1.490	1.316	1.290	1.300	1.246	1.379	1.311	1.449
	6	1.331	1.217	1.217	1.198	1.132	1.089	1.470	1.395
	7	1.304	1.284	1.377	1.293	1.277	1.259	1.376	1.409
	8	1.376	1.467	1.227	1.338	1.341	1.381	1.404	1.391
17.8	1	1.369	1.112	1.358	1.222	1.361	1.170	1.157	1.158
	2	1.353	1.356	1.047	1.235	1.380	1.004	1.176	1.207
	3	1.179	1.192	1.120	1.289	1.192	1.445	1.203	1.275
	4	1.230	1.366	0.984	1.217	1.243	1.237	1.226	1.180
	5	1.423	1.390	1.410	1.411	1.183	1.316	1.291	1.357
	6	1.290	1.179	1.414	1.357	1.124	1.115	1.405	1.454
	7	1.234	1.338	1.375	1.393	1.300	1.241	1.324	1.382
	8	1.395	1.457	1.218	1.452	1.355	1.369	1.330	1.282

Appendix 4.12a (continued)

Depth cm	Rep.	D1	D2	S1	S2	C1	C2	Z1	Z2
22.9	1	1.300	1.080	1.228	1.247	1.313	1.306	1.167	1.144
	2	1.343	1.295	1.311	1.242	1.347	1.203	1.180	1.168
	3	1.164	1.278	1.293	1.337	1.278	1.292	1.145	1.155
	4	1.144	1.298	1.056	1.310	1.173	1.295	1.193	1.158
	5	1.414	1.340	1.424	1.469	1.249	1.308	1.225	1.399
	6	1.256	1.208	1.422	1.272	1.290	1.135	1.477	1.472
	7	1.200	1.474	1.287	1.493	1.320	1.331	1.381	1.362
	8	1.415	1.522	1.297	1.318	1.309	1.297	1.327	1.267
27.9	1	1.262	1.158	1.237	1.264	1.378	1.352	1.271	1.352
	2	1.262	1.290	1.356	1.407	1.301	1.306	1.306	1.250
	3	1.206	1.336	1.633	1.502	1.493	1.511	1.412	1.303
	4	1.235	1.264	1.246	1.244	1.369	1.557	1.427	1.403
	5	1.474	1.282	1.734	1.699	1.424	1.657	1.543	1.495
	6	1.244	1.241	1.500	1.400	1.475	1.325	1.653	1.635
	7	1.206	1.403	1.426	1.610	1.556	1.539	1.656	1.653
	8	1.522	1.540	1.407	1.419	1.347	1.475	1.734	1.675
33.0	1	1.341	1.185	1.591	1.346	1.482	1.597	1.392	1.402
	2	1.192	1.417	1.477	1.455	1.410	1.427	1.299	1.308
	3	1.421	1.716	1.770	1.630	1.676	1.204	1.678	1.111
	4	1.522	1.648	1.313	1.357	1.494	1.554	1.562	1.445
	5	1.766	1.438	1.659	1.801	1.567	1.662	1.598	1.618
	6	1.407	1.297	1.621	1.518	1.634	1.425	1.739	1.798
	7	1.327	1.220	1.643	1.698	1.783	1.639	1.611	1.621
	8	1.519	1.650	1.745	1.682	1.528	1.584	1.712	1.747

Appendix 4.12b Analyses of variance for dry bulk density results for different depths for South Road Field experiment at time of emergence

Depth cm	Source of Variation	D.F.	S.S.	M.S.	F	Sig. of F
2.5	Reps	7	0.086	0.012		
	Treatments	3	0.235	0.078	8.04	**
	Expt. error	21	0.205	0.010		
	Sampling error	32	0.273	0.009		
	Total	63	0.799			
7.6	Reps	7	0.122	0.017		
	Treatments	3	0.312	0.104	9.93	**
	Expt. error	21	0.220	0.010		
	Sampling error	32	0.239	0.007		
	Total	63	0.893			
12.7	Reps	7	0.222	0.032		
	Treatments	3	0.113	0.038	2.75	n.s.
	Expt. error	21	0.289	0.014		
	Sampling error	32	0.248	0.008		
	Total	63	0.872			
17.8	Reps	7	0.197	0.028		
	Treatments	3	0.022	0.007	0.50	n.s.
	Expt. error	21	0.302	0.014		
	Sampling error	32	0.296	0.009		
	Total	63				
22.9	Reps	7	0.216	0.031		
	Treatments	3	0.022	0.007	0.66	n.s.
	Expt. error	21	0.232	0.011		
	Sampling error	32	0.210	0.007		
	Total	63	0.680			
27.9	Reps	7	0.537	0.077		
	Treatments	3	0.285	0.095	4.29	*
	Expt. error	21	0.466	0.022		
	Sampling error	32	0.165	0.005		
	Total	63	1.453			
33.0	Reps	7	0.531	0.076		
	Treatments	3	0.170	0.057	1.92	n.s.
	Expt. error	21	0.620	0.030		
	Sampling error	32	0.552	0.017		
	Total	63	1.874			

Appendix 4.12c Bartlett's test for homogeneous experimental and sampling error variances for bulk density tests at different depths at South Road Field at time of emergence (See Table 11.5)

Depth	Experimental Error		Sampling Error	
cm	Variance	D.F.	Variance	D.F.
2.5	0.0098	21	0.0085	32
7.6	0.0105	21	0.0075	32
12.7	0.0138	21	0.0077	32
17.8	0.0144	21	0.0092	32
22.9	0.0111	21	0.0066	32
27.9	0.0222	21	0.0051	32
33.0	0.0295	21	0.0172	32
χ^2(Calculated)	11.46	6	14.89	6
χ^2(Tabulated)	12.6 (0.05)(6)		12.6	
s^2 (pooled)	0.0159		0.0088	
$s_{\bar{Y}}$ (pooled)	0.0315			

Appendix 4.12d Analysis of variance for dry bulk density results obtained at time of emergence of barley at South Road Field using pooled data for all depths and a split-plot design with systematic arrangement of sub-plot treatments (2 samples per plot per depth averaged before analysis)

Source	D.F.	S.S.	M.S.	F	Sig. of F
Reps	7	0.699531	0.099933		
Ploughing Treatments	3	0.173568	0.057856	2.11	n.s
Error (a)	21	0.576272	0.027441		
Depths	6	3.388569	0.564760	-	-
Error (b)	42	0.253862	0.006044		
Treatments x Depths	18	0.403569	0.022420	4.76	***
Error (c)	126	0.593090	0.004707		
Total	223	6.088461			

For comparison of the effect of two ploughing treatments at any one depth the appropriate standard error of treatment differences is given by

$$S_{\bar{Y}_1 - \bar{Y}_2} = \sqrt{2\left[(b-1)E_c + E_a\right]/rb} = 0.0446 \text{ g cm}^{-3}$$

where in this case b is the number of depths, r is the number of replications and E_c and E_a are the mean squares for error (c) and (a) respectively. An L.S.D. value at P=0.05 would therefore be

$$\text{L.S.D.}_{(.05)(21)} = 2.080 \times 0.0446 = 0.093 \text{ g cm}^{-3}.$$

The appropriate value of t lies between 2.080 (D.F. = 21) and 1.959 (D.F. = 126). Since the difference between these values is small the larger t value has been used in order to calculate the L.S.D.

Appendix 4.13a Experimental data obtained at time of emergence in field experiment on ploughing methods at Inchcoonans (See Fig. 11.4)

N = Normal ploughing

Z = Zero ploughing

		Dry bulk density, g cm^{-3}			
Depth cm	Rep.	N1	N2	Z1	Z2
2.5	1	1.091	1.087	1.377	1.431
	2	0.951	0.964	1.201	1.365
	3	1.051	1.152	1.152	1.313
	4	1.264	0.988	1.110	1.072
	5	1.009	0.894	1.153	1.303
	6	1.056	1.066	1.404	1.442
7.6	1	1.318	1.196	1.465	1.521
	2	1.214	1.308	1.112	1.301
	3	1.192	1.313	1.435	1.458
	4	1.170	1.211	1.313	1.450
	5	1.296	1.176	1.463	1.397
	6	1.170	1.256	1.506	1.292
12.7	1	1.052	1.004	1.433	1.028
	2	1.206	1.267	1.013	1.422
	3	1.234	1.260	1.456	1.359
	4	1.355	1.331	1.414	1.524
	5	1.396	0.968	1.294	1.249
	6	1.196	1.424	1.390	1.036
17.8	1	1.050	1.075	1.345	1.390
	2	1.124	1.187	1.162	1.411
	3	1.422	1.262	1.361	1.407
	4	1.348	1.318	1.363	1.435
	5	1.415	1.056	1.071	1.371
	6	1.467	1.398	1.311	1.069
22.9	1	1.324	0.989	1.539	1.565
	2	1.247	1.377	1.334	1.262
	3	1.519	1.345	1.502	1.470
	4	1.224	1.498	1.475	1.430
	5	1.300	1.184	1.180	1.482
	6	1.380	1.422	1.371	1.442
27.9	1	1.589	1.420	1.620	1.628
	2	1.483	1.561	1.572	1.513
	3	1.646	1.552	1.590	1.557
	4	1.519	1.595	1.576	1.554
	5	1.595	1.613	1.532	1.631
	6	1.498	1.564	1.484	1.537

Appendix 4.13a (continued)

N = Normal ploughing

Z = Zero ploughing

Depth cm	Rep	N1	N2	Z1	Z2
		Dry bulk density, g cm^{-3}			
33.0	1	1.559	1.520	1.553	1.636
	2	1.603	1.603	1.622	1.585
	3	1.643	1.603	1.610	1.610
	4	1.534	1.632	1.610	1.581
	5	1.638	1.684	1.661	1.665
	6	1.592	1.624	1.625	1.562

Appendix 4.13b Analyses of variance for bulk density results for different depths for Inchcoonans experiment at time of emergence (See Table 11.5)

Depth cm	Source of Variation	D.F.	S.S.	M.S.	F	Sig. of F
2.5	Reps	5	0.094			
	Treatments	1	0.315	0.315	13.59	*
	Expt. error	5	0.116	0.023		
	Sampling error	12	0.091	0.008		
	Total	23	0.615			
7.6	Reps	5	0.051			
	Treatments	1	0.149	0.149	13.40	*
	Expt. error	5	0.056	0.011		
	Sampling error	12	0.085	0.007		
	Total	23	0.341			
12.7	Reps	5	0.180			
	Treatments	1	0.036	0.036	2.75	n.s.
	Expt. error	5	0.065	0.013		
	Sampling error	12	0.361	0.030		
	Total	23	0.642			
17.8	Reps	5	0.102			
	Treatments	1	0.014	0.014	0.42	n.s.
	Expt. error	5	0.162	0.032		
	Sampling error	12	0.192	0.016		
	Total	23	0.470			
22.9	Reps	5	0.088			
	Treatments	1	0.064	0.064	2.87	n.s.
	Expt. error	5	0.112	0.022		
	Sampling error	12	0.177	0.015		
	Total	23	0.441			
27.9	Reps	5	0.016			
	Treatments	1	0.001	0.001	0.34	n.s.
	Expt. error	5	0.015	0.003		
	Sampling error	12	0.036	0.003		
	Total	23	0.069			
33.0	Reps	5	0.020			
	Treatments	1	0.000	0.000	0.46	n.s.
	Expt. error	5	0.003	0.001		
	Sampling error	12	0.014	0.001		
	Total	23	0.038			

Appendix 4.13c Bartlett's test for homogeneons experimental and sampling error variances for bulk density tests at different depths at Inchcoonans at time of emergence (See Table 11.6)

Depth cm	Experimental Error		Sampling Error	
	Variance	D.F.	Variance	D.F.
2.5	0.023	5	0.008	12
7.6	0.011	5	0.007	12
12.7	0.013	5	0.030	12
17.8	0.032	5	0.016	12
22.9	0.022	5	0.015	12
27.9	0.003	5	0.003	12
33.0	0.001	5	0.001	12
χ^2 (Calculated)	15.26	6	35.83	6
χ^2 (Tabulated)$_{(0.025)(6)}$	14.4	6		
χ^2 (Tabulated)$_{(0.0005)(6)}$			24.1	6
S^2 (Pooled, 2.5 - 22.9 cm)	0.0202			
S^2 (Pooled, 27.9 - 33.0 cm)	0.0020			
$S_{\bar{Y}}$ (Pooled, 2.5 - 22.9 cm)	0.0410			
$S_{\bar{Y}}$ (Pooled, 27.9 - 33.0 cm)	0.0129			

Appendix 4.13d Analysis of variance for dry bulk density results obtained at time of emergence of wheat for 0-25 cm depths at Inchcoonans using pooled data for all depths and a split-plot design with systematic arrangement of sub-plot treatments (2 samples per plot per depth averaged before analysis)

Source	D.F.	S.S.	M.S.	F	Sig. of F
Reps	5	0.105390			
Ploughing treatments	1	0.227181	0.227181	11.83	*
Error (a)	5	0.096067	0.019210		
Depths	4	0.279174	0.069790	-	-
Error (b)	20	0.151938	0.007596		
Treatments x Depths	4	0.061938	0.015484	1.94	n.s.
Error (c)	20	0.159210	0.007960		
Total	59	1.080900			

The standard error for comparison of two ploughing treatments at any one depth was calculated by the same method as used in Appendix 4.12d and the result was found to be 0.0583 g cm^{-3}. For the calculation of a L.S.D. value an approximate value of t was calculated by the method of Cochran and Cox (1957) (Section 4.14). The result was found to be 2.268. This value was then used to calculate L.S.D. at a probability of P = 0.05 as follows

$$L.S.D._{(.05)} = 2.268 \times 0.0583 = 0.132 \text{ g cm}^{-3}.$$