Paper 1.06

DETERMINING HYDRAULIC CONDUCTIVITY WITH THE INVERSED AUGER HOLE AND INFILTROMETER METHODS

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Summary

The infiltrometer and inversed auger hole methods are briefly described and the results obtained with these methods are compared with those obtained with the auger hole method or calculated from the relation between hydraulic head and drain discharge. Measurements were made on four soil types ranging from sand to heavy clay and showing no micro-stratification. It appears that the theoretical restrictions of the infiltrometer and inversed auger hole methods are of minor importance in practice in view of the large variation due to heterogeneity of the soil.

1. Description of the methods

Infiltrometer method

When wanting to determine the hydraulic conductivity of the various layers of a soil profile, one often encounters a situation where the groundwater table is say 2 to 3 m below surface, i.e. too deep to use the auger hole and piezometer methods for the measurements. In such cases the infiltrometer method can provide a solution.

The infiltrometer can be used at successive depths in a soil pit to estimate the hydraulic conductivity of the various layers. According to the law of Darcy, the infiltration rate of water in unsaturated soil under a cylinder infiltrometer can be written as:

$$V = K_T \frac{\phi + z + h}{z}$$

where

V = infiltration rate (lt^{-1})

K_T = hydraulic conductivity of the transmission zone (lt^{-1})

ϕ = suction at the bottom of the transmission zone (1)

z = depth of the transmission zone below the infiltrometer (1)

h = height of the water in the infiltrometer (1)

The influence of ϕ and h relative to z diminishes as the depth of the transmission zone and the moisture content of the soil increases. The hydraulic gradient then tends towards 1 and the infiltration rate becomes constant, attaining the basic infiltration rate. Thus for wet soils we may write:

$$V \simeq K_T \simeq K_S$$

Although the basic infiltration rate is theoretically not equal to the saturated hydraulic conductivity, it nevertheless yields a fair approximation. The infiltrometer method can therefore be used to determine the order of magnitude of the hydraulic conductivity. One should keep in mind that the value obtained in a layered soil only applies to the layer penetrated by the infiltrometer, since lateral flow will occur below this layer if the hydraulic conductivity of the underlying layer is low. The main disadvantage of the infiltrometer method is the necessity of digging soil pits to install the infiltrometer.

Inversed Auger hole method

The inversed auger hole method, described in French literature as the Porchet method, consists of boring a hole to a given depth, filling it with water, and measuring the rate of fall of the water level.

The surface over which water infiltrates into the soil at time t (Fig.1) equals:

$$A_t = 2 \pi r h_t + \pi r^2$$

Supposing that the hydraulic gradient is approximately 1, we may, according to the law of Darcy, write:

$$Q_t = K A_t = 2 K \pi r (h_t + r/2) = - \pi r^2 \frac{dh}{dt}$$

Integrating between the limits t = o, h_o and t, h_t and rearranging gives:

$$K = 1.15 r \frac{\log(h_o + r/2) - \log(h_t + r/2)}{t} = 1.15 r \tan \alpha$$

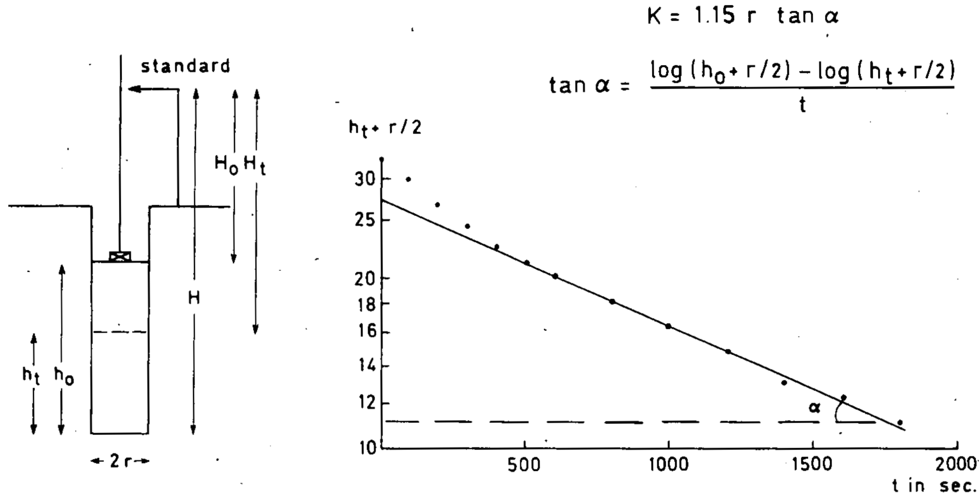

Fig.1. Inversed Auger Hole Method.

By plotting $(h_t + r/2)$ against t on semilogarithmic paper we obtain a straight line with a tangent α (Fig.1). The deviation of the first observations from the straight line may be due to unsaturated flow and a hydraulic gradient larger than 1.

In general the auger hole should be filled with water 1 to 3 times on loam and clay soils, depending upon the moisture content of the soil, in order to obtain a difference of less than 10 to 15 per cent between the successive measurements. On sandy soils it may be necessary to repeat the measurements 3 to 6 times.

The advantage of this method over the infiltrometer method lies in the difference between digging soil pits and making auger holes. Moreover, by gradually deepening the auger hole and filling it with water over the corresponding depth, the hydraulic conductivity of successive layers can be measured in the same hole.

2. Comparison of results

The inversed auger hole and infiltrometer methods were used on several soil types ranging from sand to heavy clay. On three of the four soil types it was also possible to apply the auger hole method in periods of shallow groundwater table. On one soil type the relation between hydraulic head and drain discharge could be used to calculate the hydraulic conductivity of the soil profile. It should be noted that none of the four soils was characterized by micro-stratification.

The results obtained on three soil types are summarized below. As the hydraulic conductivity, in general, shows a skew frequency distribution, the geometric mean was used to represent the average of n measurements.

Soil type	Inversed Auger Hole			Infiltrometer			Auger Hole		
	n	K in m/day		n	K in m/day		n	K in m/day	
		Range	Mean		Range	Mean		Range	Mean
Sand	12	1.2-8.9	3.1	12	1.5-8.3	2.9	-	-	-
Loamy sand	20	0.3-3.0	1.1	10	0.5-4.0	1.3	20	0.3-6.5	0.9
Silty clay loam	16	0.2-2.5	0.7	16	0.2-3.0	0.9	16	0.3-2.2	0.8

For the layer from 40 to 100 cm in a heavy clay soil (80% <2μ), the relation between hydraulic head and drain discharge yielded a hydraulic conductivity of 0.3 m/day, ranging from 0.05 to 1 m/day on 14 plots. Below this depth the soil could be considered impermeable for horizontal flow, which means that the hydraulic conductivity below 100 cm was much lower than in the upper part of the soil profile.

The inversed auger hole method yielded a mean value of 0.3 m/day for the layer 25-75 cm, ranging from 0.1 to 0.6 for 16 observations. The hydraulic conductivity measured by the auger hole method equalled 0.07 m/day for the layer 100-200 cm.

The infiltrometer method was also used to compare plots with and without a gypsum treatment. The basic infiltration rate in the surface layer equalled 0.2 m/day for plots without gypsum and 0.35 m/day for those with gypsum.

It appears from these observations that on a wide range of soils showing no micro-stratification, the results obtained with the inversed auger hole and infiltrometer methods agree quite well. They also agree with those obtained by the auger hole method or calculated from the relation between hydraulic head and drain discharge.

Although the measurements pertain in principle to unsaturated soil and the assumption of a hydraulic gradient of 1 is an approximation, these theoretical restrictions are obviously of minor importance in practice, provided the measurements are continued until stable values are obtained. Besides, the heterogeneity of the soil has more influence on the average value than the theoretical restrictions.

In view of the large variation between the individual values due to the heterogeneity of the soil, it is stressed that the number of replicates should be sufficient to obtain a representative average.

References

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Paper 1.07

NOTES ON THE APPROACH TO DRAINAGE DESIGN

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Summary

The complexity of possible drainage solutions is smaller than the input parameters that make a large number with many of them unknown, and many of them of statistical nature. The size of projects often does not offer a design procedure by the "book". Without special development of methods for investigation and design, the engineering is left in effect to the contractors. The present theoretical knowledge is sufficient to produce the required methods. Some examples of design shortcuts are: hydraulic measurements in a full-scale drain; execution in stages; on the job design; the preparation of diagnosis and design guidebook based on regional experience; redefinition of the task of various regulatory drainage communities.

1. General

The following may not add up to a complete philosophy or well seasoned cook book. Nevertheless, it points out the need, at least in some places, for revisions in engineering training, professional aids and possibly in administrational frameworks. This is in view of what we know and do not know on underground drainage.

2. The complexity of the system

There are very many phenomena that may be related to the final act of drainage installation. They are in the physics of flow, in electrochemistry of soils, in microbiology, in climatology, in hydraulics, materials and, of course, in plant growth, and mechanical activity on the soil. These are besides various aspects of organisation and economy.

In conclusion: The number of parameters involved is extremely large as compared with most engineering fields of application.

In addition to the above complexity, the system with which a drainage engineer has to work is non-uniform at any scale level both in time and space. The non-uniformity involves:

- The climatic condition
- The properties of the soil
- The economical activities on the land
- The stock of existing installation and various human constraints

This non-uniformity means:

- That every field poses a somewhat new and different problem
- Great difficulties or even impossibility in obtaining a complete enough set of data for a rational design

The non-uniformity of the medium is probably the most fundamental property the drainage engineer has to cope with and it therefore calls for special methodology. This methodology should be the subject of a fundamental and lengthy discussion that is beyond the present scope.

For the following one concludes:

- Data on a micro-scale should be averaged out on the same scale or size as the necessary engineering elements
- The drainage engineer will often meet different conditions even on the average
- Rarely, if ever, will the drainage engineer have sufficient data "by the book"

3. The design degrees of freedom

The design degrees of freedom are by far more limited than the processes and constraints involved in a complete understanding of the system. The number of possible engineering solutions is limited by

- The target and basic diagnosis
- The number of principally different techniques
- Local, clear cut, constraints due to factors such as the soil, the economical activity topography, etc.

- The available executive facilities
- Administrational limitations.

Examples are in place. The first two types of constraints are quite clear. One can list only few drainage techniques such as, surface drainage and border channels, parallel underground drains, containment of clearly defined water sources, deep pumping by wells, vertical drain cutoffs. This constitutes more or less all principal possibilities. Certain basic diagnosis and targets rule out a priori various design possibilities or dictate drainage intensity, depth and reliability. Local conditions that are relatively simple to obtain, such as permeable and impermeable layers, groundwater table level or outlet, etc., artesian state or deep leakage, further limit the possibilities and direct towards the solution. The size of the project, its accessibility, the availability of contractors with various execution techniques influence the eventual result far more than the detailed understanding of many intricate processes:in many cases institutional support that determines certain credit levels or approve or disapprove of certain procedures, limit the choice of engineering alternatives almost to a clerical work. Thus, they may influence the drainage solution far more than a lengthy and expensive in situ investigation.

Conclusion: There is a contrast between the complexity of the system on one hand and the relatively limited number of available techniques or solution alternatives.

This contrast calls for a special preparation of the drainage engineers, the text books and the handbooks.

The effect of the above is different at different levels of treatment. There must be a distinction between

- ad hoc solutions of a limited or a small problem
- regional planning, prototype for a repeating problem or one of a wide scale
- development of new application methods and refinement of drainage techniques
- research and investigation which may be tied with a given local but may lead to more general conclusions.

Each of these levels differ by the following:

- Time available for investigation
- Extent of justified investment in investigation
- Opportunity to learn from experience
- Administrational freedom to choose various designs
- Opportunity to introduce unorthodox practices
- Availability of competent professionals.

It is unfortunate that most of the texts and teaching courses make little or no distinction between the different levels. They usually shoot too high and leave many practical problems of the lower level unsolved.

Only few drainage experts master at the same time the very complex theoretical background, the routine information necessary for a practising engineer, and some systematic approach for practical shortcuts or trouble shooting. Too often the practising engineer is puzzled at questions which have answers or should not have been asked at all. Somehow, the well-tested theoretical and experimental knowledge has not been translated into a simple minded set of rules.

Following are some such problems that often arise:

- How far downstream does an interceptor affect a drainage? This is an irrelevant question about a fictitious entity that has never been proved, long disproved and still a legend; single drain has an almost symmetrical effect (somewhat better upstream).
- Should the drains be parallel or normal to the contour lines? Few engineers will admit with certainty that it makes little or no difference as far as the underground soil water flow is concerned but it has some straight forward effects on the hydraulic design and ease of execution.
- Is there water feeding from the outside into the field? How important is it in terms of parallel drainage design?
- What are the criteria for salt leaching by drains? Is there such a thing as a control depth?
- In heavy soils is it useful to deepen the drains?
- Can one measure with common piezometers and permeameters the hydraulic characteristics of a very heavy soil? (Usually not.)
- A fast drawdown, is it a unique criterion that the drainage system is in place and works well? The lowering of a watertable is rarely a target. No drainable porosity is often associated with fast drawdown.

- There is flow out of the drains; evidently the system works, so why is there no lowering of watertable?
- A filter is expensive - how can one decide when to install it and when not?
- A mound in groundwater table - does it mean a local source of water or a non-steady flow?

Questions like these are mostly circumvented by the practising engineers, or are wrongly answered.

Conclusion: The existing theoretical knowledge should be reduced into simple rules concerning design parameters. This is necessary, especially for the practising engineers who have less time and means at their disposal to deal with any one field problem. This is in contrast to the fact that usually they have less preparation in formal learning and meet a larger variety of complicated cases. For their sake the fundamentals of drainage theory should be reduced to simple and clear elements, easy to understand and use.

4. The cost of drainage projects and design methods

The cost of underground drainage must be roughly limited to what the added production can pay or the saving on alternative expenses. Fortunately the prices of such drainage systems come close to this requirement. Consider now a farm of 10 hectares that requires drainage. The cost of such a drainage may be at most 100,000 Israeli pounds (usually less because of the fixed government support that did not follow inflation fast enough). At a reasonable rate of 5-10% engineer's fee, this means 5-10,000 Israeli pounds which constitutes not more that 5-10 working days with expenses.

This should cover:

- Preliminary investigations;
- Surveying;
- Preparation of plan and detailed design;
- Tender and contract with contractors;
- Inspection of execution;
- "As made" surveying and plotting;

- Appearing before a committee for the approval of the plan and the financial aid (including lobbying at early stages of the planning).

Naturally it is impossible to do all this properly for the allocated design fees. There is a natural trend then towards one or several of the following solutions:

- Routine design that has very little to do with the special local problem;
- The creation of unwritten or written standards that have favour with some clerk at a crucial point of the system;
- Design by a contractor (although covered up by some engineering rituals).

This is what happens unless one faces the question and produces design tools methods of trial and error, and flexible enough administration rules.

At the present state of the art the drainage practices are determined mostly by contractors and by government officials while the investigation and design stages are more of a secondary importance and are often maintained more like a ritual.

In some drainage projects although of a much larger scale than the above example, the preliminary investigation reaches 50% of the cost! In a dynamic society where officials change, and regional plans change, projects have been known to be re-designed several times. In the case of drainage it is often better, faster, and cheaper, to increase the factor of safety by 2 than fiddle with endless investigation and re-designing.

The committees that are supposed to approve or disapprove projects would do far better to consider their task as that of accumulating experience, digesting it and disseminating it for the general benefit.

In view of the above there seems to be a need for new investigation and design shortcuts to cope with the complicated drainage problems within limited time and means.

5. Some examples for shortcuts to efficient investigation and design

The examples in the following are far from exhausting the subject. Probably the number of tricks is as big as the number of good experts that convene here (in the Drainage Workshop).

Guide for the drainage engineer

Beyond the existing textbook material such guides are necessary. They may be better prepared, or at least revised on a local basis. Such a guide should start with a simple diagnosis of the problem, then simple methods of diagnosis validation, and the collection of easily obtained information. Alternatives of design should be introduced very early in the guided path. One should introduce "shorthand" or modular design that include standard elements and a system, as it is the practice in mechanical engineering and electrical engineering. Finally, a list of simple investigation methods should be suggested that are directed for specific design decisions. Any method of investigation which does not lead to such a decision or is not the simplest to lead to such a decision should be overlooked.

Sources of information

The best source of information is a neighbouring project or previous experience. Often an existing channel allows the observations of drawdown, improved yields, leaching distances. However, great care must be exercised in the accumulation of experience by the most critical experts and methods. Too often regular prejudice or habits are mistaken for a well-tested experience. Too little effort is given to learn from experience in comparison with means specially devoted for research and local investigation.

Methods of hydraulic measurements

The best, and often the fastest and cheapest method to measure the hydraulic conductivity is by digging one or two trenches and measuring the drawdown at several distances.

A series of point measurements of the hydraulic conductivity, the porosity, or drainable porosity, is a very favourable procedure by many textbooks and manuals. Such point measurements are eventually to be combined into some drainage formula. The error can be half an order of magnitude despite a very tedious procedure of sampling, the use of an auger hole method, etc.

Any reasonable drainage formula (and there is quite a number of them in steady and non-steady cases) is the result of several steps.

- Flow equation such as Darcy's law
- Law of conservation that leads to a differential equation
- Boundary and initial conditions including assumptions about the medium's properties
- A solution, exact or approximate, which is the drainage formula.

Any such solution can serve also as a method for measuring the hydraulic parameters of the medium. The assumptions made to reach the solution may be quite coarse. The design decisions using this solution will be excellent as long as the parameters have been found by measuring with the same solution.

Actual examples are beyond the scope of this article. It would, however, be a relatively easy exercise to device ones own. Usually, a non-steady flow formula will require the measurement of drawdowns in a piezometer over several times and preferably in several distances from the drain. Parameters, such as the transmissivity and drainable porosity may be found by best fit. An extreme change in conductivity with depth and extreme unisotropies may be better detected by using formulas that assume them. Sometimes drains of more than one depth may be used as a precaution.

The overall measurement of parameters led on one field to half an order of magnitude (about 5-fold) higher transmissivity as compared with the results of an auger hole which were themselves several times higher than the so-called undisturbed samples.

The overall measurement can be aided by flooding or by an irrigation system to elevate the watertable. Surely this cannot work in a remote area where over irrigation is anticipated to raise the watertable in several years. But then it would be extremely questionable to assume the hydraulic behaviour of a drainage system on the basis of some hydraulic tests on samples if they can run into 5-fold error and more.

Samples are used more effectively to identify the type of soil information on hand and look for a similar one where experience has already been gained.

Experimental execution in stages

The above discussion leads us to a very important design approach by trial and error. First stage execution of a drainage scheme can serve as an experimental for a second stage. The embodiment of this principle can be obtained in several ways. Here is one. Consider the following table of initial spacing and the number of drains inserted in between at later stages.

First stage spacing in meters	100	80	60
Number of in between drains of the second stage (distance in meters)	1 (50)	1 (40)	1 (30)
	2 (33)	2 (27)	2 (20)
	3 (25)	3 (20)	3 (15)
	4 (20)	4 (16)	4 (12)
	5 (16)		

Clearly one can gain a high flexibility in the design of the second stage on the basis of the first stage. Assume for example that the distance between drains is found to be 20-30 meters. If the initial distance was 100 meters the maximum error in final distance would be halfway between 25 and 33 (3 and 2 interdrains). This is 4 meters error or about 16%. This is an error far smaller than any error found in the measurement of soil parameters and estimating climatic conditions.

On the job design

A good drainage engineer should be able to leave some decisions for the time of execution. A framework design should exist beforehand and alternatives for decisions should also be lined beforehand. There is nothing like opening a trencher line for a thorough soil survey at length and depth. In a

matter of 24 hours drawdown result can also be computed and translated to a decision. The major framework of elevations could be fixed beforehand. There is not much further freedom in the laying of tiles between these elevations.

Such design methods should be worked out. Engineers should be trained for them. However, most important, the administrational frameworks must also be changed in the process of checking and approvals and financial support and on-the-job inspection.

6. Conclusions

Much more good can be obtained by adaptation of existing knowledge to proper practice than by a new research.

A different type of training of the drainage engineers should be based on a good understanding of the phenomena involved on one hand and on existing practices on the other. However, the emphasis should be put on a systematic approach for a fast and efficient elimination of design alternatives. Commitees and commissions for drainage project approval and all other functioners cost today more than all the possible savings which are to be obtained by their close observance. Rather, their main function should become that of accumulation and dissemination of experience and know-how. If the above changes will not be made with the help of proper guidebooks, the design of drainage projects will be done in effect by contractors and will be based often on habits, superstitions, and prejudices, rather than on really measured and checked experiences.

Paper 1.08

CHOICE OF A FIELD DRAINAGE TREATMENT

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Summary

This paper is a general review of water excess situations occurring in France and briefly describes the different field drainage treatments recommended by the Ministry of Agriculture.

Special attention is paid to the determination of the origin of excess water and the need for pedologic and hydraulic soil data.

1. Introduction

Because of the different conditions of soil, climate and crops, there is no unique solution for field drainage. It is first necessary to separate the case of local drainage (source and seepage areas) from the case of drainage of a whole field..

In the second case, theoretical considerations have shown, for the last fifteen years, the importance of determining the physical and hydraulic soil characteristics (permeable layers thickness, hydraulic conductivity, specific yield). Hydrological and economical data are also needed. For example, economical considerations can lead to choosing new techniques, such as moling or subsoiling, when drainage by tile drains alone would be too expensive.

2. Different aspects of excess of water in fields

The main origin of water is the rain falling on the catchment area. The average rainfall of a catchment area can be divided into three parts:

- the run off which runs on the surface of the soil down the slope to ditches and rivers;

- the infiltration water which percolates through the layers of the soil and contributes to its water supply or feeds the lower aquifers:

- the evaporation which represents the losses of water due to both the climate and the plant growth.

The schematic water balance is:

Rainfall = Runoff + Infiltration + Evaporation

↓ ↓

Drainage

3. Evidence of excess of water

An excess of water appears in a part of a catchment as soon as runoff and infiltration do not play their normal part, i.e. when rain water cannot reach the natural terminal outlet soon enough.

Drainage problems arise from either of the following reasons:

pounding on the soil surface is commonly found on pans in the top layer of loamy soils; the more compacted the pan, the less the soil can take up water. The compaction is mainly determined by the machinery working conditions. Working in too wet a top layer increases the compaction, shuts off the layers by their loam particles, and allows the development of mushrooms on the surface that lengthens the normal evolution of the organic matter and soon reduces root growth. A solution can be proposed to the farmer to improve the infiltration rate by modifying his farming methods.

local saturation of the top layer, without a characteristic water table is observed in many clay soils. Rain water fills in the cultivated layer, though low layers of generally high density have low infiltration capacity. That type of water-logging arises essentially on undisturbed old geologic formations where the slope is the main reason for subsurface water movement. In France, it is spread on old primary mountains: Lorraine, Massif Central, etc.

seepage, i.e. spotted seepage, spring seepage lines - have an extremely varied geologic origin often difficult to clearly make out.

waterlogging with a water table developed on an impervious layer can be easily checked by digging an auger hole. The water fills it from its bottom up to a static stable level within a time varying from 10 minutes for very permeable soils (sandy soils) to several hours for impervious pedologic formations (loamy or clay soils). The level reached in the auger hole is the water table level. That one varies throughout the year, low or very low in summer during a drought period, it can reach the surface with excessive winter rainfall.

After a dry period, rainfall water filtrates down through the soil and increases its water content. The water movements are controlled by two forces: gravity and suction. Suction allows movements from high to low moisture content areas. The greater the water content, the less the suction is. Gravity pulls the wetting front down. When moisture content increases up to saturation, gravity movement becomes dominant.

At the experimental site of Arrou (Allee & Deviliers, 1975), drain flow appears after an average rainfall of 150 mm. An impervious layer can stop the drawdown of the wetting front.

But what is really an impervious layer? A totally impervious layer never exists in natural conditions. A layer is looked upon as impervious whens its permeability does not allow the filtration of water coming from the upper layer within a fixed time. We consider that layer B is impervious with respect to layer A when

$$K_{(B)} < \frac{K_{(A)}}{100}$$

In that condition a water table grows upon the the impervious layer and a saturation front keeps on getting up till the rainfall stops.

A flow arising from the slope of the fields can create springs or seepage lines. The water table can draw down slowly thanks to a small filtration through the "impervious layer". In most of the cases a water table disappearing at the end of spring or at the beginning of summer when evaporation is at

its maximum is called temporary water table. At the opposite a permanent water table remains present in the soil all through the year (alluvial water table).

Flooding is always a temporary event caused by a river flood or by accumulation down a slope of an important runoff.

4. Origin of the excess of water

Two main situations are generaly given consideration (Feodoroff & Guyon, 1972).

a) *Water coming from the outside of a field* has either one or both of the two following origins:

Runoff: the greater the slope or the saturation of the soil, the more important the runoff.

Deep circulation of a confined or unconfined aquifer emerging in a seepage area.

b) *Water coming from the field to drain* arises from a small runoff and a bad vertical infiltration that both make a field drainage problem.

Classically four categories of seepage areas can be isolated:

Case 1: see Fig.1.

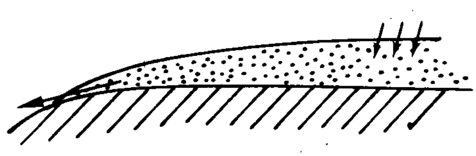


Fig.1. Emergence of an impermeable layer in a slope.

Case 2: see Fig.2

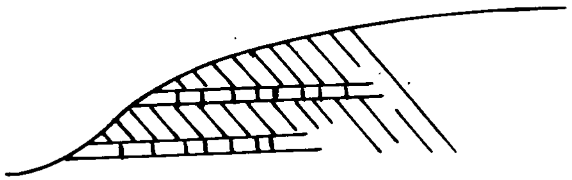


Fig.2. Emergence of a very permeable layer equivalent to a drain.

Case 3: see Fig.3

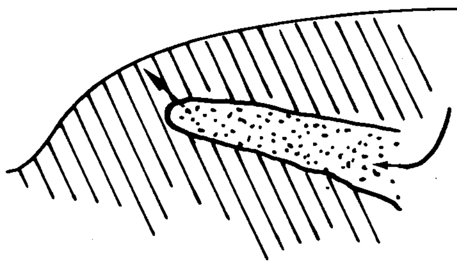


Fig.3. Confined aquifer with high piezometry.

Case 4: see Fig.4

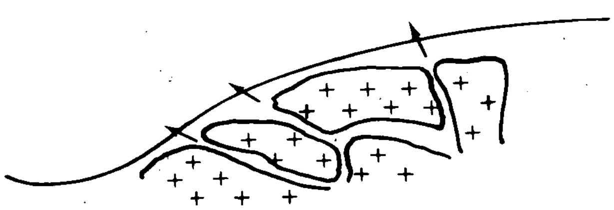


Fig.4. Confined or semi-confined aquifer in a fractured rocky formation. Springs are spread in a vast area and can move.

These specific drainage problems need specific drainage systems.

Open ditches or draining trench are dug to intercept seepage lines (see Fig.5).

Fig.5. Interception drains.

But the origin of water can be more complex and it can be rarely assumed with sufficient accuracy before drainage begins. Random drains are scarcely effective and systematic super-intensive drainage leads to a very expensive scheme that never pays back. A french national company (Comp.d'Aménagement des Coteaux de Gascogne) successfully sets the rules for a good drainage of seepage:

-Open a trench through the seepage in its main axis and with the maximum grading deep enough to reach the aquifer. (Though it is always profitable it is not always possible to reach this impervious layer.) The trench is then lengthened, and lateral trenches are added to intercept the preferential ways of water.

Trenches are 45-60 cm wide and up to 3 meters deep, fitted with a good diameter pipe (ϕ 65 mm) and backfilled with coarse angular gravel (see Fig.6

Common rules of drainage work have to be applied in seepage drainage:

- a good and regular grade of the pipe;
- pipe diameter correlated to the flow (always larger than 1-2 l/s);
- good ditch and outlet maintenance.

The average price of a seepage drainage is 700 FF but it can reach 2000 FF.

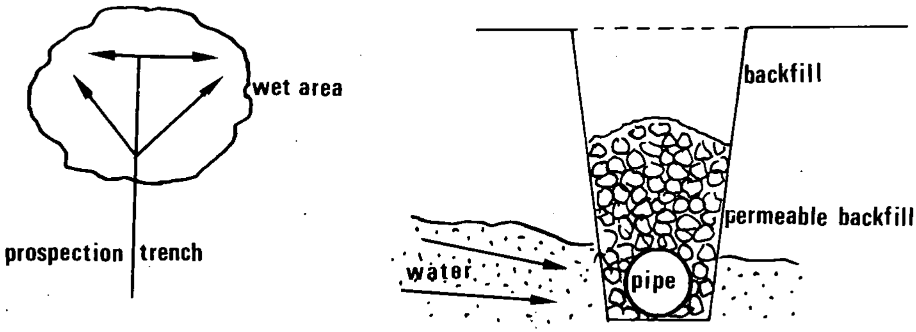


Fig.6. Trenches with backfill.

5. Drainage requirements

A good morphologic examination of a waterlogged soil gives lots of valuable information. The iron and manganese dynamics in the profile are positively correlated to water dynamics. The soil scientist can play an important role: he looks for the depth and the intensity of iron and manganic concretions. He gives the average depth of the impervious layer (when it exists). But these qualitative data must be completed with hydraulic measurements of the water table movements.

It is of great use to set piezometers in fields to be drained (Fig.7). A piezometer consists in:

- a perforated pipe (1-3 cm wide);
- permeable gravel along the holes of the pipe in order to decrease the response time;
- impervious protection above making the piezometer independent of the surface runoff or rain. A high overburdening pulverous clay (bentonite), sprayed very dry, shuts off the higher part of the auger hole rapidly.

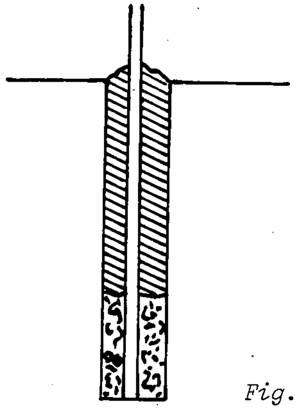


Fig.7. The piezometer.

It must be noted that these piezometers allow as well:

- hydrodynamic measurements (Guyon, 1971, 1976)
- detection of the impervious layer;
- continuous recording of the water table level.

As an example of a pedological survey of drainage requirements the chart established for the Pays d'Ouche (Devillers et al., 1975) is of great interest:

h_o : no pseudo-gley in any place in the profile

h_1 : pseudo-gley below 80 cm

h_2 : pseudo-gley within 50-80 cm

h_3^- : pseudo-gley beginning at 40 cm

h_4 : pseudo-gley at 20-30 cm

h_5^+ : pseudo-gley in the whole profile.

The piezometeric survey achieved during two very wet winters and concerning sites belonging to various pedologic situations shows a close relation between that chart and the waterlogging degree during high rainfall periods (see Fig. 8).

Water table evolution during 1974–75 winter in different sites corresponding to different logging conditions

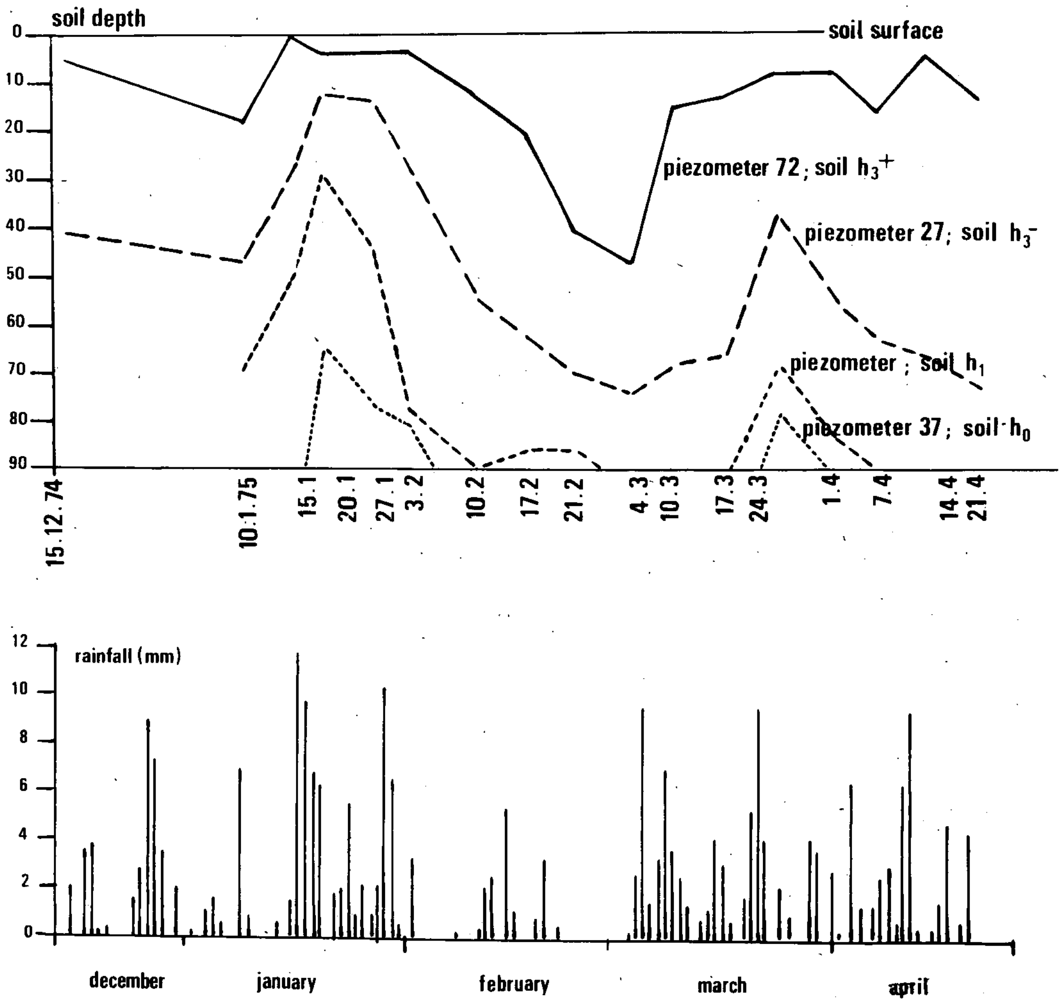


Fig.8. Water table hydrographs.

To all these "objective criteria", subjective criteria are added to give more detailed information on the situation. Farmers living with excess of water must do with specific constraints which can be divided into three categories:

a) Field preparation and soil working conditions

A saturated soil can reach the plastic - even the liquid - stage, characterized by small adherence and poor stability of field machines. The working periods become shorter. Good drainage must bring a high speed of the drawdown movement of water table - 25 cm a day beneath the ploughing depth after the rain stops.

In grassland cattle spoils when moving on a saturated soil (a cow's leg pressure reaches 2 kg/cm^2 standing and more than 6 kg/cm^2 moving). In loamy soils grass is protected when the water table is deeper than 50 cm.

b) Crops and crop system choice

Saturated soil conditions make it difficult to seed or harvest crops, resulting in low crop yields. The growth period (for barley corn, grass, maize) is shortened. Plants are subject to diseases that make them less resistant.

The yield losses can be modelled by parametric equations where a variable is the length of waterlogging period. Formulas exist which integrate both yield losses and water table drawdown speed (Guyon, 1970).

6. Drainage systems

The oldest system to drain is by various sizes of rigs and furrows. The most used french terms are "billons", "planche", "ados", etc. This system is easy to install at a low cost in a field and is very effective when drainage problems arise from flooding or ponding, but:

- it becomes difficult or impossible to mechanize field works (ploughing and harvesting);
- drainage is poor and irregular and does not provide a fast water table drawdown.

Such a method is valuable in extensive grassland or when more effective drainage is too expensive (i.e. in blocky-stony thin soils where the price of under drainage is more than 8000 F/ha).

Gutters

They consist of small ditches to intercept excessive winter rainfall. But the rootzone stays saturated during crop development. This system has been experimented for several years in "Charentes Maritimes" in dry flat soils and used to be the traditional drainage of the Flandres Maritimes in the North of France.

But:

- interception of excessive rainfall is just local, drainage is poor;
- ditches take surface off the cultivated area;
- it is difficult to mechanize agriculture.

Field underdrainage

It is first necessary to make out the difference between underdrainage with pipes alone and moling or subsoiling added to a pipe drainage scheme.

a) Underdrainage with pipes alone

Water movement in an underdrained soil depends on two families of parameters:

- *Soil parameters:* drainable porosity, hydraulic conductivity, depth of the impervious layer.
- *Topographic parameters:* natural terrain gradient, vegetation cover, sensibility of top layers to compaction or to pan formation.

The drainage scheme design depends on two other types of information:

- *Climatologic data*: average rain intensity, frequency and duration.
- *Economical parameters:* cost benefit elements (i.e. yield losses) to optimize the scheme.

b) Moling and subsoiling

In very compacted soils or in soils characterized by poor hydraulic conductivity, an extra drainage system is added, crossing the pipes of the underdrainage scheme, in order to increase, more or less quickly, both the effective depth and the permeability of the drained area. A classical drain spacing formula gives a good picture of the points played by these two parameters:

$$E = 2\ H \sqrt{\frac{K}{I}}$$

The bigger H or K the bigger the spacing.

So it is necessary to distinguish the following cases:

☆ *Deep and permeable soils:*

$H > 0.60$ to 0.80 m
and/or
$K > 0.25$ m/day (in situ measurement).

Good drainage is provided by regular parallel drains layed at a calculated spacing.

☆ *Thin or rather impervious soils:*

$H < 0.6 - 0.8$ m
$K < 0.25$ m/day.

Effective drainage is given by regular drain layout with secondary treatment:

★ *Moling* (in soils of regular texture with more than 30% of clay, a good structural stability and a gradient better than 2 $^{o}/oo$ and smaller than 5%).

★ *Subsoiling* (in compacted soils, blocky soils, unstable soils, soils or irregular granulometric composition).

Permeable backfill is necessary with a secondary treatment. But experiments began a few months ago to try to make out the situations where it is not of real use.

7. Choice of a drainage system

a) The choice depends on:

☆ *the aim*, which is linked with the evolution of the crop system in the future (transformation towards more sophisticated systems, such as greenhouse production, intensive cereals).

☆ *technical criteria* made out by the soil scientist:

- origin of the excess of water:

  geological survey ⇨ interception / drainage

- hydrodynamic properties of the soil:

  underdrainage with no secondary treatment
  underdrainage with moling or subsoiling.

- topographic survey:

  gradient (general and local)

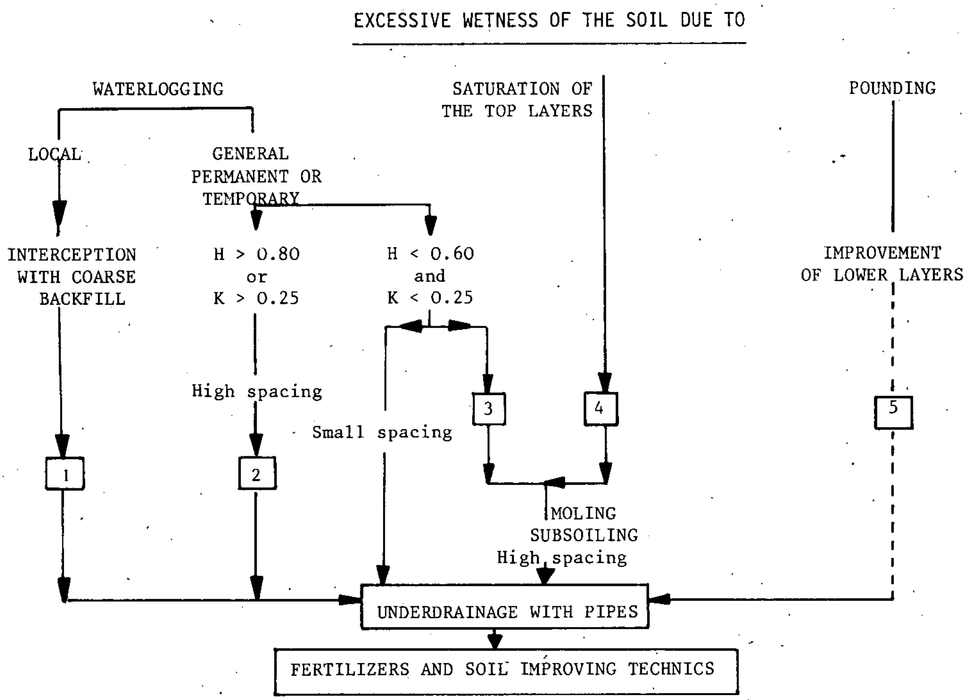
- efficiency criteria:

  clogging risk (sand, clay, iron ochre problems)
  maintenance of ditches, laterals, outlet.

☆ *economical criteria:*

- cost of the layout
- average estimated benefit
- grant aid, subsidies, ... either collective or individual.

b) Chart (Fig.9) summing up the choice of a drainage system (proposed by J.L Devillers, from R. Eggelsmann's suggestion, ICID European Congress, Sevilla, 1973).



☆ Situations:

1 Seepage spring-lines	2 Blocky sandy deep loamy alluvial soils	3 Thin loamy sandy alluvial colluvial soils	4 Clay undisturbed, thin loamy soils	5 Soils without typical hydromorphy but compacted

☆ Prescription:

Permeable backfill	Filters in sandy soils with less than 15 % of clay	Secondary treatment + permeable backfill

☆ Clogging risk:

Iron ochre problem either in organic and mineral soils or if water has a high iron content

Fig.9: Chart for selection of a drainage system.

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Paper 1.09

SOIL FUNCTIONS AND DRAINAGE

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Summary

First some general facts about climate, soils and drainage in Sweden are given. Especially the soil profile formation, the structural pattern and drainage properties are discussed. The Swedish drain test field program in the period 1947-1977 is shortly presented. Primary and secondary drainage effects have been followed on about 125 drain test fields. Some examples are given. The experience gained in this field test program gives the base for the choice of drain intensity e.g. drain space and depth in separate agricultural regions. In a second subsection the root growth and its dependence of the root environment are discussed. The third subsection on changes of functions of the soils as a result of compaction shows, using experimental data, how a number of properties of importance for the root environment is influenced, namely pore space distribution, hydraulic conductivity, air permeability, penetration resistance and root growth. The vulnerability of a soil to compaction is primarily related to the water tension acting on the soil skeleton. The primary way of regulating the moisture content and thereby to a certain extent the trafficability, is by drainage, as could be shown by the results of drainage experiments. One has, however, to realize that drainage can influence only a small part of the wide variation in soil water tension. The drainable pore space will be gradually destructed when raising the compaction forces in the soil to 200 kPa. This value will be stated as an allowable limit over which severe deterioration in the root environment and drainage properties will occur.

This paper is mainly a compilation of the authors papers in the Journal of Agricultural Land Improvement and the SIAE-Bulletin 354 written in Swedish.

1. Some general facts about climate, soils and drainage in Sweden

The climate in Sweden can be characterized as semi-humid. In the main agricultural areas normal annual precipitation is between 500 and 700 mm. Precipitation is normally much less than potential evapotranspiration in the spring and early summer, the reverse being true in late summer, autumn and winter (Fig.1).

The total arable area is 3.0 million ha. The main part of the arable soils is fine textured (clay, clay loams, silty and sandy loams). The remaining areas are coarse-textured and organic soils. Two third of the arable soils has a need of drainage and the main part is also drained with varying intensity. The intensity is based on the ratio between the costs of installing a drainage system and the benefits of better workability and trafficability and of less frequent and less severe yield depressions.

The intensity problems have been studied in a large field test program in the period 1947-1977 with about 100 drain test fields to study the drain spacing and about 25 fields to study the influence of drain depth. On these test fields in average 14 crop seasons have been followed. It means totally about 1800 crop seasons.

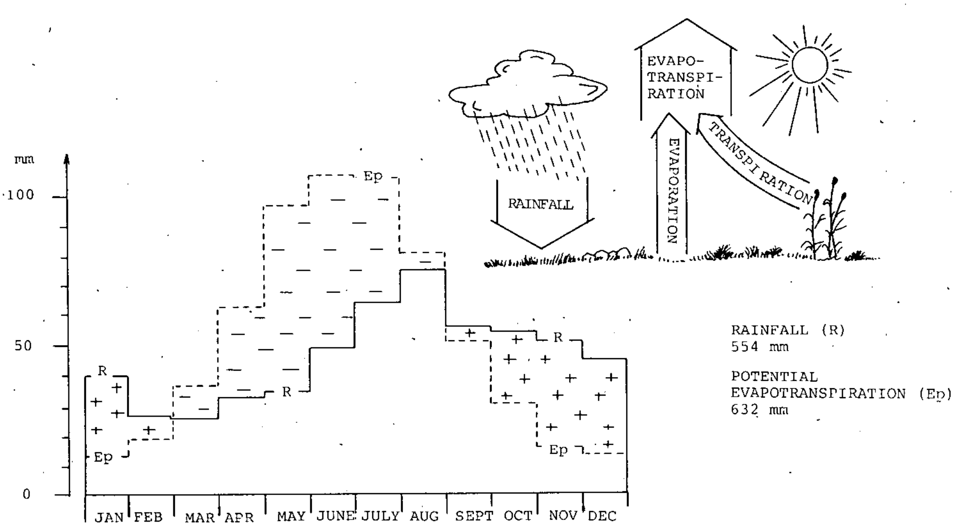


Fig. 1. The relation between rainfall and potential evapotranspiration in eastern Sweden (Uppsala). The growing season starts in April (>5°C) and ends in October (<5°C) with a length of about 200 days.

Soil profile formation and average water holding capacities

The value of soils for crop production is determined by how well it can supply plant roots with water, air, and nutrients. The soil consists of solid, liquid, and gaseous materials, forms the soil skeleton and provides the structural pattern of the pore space. In an average cultivated soil, the pore space is about half of the total soil volume. Depending on the shape of the skeleton, the pore space is divided into a complicated system of channels and cavities; the pore system below a water table is completely filled with water. If the water table drops, the pores are progressively emptied of water and air fills the pores. A favourable condition for plant roots is created in the border zone between water and air in the soil space. The distribution of air and water in the soil profile is determined by the distribution of various sized pores, the location of the water table, and the addition and removal of water.

The particular pore system that forms is mainly dependent on the particle-size distribution of the soil material, i.e. texture or soil type. The clay fraction is especially important, and the organic matter is of great importance in the topsoil. The relationship between clay content and water holding capacity in Swedish cultivated sedimentary soils is pictured in Fig.2 (Andersson & Wiklert, 1972). The pore volume is at a minimum of about 41% in a light clay. It increases with increasing clay content to about 45% in very heavy clay. Clayless and loamy soils have also developed larger pore spaces than light clay soils.

In Fig.2,the pore space is divided into two main parts by the lines separating the unavailable from the available water, denoting the so-called wilting point. The amount of unavailable water increases steadily from about 2% in clayless soils to about 25% in heavy clay and 33% in very heavy clay. Thus, the available water decreases from about 40% in the clayless and loamy soils, to about 20% in heavy clay, and then remains quite constant between 18 - 20%. Some of this water is held in such coarse pores that they empty at a water table depth of one meter. The drainable water makes up most of the available water in coarse, clayless soils, but is limited to smaller amounts from light clay through the fine-textured clays. In subsoils, which the figure prefers to, the amount of drainable water lies between 2 and 7%. In topsoils with moderate organic matter contents, it lies between 5 and 10%.

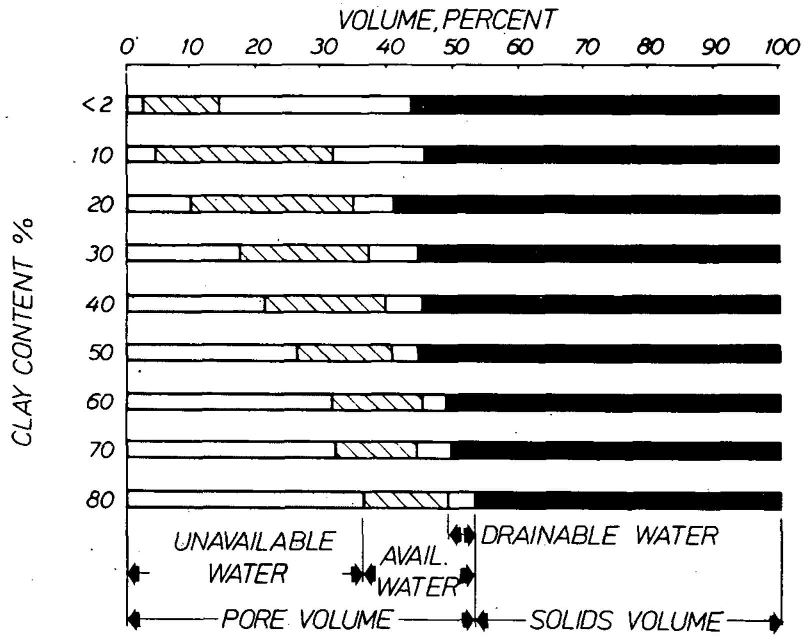


Fig.2. The relationship between clay content and water-holding capacities in Swedish mineral soils. The horizontal bars indicate solid and pore volumes. The pore space is occupied by water of different availability. The values are typical at the given clay content (according to Andersson and Wiklert, 1972).

The structural pattern and drainage properties

The concept of soil structure includes everything that deals with the fabric of soils, i.e. the manner in which individual particles are arranged and joined in large and small units to form aggregates.

The cementing agent is primarily clay particles and soil organic matter. As these particles are mutually cemented, they also bind together the larger silt and coarse-textured particles.

The structural pattern results from various structure generating factors which are illustrated in Fig.3. A summation of processes that will change the structure of a clay soil and, because of the properties of clay particles, will

cause aggregate formation and maintenance of the structural changes, is also indicated in the figure. Small channels branch out from the larger cavities and channels (cracks, worm holes, and root channels). One differentiates between macrostructure containing macropores and microstructure containing micropores. An aggregated clay soil provides for rapid movement of water and air in the macropores. Likewise, the root system can spread out in the subsoil's network of cracks and channels. Therefore, the root system can reach, and effectively penetrates, large volumes of the subsoil and thus assure water availability during prolonged dry periods.

Coarse-textured soils that lack cementing substances and ability to form a macrostructure, with cracks and channels, are called *single-grain soils*. In these types of soils, root penetration is halted immediately below the topsoil because of such various reasons as mechanical resistance, a dry zone, lack of nutrients, or low aeration. Therefore, in this case the subsoil is not available for root growth; however, a portion of any stored subsoil water may be transported by capillary action to the rootzone. It is therefore necessary in single-grain soils that the topsoil structure provides for good root development and, consequently, for good root contact with the subsoil.

Structural boundaries in the soil profile

The presence of structural boundaries can be observed with the naked eye in prepared profiles (Fig.3). They can also be determined by measuring physical properties.

The boundary for cultivation effects

Several things are involved in influencing cultivation, one of which is compaction as a consequence of pressures from passage of vehicles and machinery. This limit is most clearly demonstrated in east Swedish clay soil profiles where a very definite structural change often occurs at 30- to 40-cm depth.

The frost boundary

Coincides with the normal frost depth. Frost action produces a greater granulation than simple drying. Near the average limit at a depth of 60 to 80 cm,

there is a gradual transition to coarser aggregates, separated by cracks, that characterize the profile down to the drying boundary.

The drying boundary

The drying boundary is at that depth to which soil will normally dry because of water uptake by roots.

The structural pattern generates typical variation with the depth in the profiles, e.g. of the physical properties and thereby the root environment and the drainage properties.

In Table 1 some soil data together with results from 11 drain test fields are given. The fields are from the glacial plains in middle Sweden. The clay content varies between 40 and 80%, except in field 56, a sandy loam. The drainable pore space varies between 2.2-7.5% for the clays.

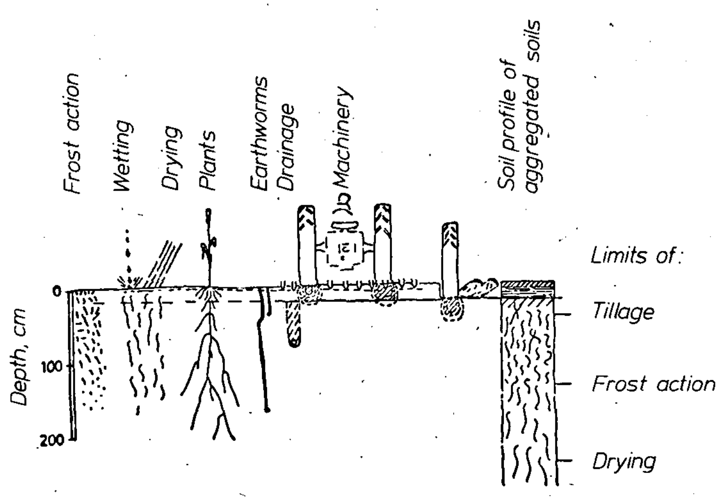


Fig.3. A: Some important factors for profile formation in cultivated soils. The macrostructure pattern in aggregated soil (clay soil) with approximate structural boundaries.

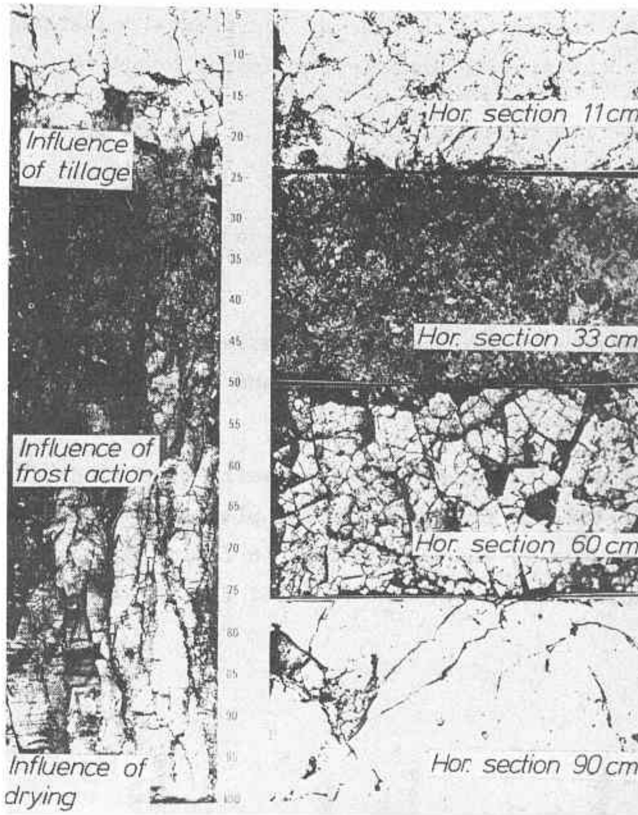


Fig.3 B: *Diagram of soil profile (Ultuna 4-55, Andersson and Wiklert) showing the pattern of the macrostructure in one vertical plane and four horizontal planes.*

There is a great variation in the depth functions of the permeability from soil to soil type but some generalization can be done. Well aggregated clay soils often have a high permeability dow to 50-70 cm, it diminishes in the layers down to 120 cm to one-tenth and to very low values in the bottom to 200 cm depth.

Table 1. Drain test field No.51 to 62 observed in a number of years in the period 1947-1977. Clay content in subsoil, drainable pore space, hydraulic conductivity: k_v = vertical with the core method, k_a = augerhole method, the drain method, the drain depth used and finally optimum distance found.

Test field	Number of years observed	Clay content in subsoil	Drain-pore space	Hydraulic conductivity (m/day) in the horizons				Drain depth used	Drain spacing optim.
				20-50 cm	50-100 cm	50-100 cm	100-180 cm		
No.		%	μ	k_v	k_v	k_a	k_a	m	m
51	17	55	6.1	2.5	0.2	0.15	0.10	0.85	16
52	20	60	4.1	3.4	2.3	0.28	0.28	1.00	16
53	10	50	7.5	4.4	0.16	0.30	0.02	0.8	20
54	19	60	-	2.3	0.21	0.06	0.19	0.95	16
55	14	70	6.3	1.7	1.2	0.05	0.05	0.85	16
56	17	17	9.8	0.28	0.37	-	0.3	0.9	25-30
57	11	40	-	1.92	0.06	0.04	0.01	0.8	12-16
58	20	60	5.6	0.46	0.01	0.01	0.00	0.75	12-16
59	5	50	-	3.80	0.03	0.01	-	0.8	12-16
60	15	82	4.7	0.11	0.04	0.06	0.04	0.65	14-16
61	19	47	4.7	2.21	0.04	0.06	0.06	0.9	18
62	21	70	2.2	0.01	0.02	0.04	0.02	0.7-1.0	16

Direct and indirect drainage effects

How the groundwater level varies and how far it is influenced by drainage is shown in Fig.4. In years with normal rainfall (1952) one can tell about a crop season and an off season period. In a year with high rainfall or an uneven distribution as in 1953, the drains have to work even in the crop season. During the early spring the groundwater level rises in connection with the melting away of the snow and the thawing of the soil. During the late spring the drainable water will flow out in natural or artificial drainage and the groundwater level will normally go down to the pipe level as shown in the groundwater diagram.

When the crops start growing their water consumption will influence the groundwater conditions to a high degree. Water is taken out by the roots even below the pipe level and the groundwater level will also drop below. During autumn with increasing precipitation and decreasing evapotranspiration the water level rises above the pipe level.

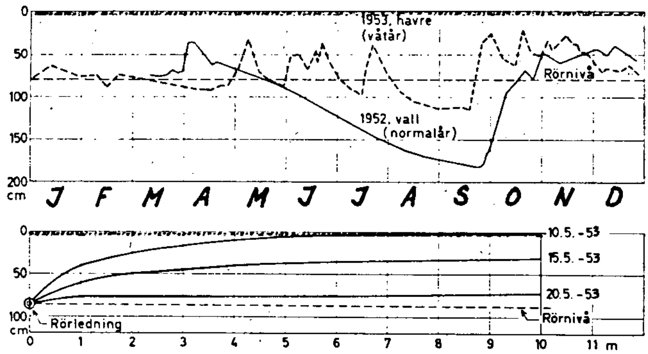


Fig.4. The variation of the groundwater level in a clay profile with about 50% clay and a developed structure to 2 m. The water conductivity 0.2-0.4 m/day and a drainable pore space of 6%. Drain test field Lanna, Skaraborgs county, 20 m drain space, 0.9 m drain depth. The upper diagram shows the average groundwater level in the normal year 1952 with a grass crop and the wet year 1953 with oats. The lower diagram shows the forms and the drawdown of water level in a 10-day period.

Due to the properties of the soil profile, especially the permeability, the drainage effect will diminish more or less rapid with the distance from a drain. The groundwater level in the vincinity of the drain will be kept down deeper which will empty the macropore system more effectively. This primary effect of a drain will induce several secondary effects of physical and bio-chemical nature which are finally synthesised in the plant growth, in the workability of the surface layer and in the variation of the trafficability.

In Fig.5, as one example, the influence of drainage on plant growth is shown from the drain test field No.52, Gunnarstorp, Skaraborgs county. The soil has 60% clay with a drainable pore space of 4%. In this particular crop season (1966) an average high groundwater level gave a bad workability in the spring, a coarse structure in the seedbed, a compressed central part of the topsoil with low permeability and finally in the crop season high water saturation in the topsoil. A high depression in the growth of the oat

plants can be seen on the 80 m space. Even on the 24 and 32 m a depression in the height and the yield could be found. On 16 m the growth conditions were acceptable over the space.

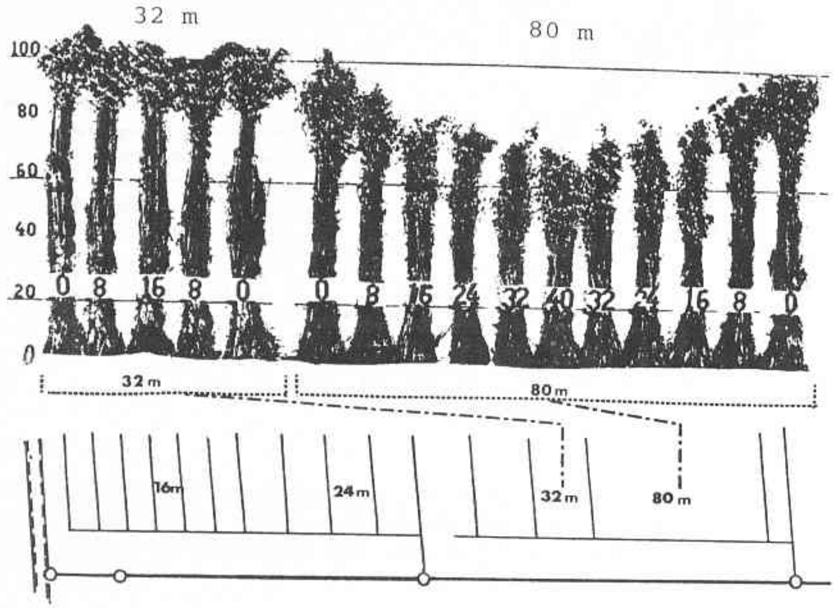


Fig.5. The influence of drainage in a spring sown, cereal crop, oats. From the drain test field No.52, Gunnarstorp, Skaraborgs county. In the test field the distances 16, 24, 32 and 80 m are checked. The picture shows a view of the crop stand in September 1966 on some points from the drains on 32 m and on 80 m.

The variation in yield shown by this example has been established through harvesting of test plots continuously from drain to drain on all test fields. Out of this data the correlations between drain space and yield have been calculated. Fig.6 shows the general fact that winter crops, because of more frequent off-season effects, give a higher response to drainage than spring crops. The off season effects are often a combination of high topsoil saturation, frost heaving, plant pathogens, etc. (Håkansson, 1960, 1961).

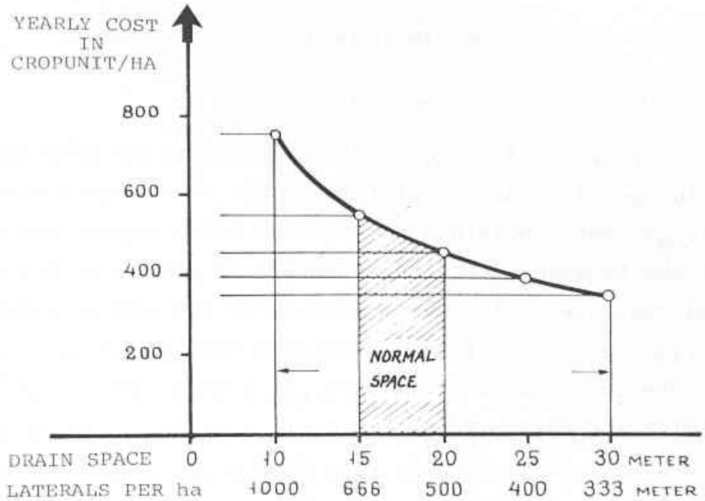
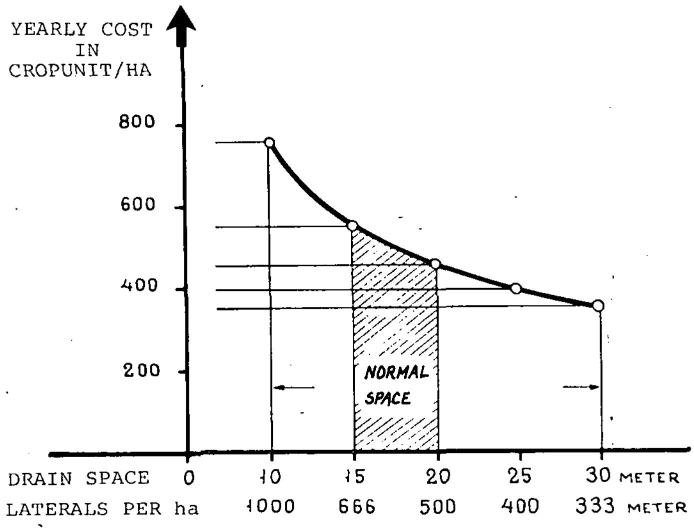


Fig. 7. Yearly cost for drainage with a variation of the drain space from 10 to 30 m. The drain space is most frequently chosen in the interval 15-20 m.

In the calculations of the yearly cost, a time for discounting of the investment cost of 30 years, 7.5 per cent interest and a recurrent cost of 0.5 per cent of the investment cost has been assumed. The yearly cost has been transformed into crop unit/ha. The crop unit has been given a value of 0.50 kronor.

If the drainage cost is compared with the benefits one can in normal case find a drain space in the interval 15-20 m justified. Some hard to drain soils, as heavy clay soils or soils with frost heaving or low bearing capacity, have shown in the drain test program that a drain space in the interval 10-15 cm can pay. In fields with a high natural drainage or in an area with low rainfall the intensity can be chosen in the interval 20-30 m.

The depth of the laterals in a drainage system is normally set at 80-90 cm. The maximum in permeability which normally lies in the niveau 30-80 cm in the profile is thereby utilized. The drain tests have, however, shown that on many soils a bigger depth gives higher yield. The average rise of yield is about 100 kg per 10 cm deeper drainage between 0.8-1.2 m. The value of this yield, however, just outweighs the cost for deeper drainage (Håkansson, 1969).



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2. The root growth and the root environment

Root types and root systems

A plant-root system is often just as dependent on inherited traits and just as set in form and characteristics as the above-surface plant parts. Nevertheless, growing conditions modify to a large degree the root system and provide the framework for its expansion. A plant can develop a deep and well-branched root system in a well-structured and well-drained soil.Another plant of the same variety will have a shallow root system with a different branching pattern in a single-grain soil, in a soil with a high water table, or in a soil with a dense horizon. The whole root system of dicotyledonous plants (herbs) is formed by one main root from which lateral roots grow. On grasses several (3-5) equal-sized roots emerge one after the other at time of germination. Besides these seminal or primary roots, so-called crown roots, playing a more or less important role in the water and nutrient supply, develop from the basal parts of the stem.

Growth mechanisms of root tips and root hairs

The roots, and primarily the root tips, are very effective organs for water and nutrient uptake. The intensity of root branching results in hundreds of thousands of root tips on a mature plant. The number of root tips is truly the most important aspect in the plant's ability to take up water and nutrients. At the very tip of the root, the root cap (Fig.8) protects the meristematic region where new cells are being produced by cell division. These cells later enlarge in the zone of elongation. This cell elongation causes the meristematic region with the root cap to be pushed forward, resulting in the longitudinal growth of the root. Only a small part of the root, at most a few millimeters, is pushed through the soil. As the root tip is pushed forward, the outer cells of the root cap are sluffed off but are replaced by new growth at the root apex.

After cell elongation and the consequent forward movement of the root surface ceases, root hairs can develop. Root hairs are hair-like growths from the epidermal cells of the roots and are about 0.01 mm in diameter and 1 to 10 mm in length. The root-hair zone varies from a few millimeters to several

centimeters long depending on plant variety and conditions under which the roots develop. On every rapidly growing root tip, new root hairs are continually formed which, during their development, reach new parts of the soil.

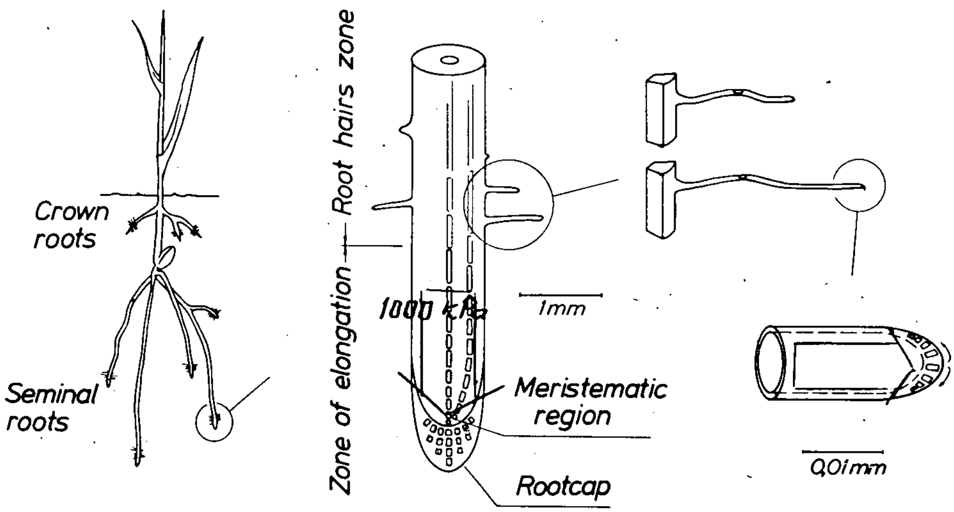


Fig.8. A sketch of the root system of small grains. Structure and growth mechanism of the root tip and root hair.

The effective root absorption surface is increased very much by the presence of root hairs. A wheat root of 0.5 mm diameter can have a surface absorption area of 5 cm^2 per cm root length. The growth mechanism of root hairs is similar to that of the root, and growth occurs by accumulation of materials in the tip of the root hair. This type of growth enables the root hairs to penetrate complicated pore channels among and in the aggregates. The new root surface secretes slime, further increasing contact with the soil particles.

Growth rate of roots

Primary roots of small grains will, for example, in soils with favourable structure, grow at the rate of 0.5 to 3.0 cm/day and will grow to a length

of 1 to 2 m. The growth rate of lateral roots is slower than that of primary roots, and their final length less. Frequency of branching commonly varies between 0.5 and 5 roots per cm of the parent root. According to investigations by Wiklert (1969), root branching begins 15 to 35 cm behind the tip.

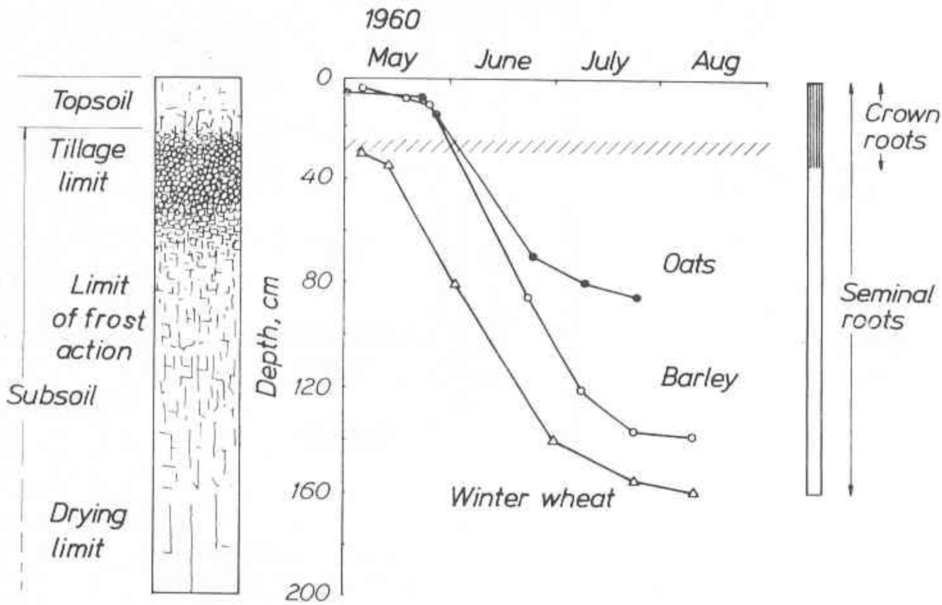


Fig.9. Development of the root systems of winter wheat, barley and oats in aggregated soil (according to Wiklert).

Depth penetration of a root system in aggregated soil is illustrated according to Wiklert's data in Fig.9. Root penetration relationships among the three grain varieties (winter wheat, barley, and oats) are, for similar root environments, most commonly as shown in the figure. Oats are not particularly deep rooted; the individual roots are vigorous and well branched. The barley roots are less vigorous and appear weaker. The barley root system is similar to oats in branching frequency but goes deeper. The crown roots of

small grains generally are limited to the topsoil or slightly deeper. According to this investigation, rate of depth penetration for the various cultivars was 2-3 cm per day during the most rapid growth period which ends at time of heading. A rapid growth rate like this is only possible by completely unimpeded growth of root tips in an open pore system or in a system of soil cracks that gradually open as the roots remove water.

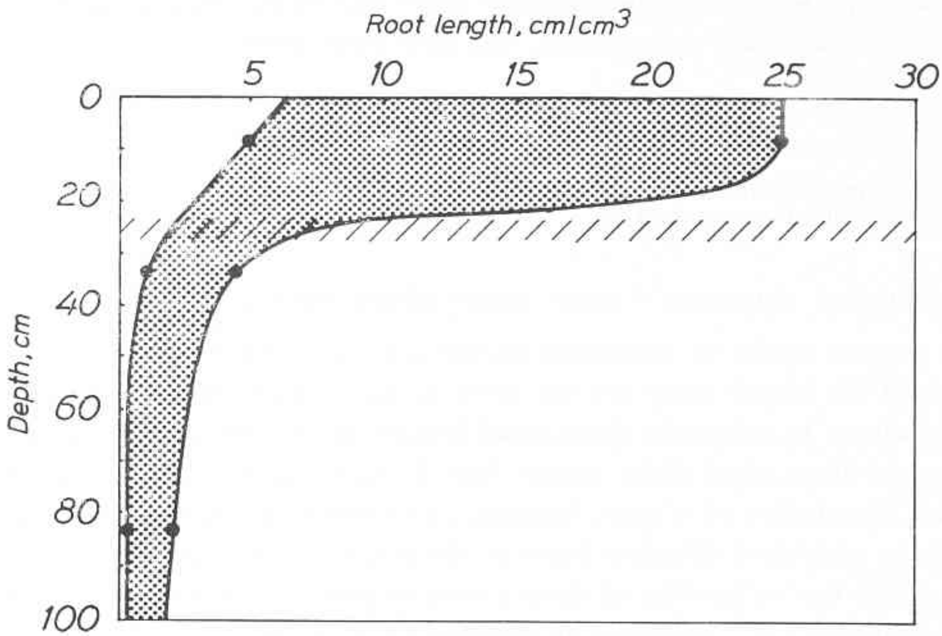


Fig.10. Root frequency for small grains in terms of root length per cm³ of soil (according to Barley, 1970).

To evaluate the effectiveness of different root systems, data about root frequency in different horizons of the soil is also of interest. In this respect, root length per volume of soil is most informative but data of that type are very few. Root length in cm per cm^3 for different grain varieties is, according to foreign investigations, given in Fig.10. The average root length in the soil profile under a fully developed crop will usually be:

in the sopsoil, 10 cm/cm^3; at a 0.5 m depth, 1 cm/cm^3; and at a 1.0 m depth, 0.1 cm/cm^3. A commonly reported average value for deep-rooted crops is 1 cm per cm^3 at 1 m depth. Even less information is available about root length per unit area of soil surface. Values ranging from 50 to 500 cm per cm^2 of soil surface have been reported. According to the cited investigations of the root system distribution in the soil profile, it seems very important to have a good root environment in the topsoil and in the top portion of the soil profile; a slight change of structure in these portions of the soil can be very detrimental. It is primarily there that heavy vehicle traffic affects the pore system and consequently, the root environment.

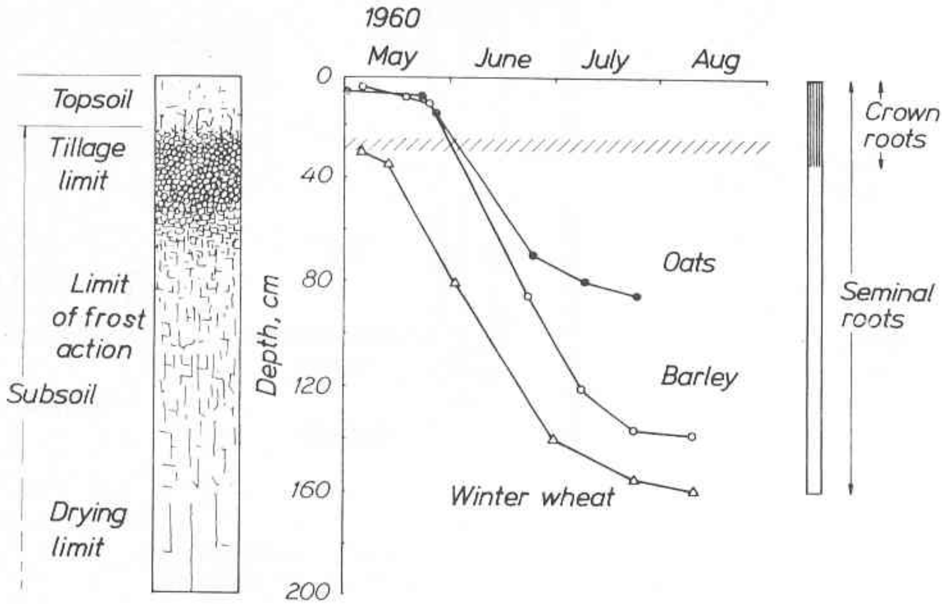
3. Compaction-induced changes in soil properties

Compaction pressure - pore space distribution

The primary effect of compaction on the soil is to decrease total pore volume and the coarse pores are the first to be affected. The geometry of the pore system is extremely complicated because pores continuously change in size and shape along their length. Therefore, it is not possible to give an exact description of a pore. Instead, it is common to characterize a pore with an equivalent diameter based on the suction, i.e. the soil water pressure that has to develop to empty a pore of water. This so-called equivalent pore diameter, d_v, in cm can be obtained from the equation $d_v = 0.3/h_t$ where h_t is the soil water pressure in terms of the height in cm of a water column. A tile drain at 1 m depth develops a soil water pressure of 100 cm in the pore system of the topsoil. Thus, the pores that will empty in this case, can be described with the help of the equation $d_v = 0.3/h_t = 0.3/100 = 0.003$ cm = 0.03 mm.

Soil water tension can vary from 0 at saturation to about 100,000 m water-column equivalent under very dry conditions. Nature can be simulated experimentally with the aid of the pressure chamber technique and the humidity chamber technique and in this way the pore system and its water retention capacity can be described. In a discussion of soil-water relationships in connection

of 1 to 2 m. The growth rate of lateral roots is slower than that of primary roots, and their final length less. Frequency of branching commonly varies between 0.5 and 5 roots per cm of the parent root. According to investigations by Wiklert (1969), root branching begins 15 to 35 cm behind the tip.



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structure with about 10% of the pores larger than 0.03 mm, which drain at a tension of 1 m. It is these pores that provide ready access for roots and secure high water permeability. It is noticed (Fig.11), that the number of coarse pores decrease successively with increasing pressure. The coarse pores are completely compressed at 800 kPa (8.0 kg/cm^2). Already at a pressure of 200 kPa, the number of coarse pores begin to reach critically small values. Contrarily, one cay say that the coarse pore system has a structure that can withstand a maximum pressure of approximately this value.

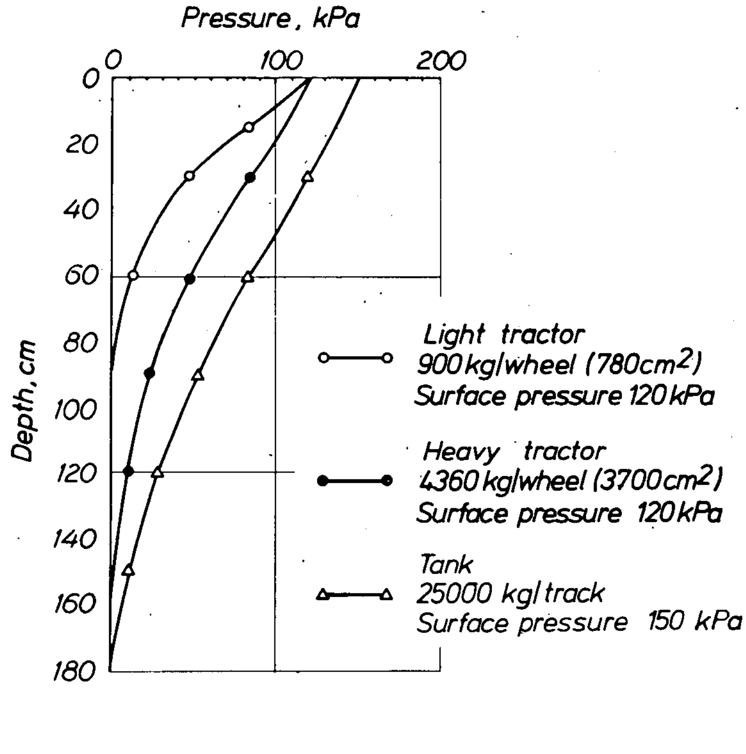

Fig.12. Increase in soil pressure under a light tractor with 0.9-ton wheel-weight and tyre width of 30 cm; heavy tractor with 4.4-ton wheel weight and tyre width of 62 cm; battle tank with total weight of 50 tons and track width of 61 cm.

As the coarse pores collapse, smaller pores are formed. The pores smaller than 0.03 mm were, therefore, maintained until a pressure of 200 kPa (2.0 kg/cm^2) was reached. At pressures beyond 200 kPa, this portion of the pore

system was, however, also affected. The same relationships that are described in this detailed example of an aggregated clay soil have been observed in studies of a series of fields with different soil types and pore volume distributions. The coarse pores begin to break down at a pressure of about 200 kPa.

The pressure exerted by a vehicle load at the soil surface diminishes with depth in the profile. As an example of what effect extremely heavy vehicle traffic has on the soil, we shall herein describe the results of an investigation where two identical clay soil profiles at a military exercise area were compared. One profile has been exposed to heavy military traffic for 30 years, of which 15 years with 50-ton tanks, the other has been protected and in grass during the same period; previously the entire research area was cultivated. Maximum pressures that occurred in the profile are shown in Fig.12. For purposes of comparison, calculated pressure curves from light and heavy tractors are included. In the top portions of the profile, pressures from the tanks are comparable to those from agricultural transport vehicles while in the deeper portions, they are substantially higher.

The comparison of compacted and uncompacted profiles, to 1 m depth, includes structure, earthworm-hole frequency, macro-aggregation, water infiltration, total pore volume, pores larger than 0.03 mm, and shrinkage. A clear difference could be established between profiles in all properties investigated. The clearest connection between pressure and physical changes was found in total pore volume and in the coarse pore system > 0.03 mm. The effects could be detected to the 100 cm depth (Fig.13a and b). In the top 50 cm of the profile, the influence on macrostructure and earthworm-hole could be visually observed. There was also a clear difference in permeability, a property markedly dependent on the macropore system, between the profiles in the top 50 cm. The influences were less below 50 cm (Fig.13c).

Compaction pressure - air permeability

The soil air is the source of oxygen needed for root respiration and the oxygen demand of microbial organisms. On the other hand, it is the recipient of the carbon dioxide produced by root respiration and by the microbial organisms. In order for the soil air not to be depleted of oxygen and be filled

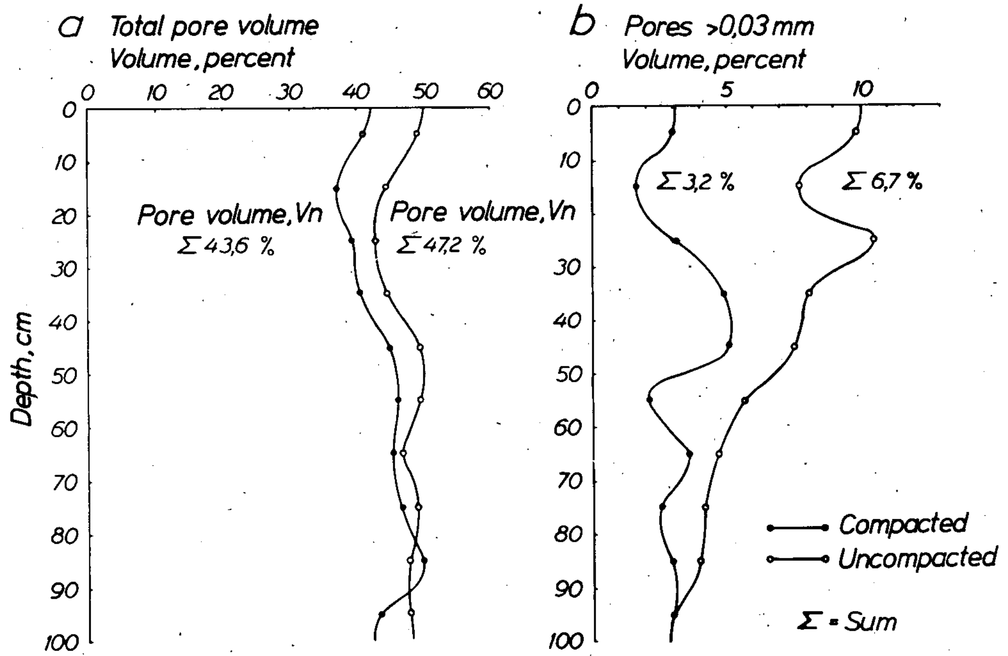

Fig.13. a) Comparison of total pore volume in a protected soil profile below a grassed surface, with a soil profile exposed to heavy traffic during 30 years, 15 of which were with 50-ton battle tanks. b) Comparisons of number of pores greater than 0.03 mm (drainable at 1 m tension).

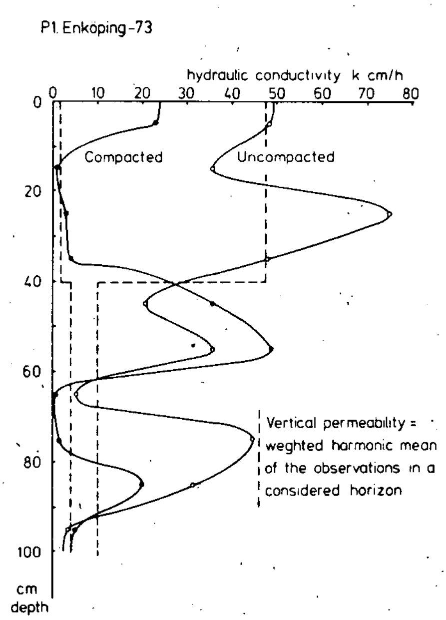

Fig.13 c) Hydraulic conductivity, k cm/h, to a depth of 100 cm in the compacted and uncompacted profiles. The vertical permeability 0-40 cm and 40-100 cm calculated as weighted harmonic mean of 10 cm horizons.

with carbon dioxide, it must be exchanged. Gas transport can be accomplished partly through diffusion, i.e. molecular movements in the stagnant air mass, and partly through mass transport, i.e. streaming of the whole air mass. For these air movements, the coarse pore system which can be drained at small tensions is of great importance. Diffusion and streaming depend on the air-filled pore volume; in addition, streaming depends on a certain number of coarse pores with low streaming resistance. When drainage is poor, air exchange is completely dependent on the coarse pores because the small pores are blocked by water. Oxygen and carbon dioxide differences in the soil are, however, balanced mainly through the process called *diffusion*.

The rate of respiration is determined by the mass and vigor of roots and microbes plus the soil temperature. The respiration process is considered to consume 5 to 20 liters oxygen and to produce an equivalent amount of carbon dioxide per 24 hours per square meter of soil surface.

A complete infiltration of the soil profile with roots is dependent on a well-developed network of cracks and channels for the movement of air, permitting the roots to push forward in all directions in close contact with the soil-air's supply of oxygen as well as the soil's supply of water and nutrients. Roots cannot commonly penetrate more than a few millimeters into free soil water from the boundary between air and water. It has been shown experimentally that roots, to maintain normal growth, need to have close contact with air containing at least 8 to 10% oxygen. Commonly, this oxygen concentration can be maintained as long as the air-filled pore volume does not drop below 5 to 10%. The active root is always surrounded by a water film through which the oxygen must diffuse. It has been shown experimentally that this water film will attain a thickness that permits optimum oxygen supply and root growth at a soil water pressure equivalent to 1 m suction.

That part of the pore system which is free of water determines the air exchange in the soil, regardless of whether it takes place in the form of diffusion or streaming. Therefore, a simple air permeability determination is a good measure of the air exchange capacity. It is most convenient to perform this determination at a suction of between 1 and 6 m.

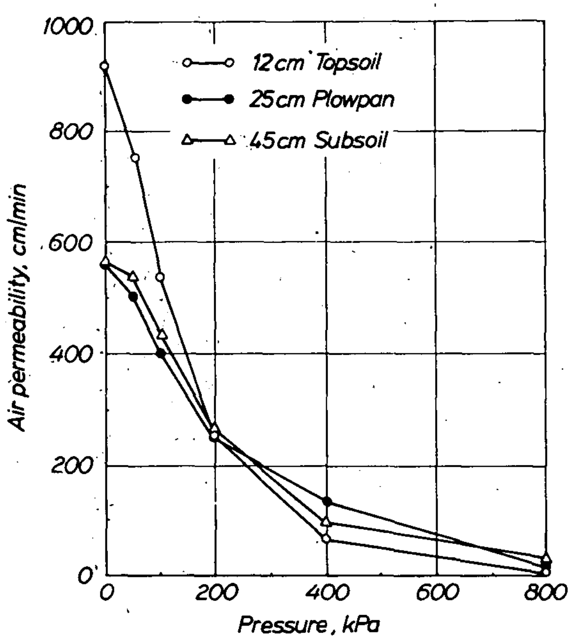

Fig. 14. Relationship between pressure increase and air permeability. Topsoil, plough layer and subsoil in claysoil profile, Ultuna.

The relationship between compaction pressure and air permeability for clay soil, Ultuna D-1973, is shown in Fig.14. Cores were taken from topsoil, ploughsole, and subsoil and drained at 6 m equivalent water tension. Subsequently, they were exposed to pressures of 50, 100, 200, 400 and 800 kPa and air permeability was determined. As seen in the figure, air permeability decreased greatly with pressures even as low as 200 kPa and reached very low values at 800 kPa. The test site, with a third-year hay crop, had a relatively uniform topsoil and air permeability was initially high, indicating the presence of coarse pores. However, the coarse pores in the topsoil apparently collapsed more easily with increasing pressure, and air permeability became lower than that of the ploughsole and subsoil at 400 and 800 kPa. In agreement with results from the investigation of pressure increase and pore-size distributions, it can be concluded that air exchange gradually deteriorates with increasing pressure and becomes critically small at pressures above 200 kPa. This is especially true at suctions of 1 m because

more pores are blocked by water, with a consequent considerable reduction permeability, as compared to 6 m suction.

Compaction pressure - penetration resistance

According to several investigations, a root tip can develop a maximum pressure of 1,000 kPa. The larger cracks and channels provide unrestricted room for root growth. As pore diameter approaches that of root diameter, pore tortuosity will influence root growth. Roots cannot penetrate a completely rigid matrix unless the pore diameter is the same, or larger than that of the root diameter. Soil mechanical resistance is closely related to soil density and texture. Depending on soil type, root growth is halted at a volume weight somewhere between 1.3 and 1.8 kg/dm^3. Attempts have also been made to relate root growth directly to the mechanical properties of soils, for example, penetration resistance. However, soil resistance to a root tip compared to a steel tip of the same dimension, is considerably lower. The needed force for root penetration in an average soil has been found to be 1/4 that needed for penetration of a steel penetrometer. In a compacted soil the relative power need is only 1/8. In soils suitable for root penetration, limiting values ranging between 800 and 5,000 kPa have been obtained with steel penetrometers. Several explanations can be given for the ability of the root tip to penetrate so easily.

a) The root tip, in contrast to the steel tip, follows the path of least resistance and takes advantage of small variations in density since it has a certain amount of freedom of movement.

b) The root tip has a tendency to compress the soil in a cylindrical fashion, i.e. the forces developed by the tip have a relatively large component at right angles to the direction of growth and relatively small components in the direction of growth.

c) When the root encounters resistance, it will, just behind the root cap, expand two to three times its normal diameter; this radial expansion of the root causes the soil resistance to be eased against the root tip itself so that it can further penetrate, as illustrated in Fig.15.

d) Fluid transport to and from the root tip can alter the mechanical properties of a soil; water uptake by the root causes shrinkage cracks, and cracks originally inaccessible to the root open up.

e) Friction against the root tip is considered to be small, partly because of its ability, even at high soil resistances, to maintain a pointed form and partly because it secretes plenty of slime.

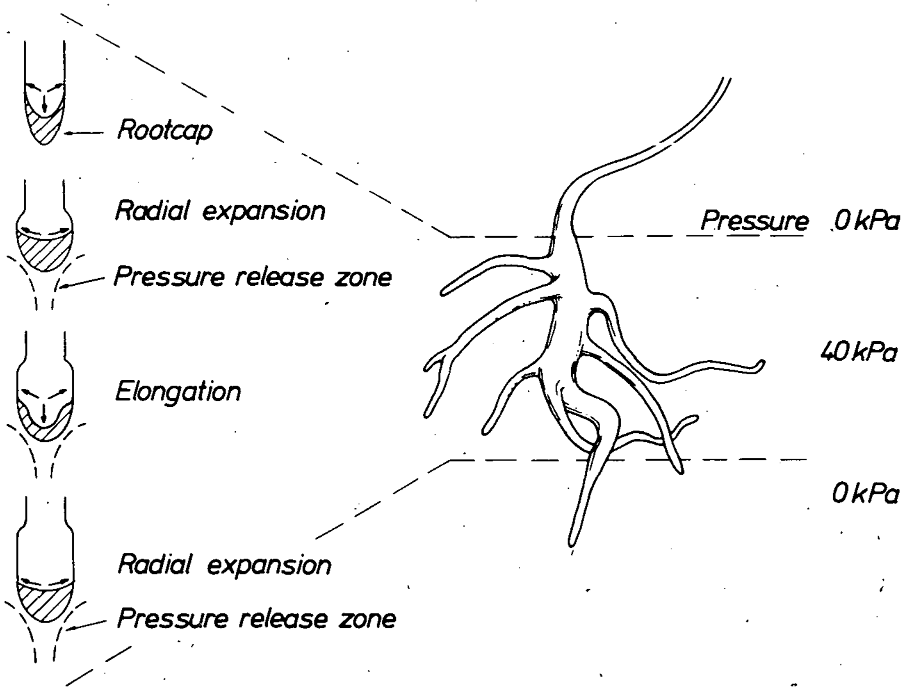

Fig. 15. Reaction of roots to high soil resistance. There is partly an increase in size of radius resulting in a pressure decrease in front of the root tip, and partly a profuse branching allowing some branches to find paths of less resistance (after Abdulla et al., 1969).

The relationship between pressure increases and penetration resistance in a clay soil from Ultuna is illustrated in Fig. 16. Penetration measurements were accomplished using 2 mm diameter needles with 60° cones. Each value is the average of twenty-four measurements and is shown in kPa. The penetration resistance was measured at suction of 0.05 and 6.0 m. At a soil suction of 0.05 m under non-compacted conditions (0-treatment), the resistance of all investigated horizons was under 1,000 kPa. With increases in compaction

pressures up to 200 kPa, the resistance increased quite sharply. The mechanical properties of the topsoil especially seem to change in this regard, but the penetration resistance of the ploughsole also increased sharply. The subsoil, which had the most favourable structure, changed the least. The sharp increase in penetration resistance that occurred when the soil suction was raised from 0.05 to 6 m is also interesting. All curves at the 6 m soil suction lie above the values of penetration resistance, that, according to the earlier mentioned investigations, can be judged to give a reasonable root resistance. A 200 kPa compaction pressure results in a penetration resistance that, according to the following study about root growth, results in a critically limiting value for root penetration.

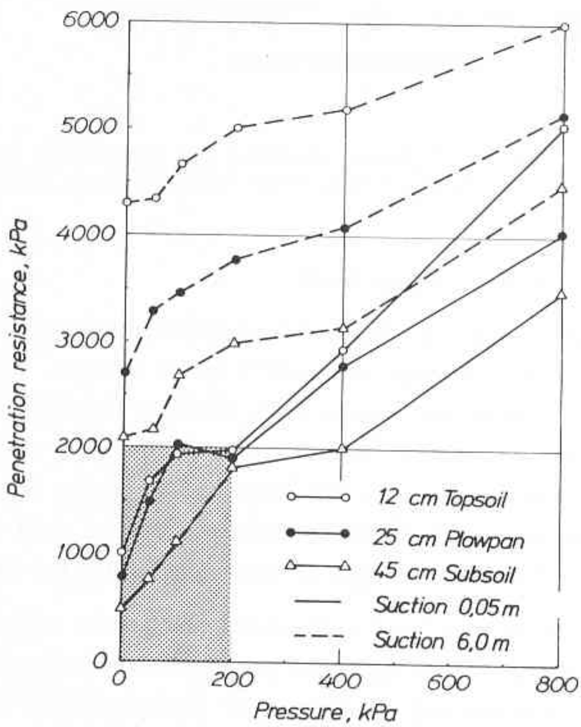

Fig. 16. Relationship between pressure increases and penetration resistance at 0.05 m and 6.0 m tensions. Topsoil, plough layer and subsoil in clay-soil profile at Ultuna. Shaded portion indicates an area of moderate root resistance.

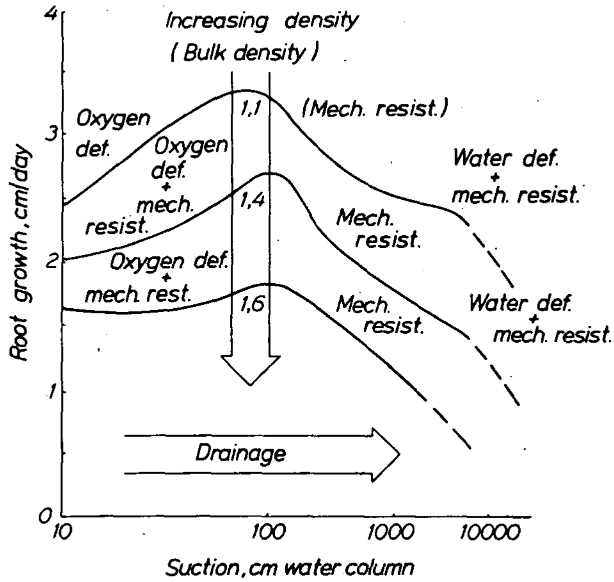

Fig. 17. Root growth at different degress of compaction and soil tension. Soil type: loamy sand (according to Eavis, 1972).

Compaction pressure - root growth

Under field conditions, the soil is continuously exposed to internal and external forces that tend to change the soil's total volume. When a soil is compressed, the pore volume decreases, bulk density increases, and the proportion of large pores decreases. The changes in the soil volume can be caused by shrinking and swelling of the soil matrix which in turn is caused by freezing and thawing or alternate wetting and drying, and also from compaction pressures in the soil profile by machines, vehicles and implements.

The physical condition of the soil influences the amount of water and nutrients that the root system takes up. This influence can arise from changes in the soil's ability to store and conduct water and nutrients or indirectly from effects on root growth and root functions and also from chemical and biological reactions in the soil. The interactions among root growth, mechanical resistance, oxygen availability, and water availability are apparent from Fig. 17 (Eavis, 1972). Root growth of field peas with increasing suction

in soil (loamy sand) of various densities is illustrated in the figure. With increased degree of compaction - increased bulk density - root growth decreases. There is a fairly wide maximum range in root growth at about 100 cm tension. Root growth is retarded at tensions below 100 cm because of oxygen deficiency. At high tensions, the firmness of the soil matrix increases and root growth decreases because of mechanical resistance. With further increases in tension, water deficiency also becomes a cause of reduced root growth. Mechanical resistance becomes more apparent at higher densities.

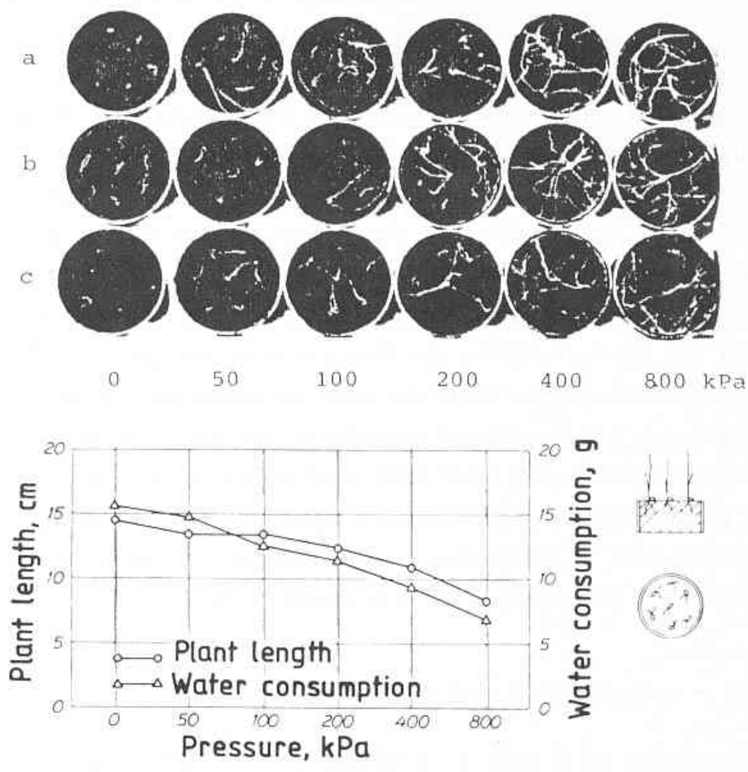

Fig.18. Relationships between compaction pressure, plant height, root development and water use for spring wheat. The wheat was grown on soil cores as shown in the diagram. The photograph of the upper surface of the cores shows an increasing number of roots on the surface, i.e. less root penetration with increasing degree of compaction.

a) Topsoil. b) Plough layer. c) Subsoil.

Clay-soil profile, Ultuna.

The relationship among compaction pressures, root growth, water use, and plant length in a clay soil is illustrated in Fig.18. Wheat was grown on soil cores which were 72 mm in diameter, 25 mm in height, and packed with pressures up to 800 pKa. Soil samples from the topsoil, ploughsole, and subsoil were taken from a well-aggregated clay soil at Ultuna (profile D72). Soil suction was 0.05 m. Seven wheat kernels were placed on the surface of each soil core and allowed to grow and develop roots. As is apparent from the picture of the roots, their penetration was unrestricted through the surface of the control treatment (0 kPa). At pressures of 50 and 100 kPa, root penetration was likewise good though a few roots had a tendency to grow laterally on the surface of the soil core. At 200 kPa, roots began to experience more restriction to penetration and grew for long distances on the surface, particularly in the case of the ploughsole. At 400 kPa, root penetration was poor and at 800 kPa, it was completely stopped and all roots grew on the surface. There was good wheat growth on the control treatment and at the lower pressures where the roots penetrated the core. At 200 kPa, plant growth began to decrease and at 400 and 800 kPa there was a further decrease. Water use also decreased with increased compaction. Wheat plants at 400 and 800 kPa were first to show water stress and to wilt. The experiment ended at this stage. Both the root pictures and curves depicting plant length and water use suggest a sequential influence of pressure increases on the root environment, and that when a pressure of 200 kPa is reached, a relatively large negative influence is imparted. Root penetration is brought to a complete halt by mechanical resistance at the high compaction pressures. Thus, again, 200 kPa emerges as a critical value.

Drainage - compaction vulnerability

The vulnerability of a soil to compaction decreases with increasing suction or degree of dryness. Tile drains will create a maximum soil-water pressure equivalent to a 1 m water column. At that water content, the soil is very vulnerable to compaction. More water must be removed by evaporation before the soil is suitable for cultivation and, according to laboratory experiments, the soil is then at a stage of dryness equivalent to a soil water pressure of 6.0 to 60.0 m.

Coarse-textured soils lie near the lower limit of this range, while clay soils don't gain necessary firmness, and cannot be cultivated without compaction damage occurring until a pressure equivalent of 60.0 m is reached. In a study of compaction on a series of clay soils with clay content between 40 and 80%, it was found, among other things that compression from a compaction of 200 kPa at 6 m suction repeatedly averaged 80% of the compression resulting from the same compaction pressure at a high degree of saturation, i.e. 0.05 m suction.

On areas with tile drains, a rapid removal of surplus water is insured and the water table drops to the level of the drainage tiles, i.e. at the most 1 m. By direct evaporation from the surface, the topsoil eventually reaches a degree of dryness that will be within the stated range of 6 to 60 m and the soil can be cultivated and seeded.

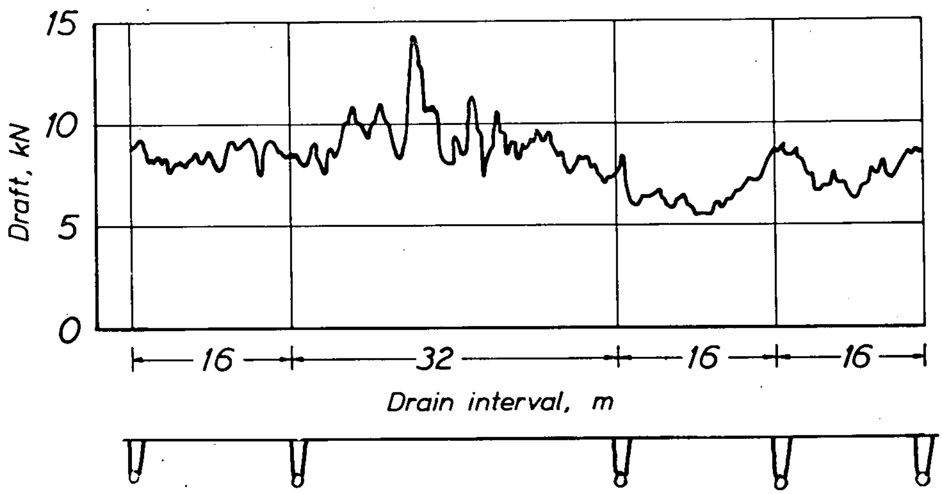

Fig.19. Results from a combined drainage - time of seeding - experiment at Lanna experimental farm, Skaraborg county. Variations in draft requirements in intervals between covered drains at two spacings, 16 m and 32 m. Measurement 1967-09-13 during fall ploughing. The topsoil was dry.

Results from a combined drainage and time-of-seeding experiment, conducted at Lanna Research Farm, Västergötland, are shown in Fig.19. Drain intervals of 16, 32 and 80 m were included in the experiment; depth to the tile was 0.8 m. A clear difference in soil dryness among tile distances is most often evident during the spring, and the 16 m interval can be used during the normal period for spring tillage without incurring any compaction damage. This was the case during spring tillage in 1967 for this experiment. In contrast, at normal time for spring tillage, the 32 m, and especially the 80 m interval, was so wet that severe compaction and unfavourable structure in the topsoil resulted. This was reflected in crop development, in final yields, and in the resistance of the central part of the topsoil to fall ploughing. Draft requirements were measured in conjunction with the harvest when the soil was dry, and a portion of measurements for the 16 m and 32 m tile drain spacings are illustrated in Fig.19. At a tile drain spacing of 16 m the soil structure was good and the drag resistance was low and even, while, at the 32 m distance, compaction during spring tillage resulted in an unfavourable structure difficult to penetrate with a ploughshare. The soil broke into large clumps and the draft requirement increased stepwise to double that of 16 m. Soil water content is one of the most important factors determining compaction vulnerability and structural deterioration. The most important possibility for regulating water content is by drainage, which is nicely illustrated by the results of this experiment. There are available data over a 25-year period pertaining to the relationship between tile spacing and dryness of Swedish cultivated soils that, in general, confirm this conclusion.

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Paper 1.10

AN ELECTRIC ANALOG FOR UNSATURATED FLOW AND ACCUMULATION OF MOISTURE IN SOILS

(This workshop paper will be published in one of the forthcoming issues of the Journal of Hydrology. Therefore, these proceedings contain only the abstract.)

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Abstract

An electronic analog model of the unsaturated zone was developed. The similarity between the integrated flow equation and Ohm's law is the base of the model. The main difference between the two equations is compensated for by amplifiers. The model simulates one day in 2 seconds. There are ten normal layers, each with adjustable magnitude. Moreover there is a top layer in which infiltration, ponding and run-off are simulated, and a drain layer with adjustable drain-intensity. The normal layers are containing an adjustable resistor for the connection with an other layer and a function generator for the $K(\theta)$ relation. There are two transition layers which have to be placed at the boundary between two layers of different soil properties.

In saturated conditions the model is acting incorrectly. This causes a calculated thickness of the saturated layers of a too small magnitude, which can be compensated for by using an equivalent drain intensity, lower than the real one.

This model can be used to simulate the effect of natural rainfall and evaporation on moisture content at every depth. Soil physical properties and drainage conditions can be adjusted. Homogeneous as well as layered soil can be represented by the model. It can especially be applied to investigate drainage requirements of soils.

Some examples are given to show the applicability of the model. A short technical description is given at the end.

Paper 1.11

SIMULATION OVER 35 YEARS OF THE MOISTURE CONTENT OF A TOPSOIL WITH AN ELECTRIC ANALOG FOR 3 DRAIN DEPTHS AND 3 DRAIN SPACINGS

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Summary

With an electronic analog model the moisture content of the top 10 cm of a schematized silt loam soil was calculated over 35 years. Drain depths of 70, 100 and 130 cm below surface were used, each with three drainage intensities as shown in Table 1.

To obtain a low number of days with a very wet soil, a high drainage intensity appeared to be important, the drainage, however, should not be shallow.

To obtain a high number of workable days deep drainage is important, and drainage intensity has little significance.

Introduction

Drain depth and drainage intensity both affect the moisture content of topsoils. The Netherlands drainage criterion pays more attention to drainage intensity than to drain depth. It was found by WIND (1976) that as regards workability, drain depth is more important than drainage intensity. Because of this difference in point of view we were anxious to see what interrelations exist between depth and intensity.

The electronic analog (WIND and MAZEE, 1978) gives the possibility to simulate long time-series with low costs. Therefore we simulated 35 years between 1941 and 1977 from September 1 to May 31, for three drain depths and three drainage intensities. So about 85,000 days were calculated, which calculation lasted about 48 hours. The same simulation executed with a numerical model would have cost US $ 80,000.

The aim was to determine during how many days there was:

1. a very wet soil with less than 2% air content;
2. a wet soil with less than 5% air content;
3. a workable soil defined as having more than 100 mbar moisture suction
4. a soil with workability for special operations defined as having more than 200 mbar moisture suction.

In order to avoid complications a very simple soil was used and a simple initial condition.

The soil

The soil used is a 'silt loam' with a straight moisture characteristic: $\Psi = 10\,\theta - 500$, where Ψ is expressed in mbar and θ in % by volume. Rijtema's (1965) expression for the $K(\Psi)$ relation was used:

$$K = K_o e^{\alpha\Psi} = 2e^{0.025\Psi}$$

The soil was taken to be uniform through the whole profile.

Initial condition

Regardless of the weather in the preceding summer, for every year the same initial situation on September 1 was used. This was a situation in which there is equilibrium with a constant downward flux of 1 mm/day^{-1}. So the moisture content on September 1 was dependent on the drainage of the soil.

Weather

Rain and evaporation data were obtained from observations of the Royal Netherlands Meteorological Institute (KNMI) at De Bilt in the centre of The Netherlands. The first year was 1941/42, the last 1976/77. The year 1944/45

was omitted because some observations were lacking.

Evaporation data were calculated according to Penman and multiplied by 0.8. These data concerned periods of one month. The evaporation rates were distributed over the days proportional to radiation data.

There was no device to reduce evaporation data in dependence of moisture contents.

Drainage

Three drain depths and three drainage intensities were applied as shown in Table 1. Drainage intensity here is defined as drain outflow rate (cm/day^{-1}) divided by the height of the groundwater level above drain level (cm).

TABLE 1. Drainage intensities applied in the simulation with three drain depths

Drain depth (cm)	Drainage intensities (day^{-1})		
70	0.0100	0.0150	0.0250
100	0.0050	0.0100	0.0150
130	0.0050	0.0075	0.0100

Surface runoff occurred when there was more than 1.0 cm water upon the surface. The water in excess of 1 cm was removed at once.

Results

The analog simulation was carried out with soil layers of 10 cm, except in the drain depth of 130 cm, where some deep layers of 20 cm thickness were used.

The moisture content of the top 10 cm was continuously recorded with a line recorder. From these graphs the number of days that the moisture content did exceed a certain value was read.

Table 2 gives an example for the value of 45% moisture (5% air in the soil drained at 100 cm depth).

TABLE 2. Number of wet days (topsoil contains less than 5% air) in 35 years for drain depth 100 cm and three drainage intensities.

Month	Drainage intensity (day^{-1})			Mean rainfall minus evaporation (mm)
	0.005	0.010	0.015	
Sept.	103	71	57	22.4
Oct.	217	163	94	49.8
Nov.	368	182	125	62.8
Dec.	460	254	190	61.0
Jan.	405	179	127	64.8
Febr.	306	135	90	40.5
March	65	26	16	11.0
April	51	11	9	- 13.6
May	11	6	4	- 35.7
TOTAL	1986	1027	712	

The month December seems to be the wettest although in the months November and January there is somewhat more rainfall. The total amount of wet days comes to 57, 29 and 20 days per year for the three drainage intensities. So there is a pronounced effect of drainage intensity on the wetness of the topsoil, which was to be expected. In Fig.1 this effect is shown graphically. Drain depth seems to have an effect at least as important as drainage intensity.

The effect of drain depth and drainage intensity on the number of very wet days (topsoil with air content less than 2%) is shown in Fig.2. There it seems that drainage intensity is more important than drain depth. Nevertheless a very low number of very wet days will not easily be obtained with shallow drainage.

To reach a high number of workable days (θ < 40%, which means suction > 100 mbar) in March, drain depth is apparently more important than drainage intensity (see Fig.3).

This is even more pronounced in Fig.4 which considers the situation where the soil is dry enough for special operations, as seedbed preparation for potatoes and sugar beet. The most striking is the large difference between the drain depths 100 and 130 cm.

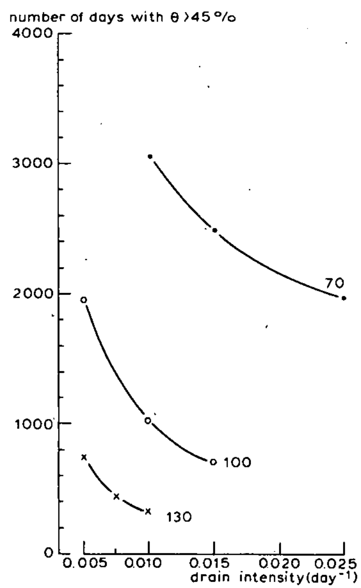

Fig. 1. Effect of drain depth and drainage intensity on number of days with wet topsoil; air content <5%, suction <50 mbar.

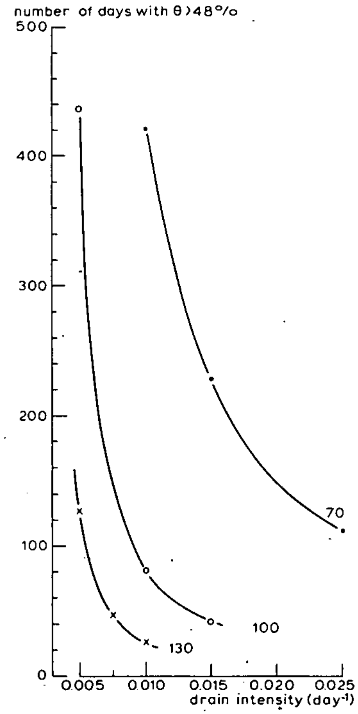

Fig. 2. Effect of drain depth (70, 100 and 130 cm below surface) and drainage intensity on the number of days with a very wet topsoil; air content <2%, suction <20 mbar.

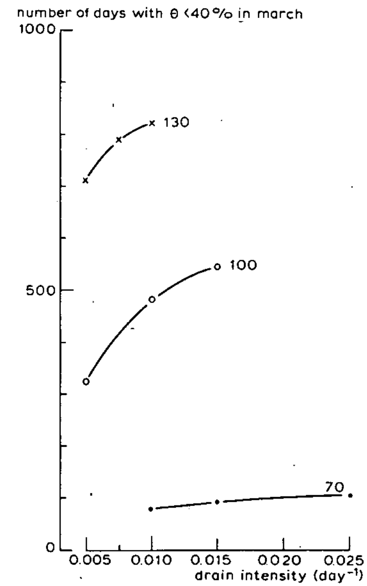

Fig. 3. Effect of drain depth and drainage intensity on the number of workable days; suction <100 mbar.

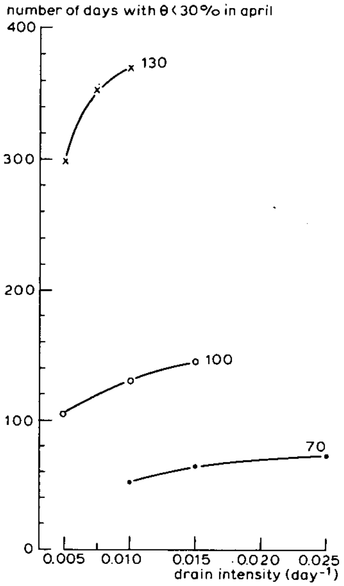

Fig.4. Effect of drain depth and drainage intensity on the number of days with workability for special operations, suction >200 mbar.

Discussion

The lines in Fig.2 are steep; the higher the figure-number the less steep the curves are. This means that the drier the reference value of moisture content is chosen, the less influence drainage intensity has. The conclusion of this somewhat schematized investigation is:

- To avoid very wet conditions drain spacing is an important factor, although the effect of drain depth is not negligible.
- To promote workability, the most important factor in drainage design is drain depth.

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Paper 1.12

DRAINAGE OF CLAY SOILS IN ENGLAND AND WALES

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Summary

There is an estimated drainage need on 2.6 million ha of agricultural land in England and Wales. Of the work currently being carried out 75% is on clayey soils.

In the clay soils of low conductivity, it is concluded that the only effective way of draining the subsoil is by secondary treatments of mole drainage or subsoiling over permanent pipe systems. These two operations are defined, and the conditions under which they are likely to be successful discussed.

In terms of current drainage design practices on these soils there is a large traditional factor, related to the particular part of the country. A more scientific approach is advocated, but due to the fact that most schemes are small (7 ha), there is an economic limit to the amount of pre-design survey that can be reasonably carried out. The options available are discussed, and a design philosophy suggested.

1. Introduction

There is a current estimated drainage need of 2.6 million ha of agricultural land in England and Wales. By far the greater proportion of work is on soils falling within the clayey textural classes, and its satisfactory drainage is therefore of paramount importance to British agriculture. The major factor influencing drainage design of these soils are:

i) hydraulic conductivity of the subsoil is generally very low and often decreases with depth

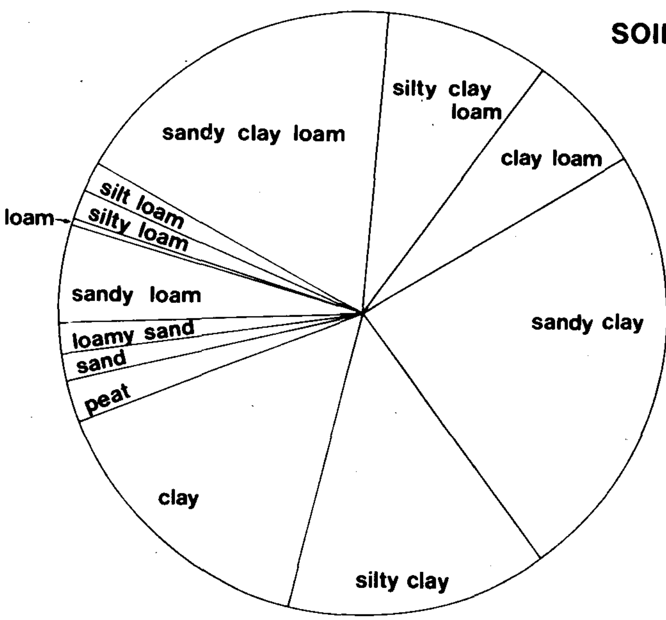
ii) because of i) some form of secondary drainage treatments are required in the form of mole drainage or subsoiling if the subsoil is to be effectively drained

iii) there can be considerable soil variation within relatively short distances

iv) average scheme size is only 7 ha, thus limiting the amount of time and effort that can be economically justified in individual site investigation.

2. Clay soils of England and Wales

Of all drainage work carried out in the UK 75 - 80% is on clayey soils, and as a soil group it creates the greatest problem in field drainage. The textural classes of all soils currently being drained are shown in Fig.1.



SOILS WHICH ARE BEING DRAINED

%	soil texture
15	clay
14	silty clay
24	sandy clay
6	clay loam
9	silty clay loam
17	sandy clay loam
2	silt loam
2	silty loam
0·26	loam
5	sandy loam
2	loamy sand
2	sand
2	peat

Fig.1. Soils which are being drained.

Due to the effects of glaciation the clay soils can vary over relatively short distances, and over considerable areas the conductivity tends to reduce with depth. Many of the subsoils have hydraulic conductivity (K) values less than 0.1 m/day and would require pipe spacings of 2-3 metres to effect adequate subsoil drainage. Table 1 lists some K-values of British clay soils,

related to the Soil Series on drainage experimental sites. The Soil Series is the basic unit of soil classification used by the Soil Survey of England and Wales, and is defined as a class of soils with similar profile characteristics.

The conductivity values in Table 1 were determined by single auger hole method, and in all cases there is considerable range. The Drayton EHF experimental site, detailed in Appendix II, ranged from 0.006-0.02 m/day. If a permanent pipe system at 10 m spacing is taken as an arbitrary economic limit for drainage installation, then some form of secondary drainage treament (Section 3.3) is necessary on sites with K-values less than, say, 0.3 m/day, if subsoil drainage is to be achieved at realistic cost.

TABLE 1. Some hydraulic conductivity values of British soil (after Kellett, 1975), in order of K-value *

Site	Soil series	Texture	Depth (cm)	Median K-values
W Sedgemoor Somerset	Midelney	silty clay	(30-40)	0.00001
Samlesbury Lancs	Salop	clay	(70-87)	0.0035
Drayton EHF Warwicks	Evesham/ Denchworth	clay	(40-100)	0.0038
Cefn Coch (OS 270) Wales	Ynys	silty clay	(20-30)	0.01
W Sedgemoor Somerset	Sedgemoor	peat	(30-40)	0.02
Wilburton Cambs	Peacock	clay	(40-100)	0.03
Boxworth EHF Cmabs	Hanslope	clay/clay loam	(40-100)	0.03
Cross Moor Somerset	Allerton	silty clay	(40-100)	0.1
Cheddar Moor Somerset	Allerton	silty clay	(40-100)	0.23
Wrea Green Lancs	Clifton	clay loam	(50-65)	0.24
Bleadon Levels Somerset	Wentlloog	silty clay	(40-100)	0.28
Brooksby Leics	Hanslope Ragdale	clay/sandy clay	(40-100)	0.32
Thornham Marsh Norfolk	Unclassified (Recent)	sandy loam/ clay loam	(45-100)	0.7

* *all values in metres per day*

3. Present drainage practices

3.1 Survey of current practices

Armstrong & Smith (1977) have examined current practices on 36,000 drainage schemes from data abstracted from the Ministry of Agriculture's records on schemes submitted for Government grant aid. The dominant drainage practices are shown on Fig.2 and the distribution of areas drained and average scheme size data on Fig.3 - the data is shown in terms of the Ministry's administrative divisions.

There is an area in East and Central England where the dominant practice is mole drainage over widely spaced drains. To the North and West of this area there is a transition zone of varying practice, with close drain spacing in the North and West of the country. The South East shows a departure from the East and Central England practices, but this probably reflects the soils which lie outside the zone of heavy glacial tills found in the other parts of the country. There is also a local practice of using straw over pipes in this region, and the analysis has shown this incorrectly as a *permeable trench backfill treatment.*

Critical examination of these data has identified inconsistencies of drainage design on similar soils in different parts of the country that cannot be explained by climatic or geographic variation.

Arising from this study national research priorities have been determined on the following basis:

High priority:	soils with gross differences in drainage practices	
Medium priority:	a)	soils with minor differences
	b)	soils uniformly treated, but with questionable effectiveness
Low priority:	soils uniformly treated, with demonstrable effectiveness.	

3.2 National study of soil water regimes

A national investigation to examine soil water regimes on drained and undrained sites, Rands (1976), Thomasson (1976), has shown that on many clay

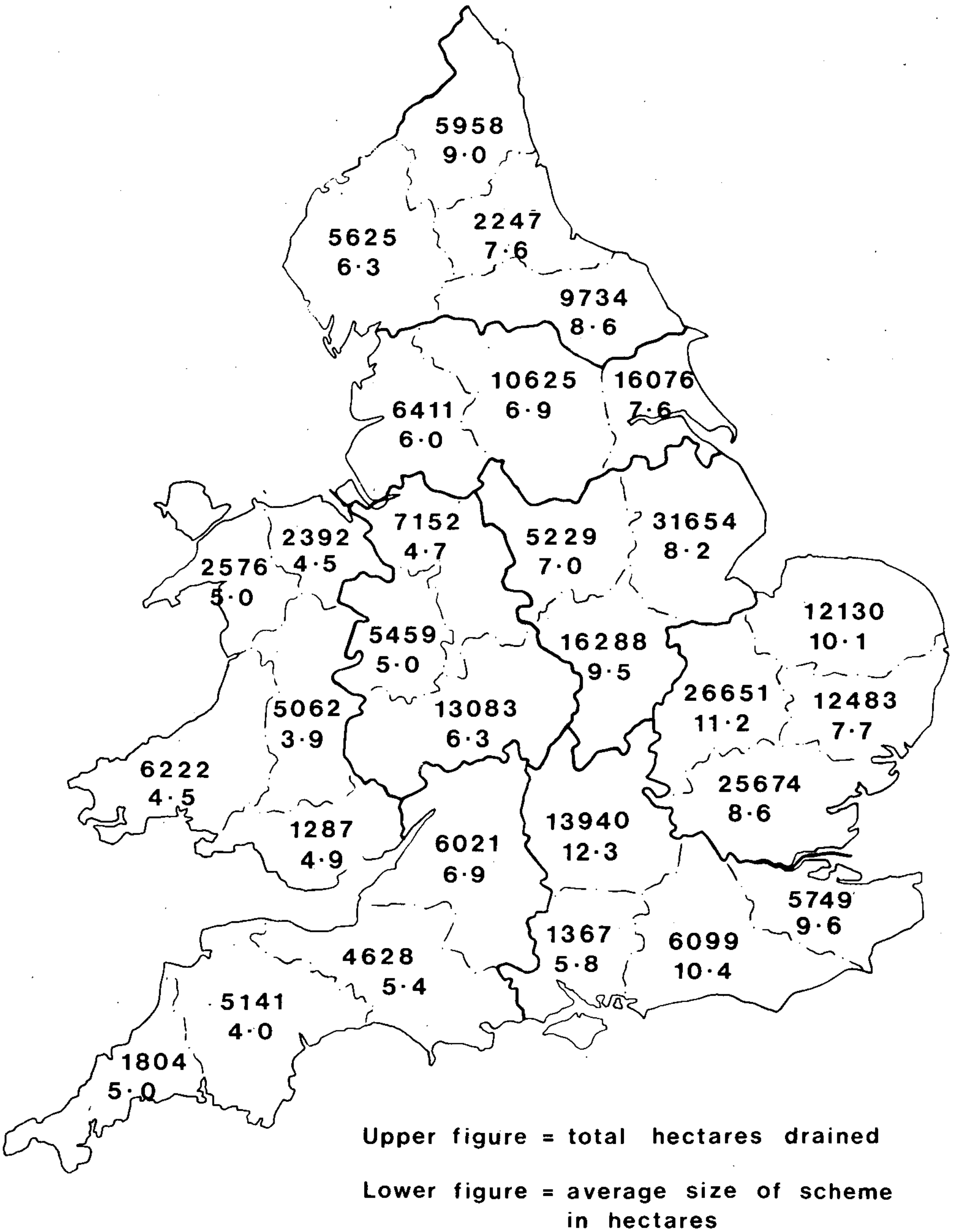


Fig.2. Distribution of areas drained, England and Wales, during period 1.4.73 to 31.3.76.

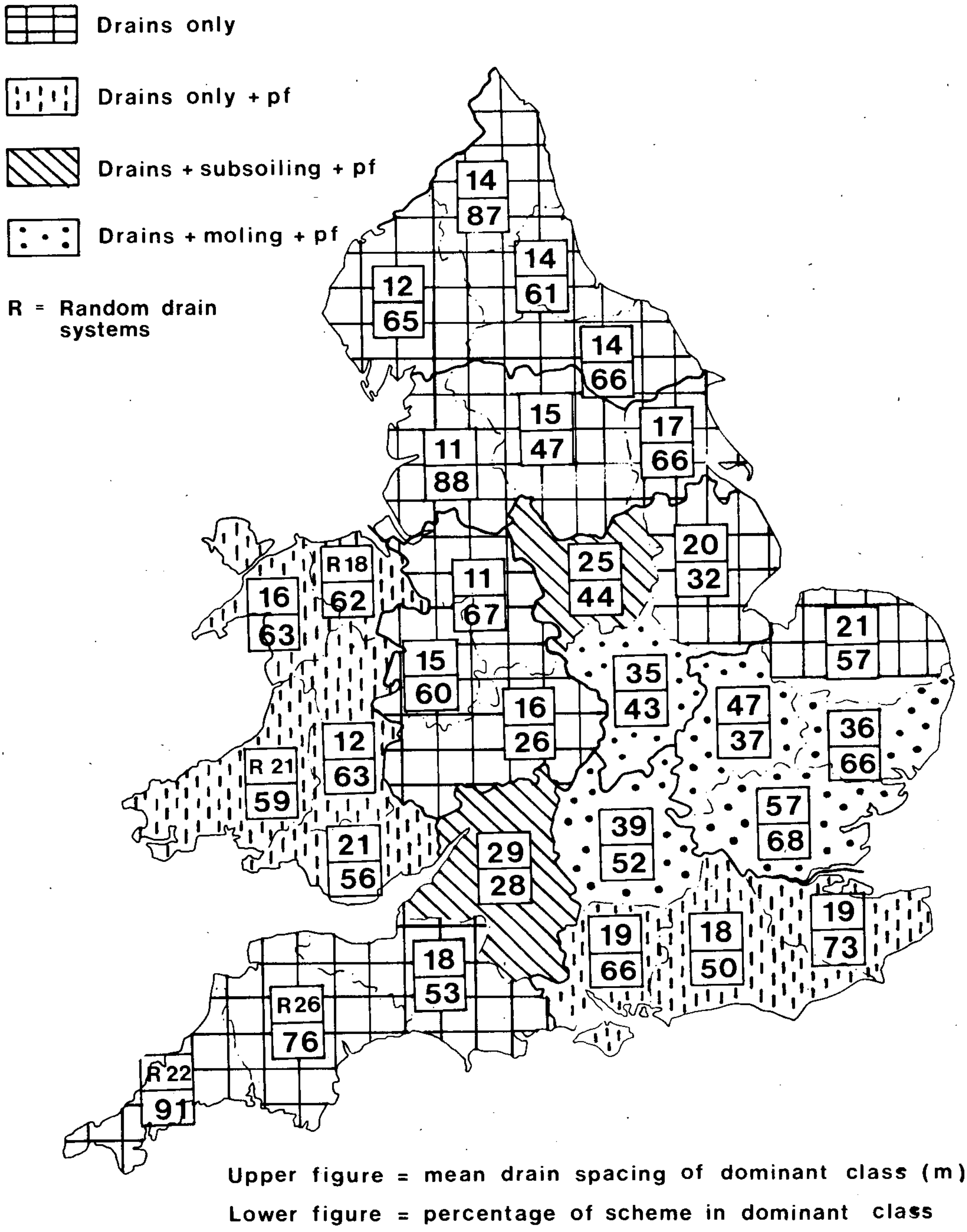


Fig.3. Dominant drainage practices in England and Wales.

soils, close spaced drainage systems (10 m), in the northern and western parts of the country, are not draining the subsoil during the drainage winter and the effectiveness of some of these designs must be questioned.

There is a particular need to encourage successful subsoil drainage practices in some of the problem areas evaluated under the investigation discussed at Section 3.2. Many of these soils have K-values less than 0.3 m/day and requir either, even closer pipe spacing, or modification of the subsoil to increase the hydraulic conductivity. The soil water regime investigation is clearly showing that only surface drainage is being achieved on many soils and that there is scope for expanding secondary treatments of mole drainage or subsoiling into non-traditional areas.

3.3 Secondary drainage treatments

Moling

The technique of moling seeks to place inexpensive 'drains' at close spacing, intercepted by permanent pipe laterals at wider spacings determined by the stability of the soil to retain a channel. Present practice is to form a 75 mm diameter channel in the soil at a depth of 60 cm, see Fig.4. The timing of operations and stability potential of soils to retain a mole channel are critical factors and are priority research areas. Current advice has been set out in guidelines by Trafford and Massey (1975), and is summarized at Appendix I.

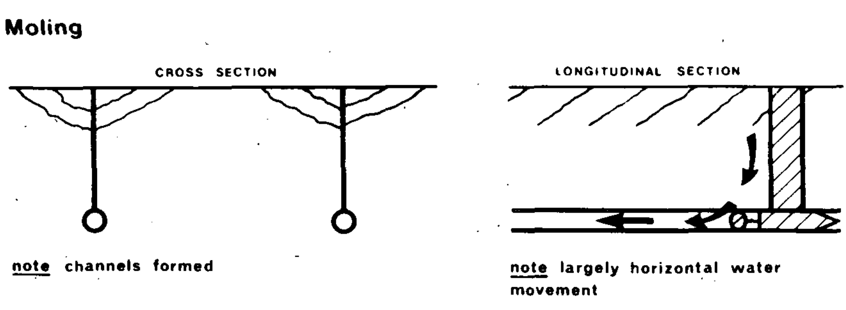


Fig.4. Diagrammatic illustration of moling.

Subsoiling

Subsoiling in the drainage mode seeks to lift and shatter the soil peds to induce improved structure (Fig.5) and so improve the water movement to the permanent pipe system.

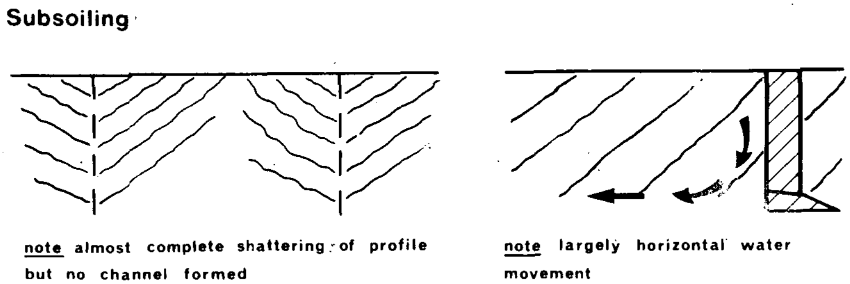


Fig.5. Diagrammatic illustration of subsoiling.

The basic difference between the mole plough and subsoiler is that the tine is wedge shaped tapering up to a square section; to achieve maximum shatter the subsoil must be dry.

Recent work by Spoor (1976) has shown that there is a critical depth, below which the failure is plastic with the subsoil being compressed rather than shattered (Fig.6).

The significance of this work is that effective subsoiling can only be achieved to a critical depth, which depends on soil moisture content, and rake angle and width of the tine - in UK conditions the critical depth is approximately 40 cm.

A recent examination of 50 subsoiling schemes revealed that in 80% a channel was created, indicating that the majority of operations were being carried out below critical depth and producing inferior mole channels. The effective shatter in the 20-40 cm zone was only 40% - a typical shatter diagram from adjacent tines is shown in Fig.7. This work was carried out with conventional single tine or multi-tine subsoilers, with mean implement foot width of 8 cm, and mean spacing between tines of 1-2 m.

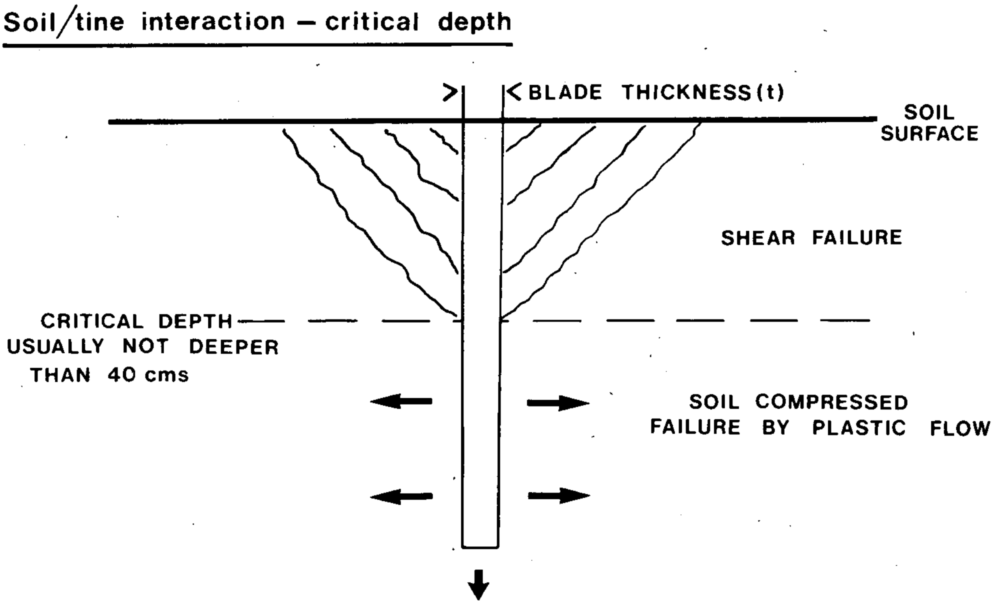


Fig.6. A diagrammatic representation showing upward soil failure in shear above the critical depth and plastic flow below this.

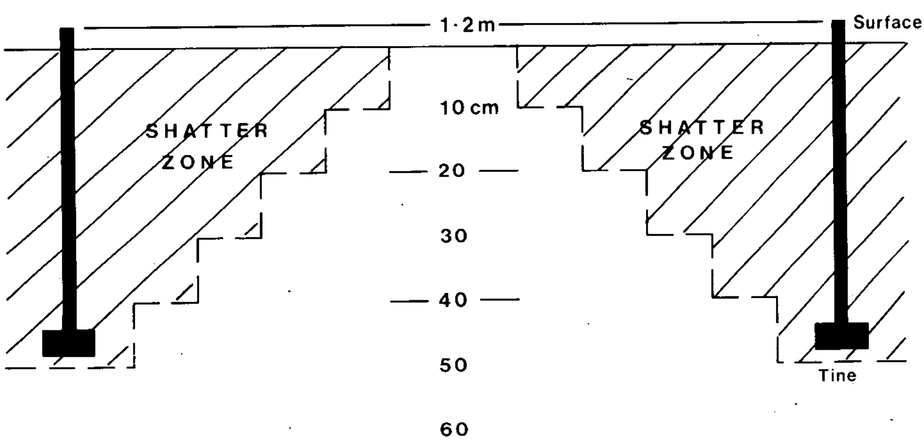


Fig.7. Typical shatter diagram for subsoiling giving the median shatter of 42% of the 20-40 cm zone.

Spoor's work shows that the addition of 'wings' to the subsoiler foot can significantly improve shatter with only small increases in draught requirements. The relationships of soil moisture conditions, implement design and depth of operations are high priority research areas.

3.4 Experimental evidence effectiveness of secondary drainage treatments

Over the last 7-8 years several field experiments on heavy land have been carried out to evaluate the hydrologic/economic factors of various drainage designs. May and Trafford (1977) have evaluated the results of the hydrological data at a site in the West Midland Region of England, the Drayton Experimental Husbandry Farm, Stratford-upon-Avon, Warwickshire. These results are representative of the other sites and the more important are presented at Appendix 2.

The Drayton experiment examined the relative performance of drains laid at 15 m, 30 m and 60 m spacing, with and without secondary drainage treatments of mole drainage and subsoiling. The best drained plots were those that had been mole drained over permanent pipe systems and showed an increase of 1 tonne/ha of winter wheat over the undrained control (Armstrong, 1976).

The main conclusions are:

a) The drainage treatment ranking in terms of hydrologic and yield performance is:

moling + pipes
subsoiling + pipes
pipes only.

b) The permanent drain spacings were not in themselves significant. In the case of the mole drains these effectively acted as pipes at 2 m spacing and controlled the water table at 50 cm. This accords approximately with the theoretical spacing required with a K-value of 0.01 m/day at 50 cm depth.

c) Mole drainage channels may be expected to remain effective for 4-6 years provided that they are drawn under reasonable soil moisture conditions.

4. Practical design options

There is evidently a large 'traditional' factor in current designs practices on the clay soils. A good deal of research effort has been, and is currently being given to methods of draining the subsoil by secondary treatments. A prerequisite, however, is a more objective determination of the hydraulic conductivity values of the soil to enable further application to a satisfactory design.

4.1 Individual scheme investigation

The majority of design work is undertaken by Land Drainage Services advisers of the Ministry of Agriculture's Agricultural Development and Advisory Service, located at 30 divisional centres throughout England and Wales. Over recent years the Land Drainage Service has been receiving approximately 20,000 schemes/annum, with an average scheme size of less than 7 ha (see Fig.3).

Field experience has shown that due to the wide variation of soils, K-values by auger hole methods would require at least 5 wells/ha. Thus each scheme, average cost £2,000, would demand a very large time and resource commitment relative to the value of the work, and except in special situations could not be justified.

4.2 Design based on soil series

Based on the characteristics of the soil profile it is reasonable to suggest that for any soil series a fairly narrow range of field drainage design options could be stated. In the absence of hydrological measurements in an individual situation, soil series offers a reasonable design basis.

Using soil series as a basis Rands et al. (1973) suggested drainage designs for the soils in Eastern England. To overcome the lack of data on hydraulic conductivity, the soil series are allocated a 'class' based on the work of O'Neal (1952) - Table 2.

TABLE 2. Hydraulic conductivity classes

Class	Hydraulic conductivity value K in m/day
Very slow	less than 0.03
Slow	0.03-0.1
Moderately slow	0.1 -0.5
Moderate	0.5 -1.5
Moderately rapid	1.5 -3.0
Rapid	3.0 -6.0
Very rapid	more than 6.0

Application of this technique to a specific soil series is shown in Appendix III. This technique can be readily applied where soil maps are available, or where the soil series can be identified in the field in a non mapped area. The major limitation to use is that there can be a variation of soil within a defined series, and the application of a design layout from this may be too generalized in a specific field situation.

4.3 Design based on inferred 'K' values

Given that individual site determination of hydraulic conductivity is uneconomic, and that soil series approach has limitations in specific field situations, effort has been directed towards determining 'K' from site observations of more readily observable soil characteristics.

Work by Renger & Henseler on soils in Lower Saxony suggests that an estimate of hydraulic conductivity can be obtained from soil texture, structure, packing density and organic matter. Work is currently underway by Tring (1977) to examine the relationship of structure, packing density and hydraulic conductivity on a number of British soils.

Results are showing a correlation between packing density and structure (Tab. 3). This investigation is being given national research priority, and work is underway to measure 'K' values on the major soil series during the 1977/78 drainage winter. The work seeks to establish a relationship of a range of hydraulic conductivity values, with soil characteristics readily observable or obtainable by the drainage designer from a soil profile pit, and that does not require the presence of a water table.

TABLE 3. Comparison of soil structure/packing density values

Structure details	Arithmetic mean at 95% Confidence Level 1974-77
Medium prismatic moderate	2.01 ± 0.08
Medium prismatic close	1.96 ± 0.12
Coarse blocky close	1.99 ± 0.05
Coarse prismatic close	1.95 ± 0.06
Medium blocky close	1.94 ± 0.05
Medium prismatic free	1.91 ± 0.02
Fine blocky moderate	1.78 ± 0.07
Medium blocky free	1.68 ± 0.07
Single grain	1.30 ± 0.65
Medium blocky moderate	1.70 ± 0.07
Fine blocky free	1.61 ± 0.11
Coarse granular close	1.56 ± 0.03
Fine granular free	1.37 ± 0.04
Massive	1.33 ± 0.29

5. A design philosophy

Arising from the factors presented in the discussion paper a general philosophy is evolving for the drainage of the clayey textured soils of England and Wales. For drainage design purposes, clayey soils in England and Wales can be considered in 3 classes:

1. Soils with 'K' values in excess of 0.3 m/day, usually can be effectively drained by pipes at economic spacing.

2. Soils with 'K' values between 0.01 and 0.3 m/day, reasonably stable, and free of sand pockets and stones, may be drained with combined mole/pipe systems or where subsoiling above the critical depth can achieve an improved 'K' value then subsoiling/pipe systems.

3. Unstable soils and soils with 'K' values less than 0.01 will need to rely on surface drainage techniques.

Division of the drainage classes in this manner suggests that ranges of conductivity are more meaningful than specific values. The determination of these ranges is vital to improve the design of UK schemes and will be applied thus:

a) Design based on individual site measured hydraulic conductivity values. This method will only be used for exceptional cases.

b) Design based on Soil Series.
This method offers designers a useful guide at feasibility level, but there are limitations to the application due to field deviation from the standardised Soil Series profile.

It could be considerably enhanced if data on median 'K' values, together with the likely range, was readily available.

c) Design based on 'inferred' values of 'K'.
This approach would offer the UK designer the most realistic solution. It will enable the determination of meaningful design parameters at realistic costs.

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APPENDIX I

A guide to mole drainage
(after Trafford & Massey, 1975)

i) Stability to water

Previous experience, laboratory tests, or a crude test on a moulded lump immersed in water, are the best guides until advice on specific soils can be given. If the soil has a low hydraulic conductivity and is unstable to water subsoil drainage should not be attempted. If the soil has reasonable water stability underdrainage using moling may be considered.

ii) Timing of moling

The best practical advice would be that the soil at moling depth should be within the plastic range but not wetter than field capacity. This can be checked in two simple ways.

Plastic limit test

Take a small sample of soil from moling depth and attempt to roll out a thread 2½ mm in diameter. If this can be done the soil is within the plastic range.

Field capacity test

Auger a hole to mole depth (55/60 cm) and leave for several days, making sure that surface water cannot enter. If water seeps into the hole then it is very likely that the soil is too wet to mole.

iii) Spacing of permanent drains

Permanent drains backfilled with gravel or similar material should be located in any natural depressions in the field. Closer spacings than this should be used if the soil is only moderately stable to water or there are sand pockets or other non-uniform areas. Maximum spacings might be 200 m and minimum spacings 10 m, although 20 - 60 m is more typical.

iv) Spacing between moles

A basic spacing of 2 - 3 m for the better clays (i.e. > 0.2 m/day) with spacings of 1 - 1½ m for the more difficult clays (i.e. < 0.2 m/day) would seem the most cost effective approach. The moles are the "drains" and closer moling will give a quicker drawdown and more effective control of the water table.

v) Depth of moles

Mole depths significantly shallower than 50 cm are not generally recommended as these are unlikely to give the desired soil moisture control. On some soils more stable clay may be found at greater depth and in this case it is desirable to take advantage of this up to about 70 cm. Beyond this depth the increased draft required may make the operation impracticable and it may be better to accept a shorter mole life.

vi) Frequency of remoling

No hard and fast rules can be offered as mole life seems to depend to a considerable extent on the conditions under which they were drawn and conditions soon afterwards. The important factor is to re-draw the moles before it is self-evidently necessary. As good moling conditions do not coincide with the land being free of crops in all years the precise life is not of practical interest. Most farmers who are successfully using moling re-mole a portion of the land (often 25%) each year that conditions are suitable. This means that re-moling is done every 4 - 5 years or so even though it might last 8 or 10 years.

vii) Mole gradients

It would seem to be good design practice to angle the moles with respect to the slope so as to have grades of 2 - 5% as a compromise between avoiding backfalls and erosion.

APPENDIX II

The Drayton experiment

i) Site details

Mapped as an Eversham Soil Series of the Lower Lias Clay (see Table 1). The site slopes south-southeast at 2%, and the cropping is arable with a mainly cereal rotation. Annual average rainfall is 625 mm.

ii) Layout

The experiment includes 11 plots, approximately 0.4 ha in size. There are 3 drainage treatments:

drains at 15 m - no permeable trench backfill
drains at 30 m - with and without permeable fill
drains at 60 m - with permeable fill

The pipes are laid at 80 cm depth.

There are 3 levels of secondary treatment:

none
subsoiling - 45 cm deep, 1.5 m spacing
moling - 55 cm deep, 2.0 m spacing

Two undrained plots are included.
The detailed layout is at Figure 8.

iii) Equipment

Raingauge, vane-in-orifice and tipping bucket flow meters, water table recorders, dipwells.

iv) Length of experiment

The experiment commenced in 1969 and after 7 years it is considered that the original objectives have now been met. Further experimental work is under way on the site looking at more closely the relative roles of moling and subsoiling.

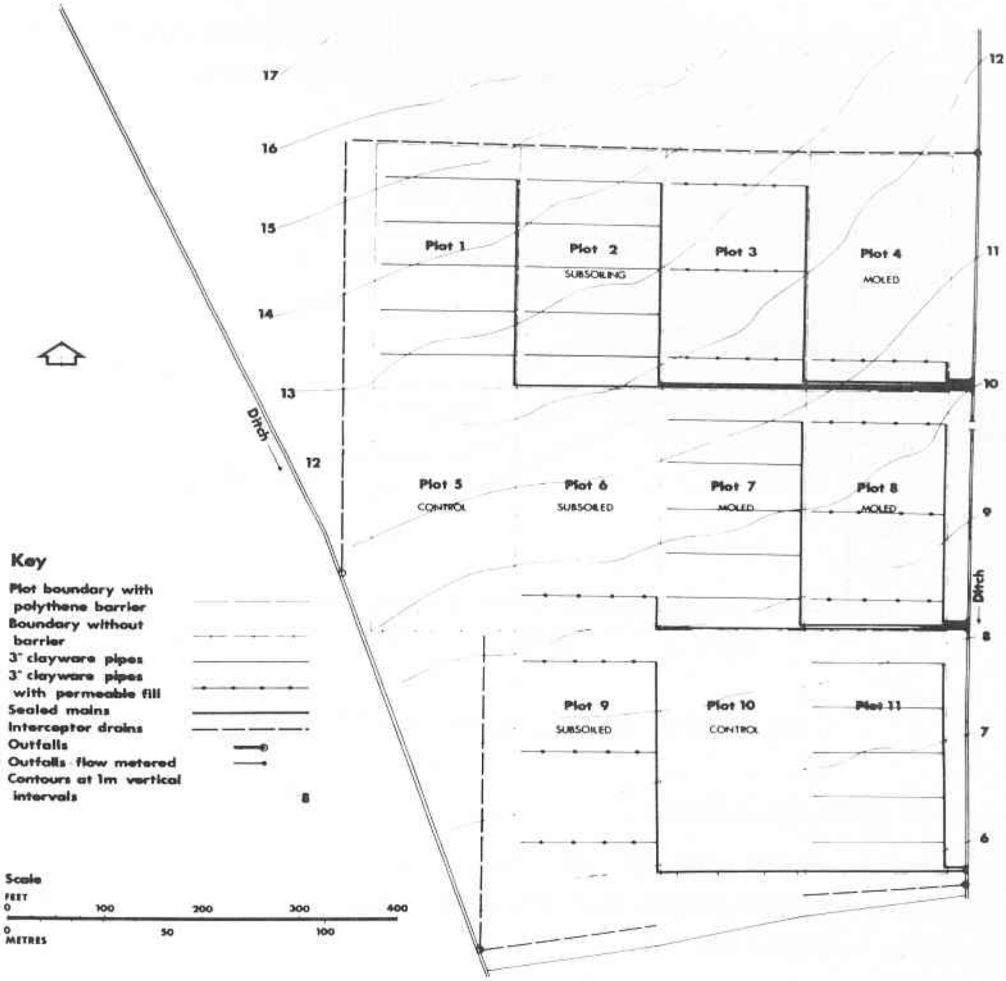

Fig.8. The Drayton experiment.
Site plan.

v) Hydrologic results

a) Drainage performance

With factors of slope, exposure, cultivations being equal, a measure of the relative efficiency of the various treatments is the ratio of actual drain flow (Qx) to potential drain flow (Qy). The potential drain flow is defined as that rainfall falling in the drainage 'winter' less any evaporation and any small moisture deficit.

Figure 9 shows the position when mean values $\frac{Qx}{Qy}$ are plotted against time for the 3 treatments of pipes only, subsoiling, and mole drains.

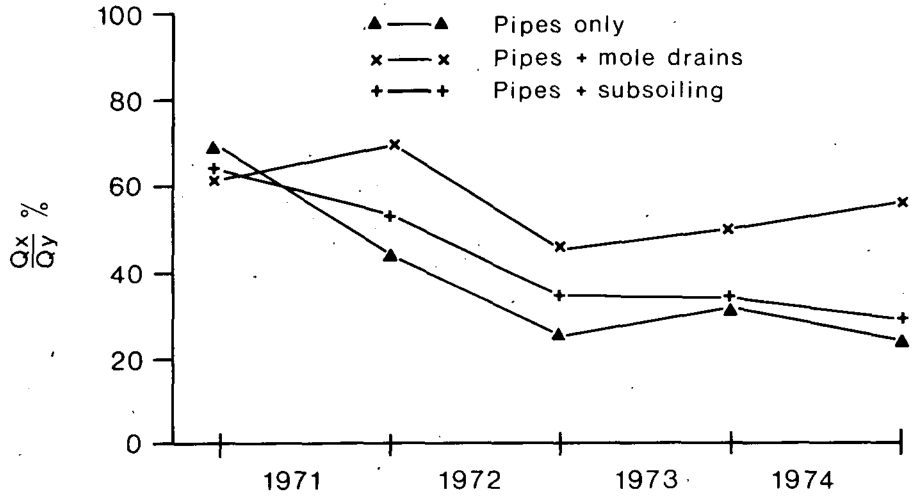

Fig.9. Mean drainage efficiency $\frac{Qx}{Qy}$ /time.

b) Water table control

The general pattern of water table control is that the moling and subsoiling treatments performed better than the pipes only. The results of 5 'winters' are shown in Figure 10.

c) Effect of pipe spacing

Pipes only - there was little variation in drainage efficiency $\frac{Qx}{Qy}$ and water table control despite a 2:1 variation in drain spacing. The explanation is likely to be that most water movement takes place in the topsoil with the drains acting only as interceptors.

ca) Mole drainage

With a 4:1 variation in drain spacing there was little evidence of reduced performance with the wider spacing, but there was a general failure of the mole channels after a 5-year life.

cb) Subsoiling

Although not totally conclusive there is evidence that the 15 m drain spacing performed better than the wider spacing. As discussed in Section 3.3 an 'inferior' channel was formed in the subsoil operation, and therefore although acting as mole channels, over the 30 m, 60 m drain spacing they are more likely to breakdown.

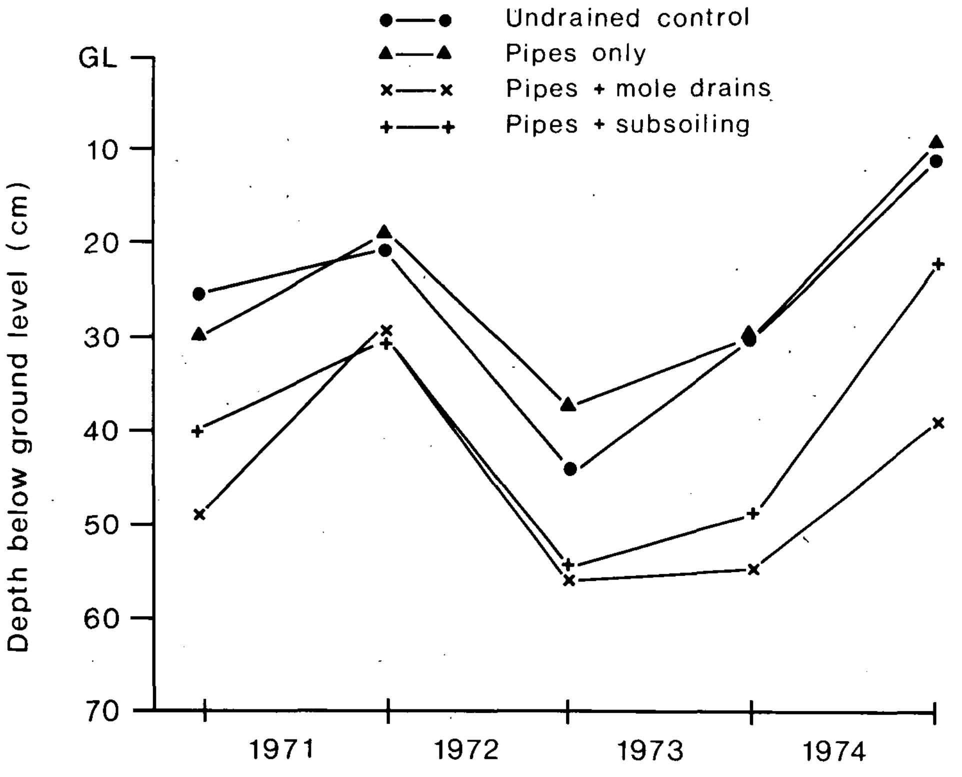

Fig.10. Mean winter water table/time - all treatments.

vi) Crop yield results

Of the 6 years of record only 3 were for winter wheat - 1971, 1973 and 1974. Examination of the data showed that differences between years had an overriding effect on the absolute yield figures, and subsequent analyses were per-

formed on data from which the annual means had been subtracted. The results show that no significant differences in yield can be attributed to drain spacings as such, but that secondary drainage treatment has a significant effect.

TABLE 4. Mean drainage effects. Increase in winter wheat yields over control (tonnes/ha)

Drain spacing	Secondary treatment			Mean
	mole	subsoiling	none	
15 m	1.10	1.07	0.58	0.91
30 m	0.90	0.16	0.78	0.62
60 m	0.98	0.48	–	0.73

APPENDIX III

Application of Soil Series to drainage design

Hanslope Series

(see also Table 1)

i) Soil Series

Hanslope

ii) Distribution of soil

Widespread in the Eastern Region.

iii) Topography

An upland soil found in rolling situations on plateau tops and on gentle upper slopes.

iv) Important drainage characteristics of the profile

A stable well structured calcareous clay permitting some natural water movement.

v) Soil/drainage design factors

Stability of topsoil	stable
Stability of subsoil	stable
Hydraulic conductivity class	slow/moderate
Variability	low
Occurrence of the soil in complex situations	infrequent

vi) Present drainage treatments

Slope is important and treatments tend to vary as follows:

	Plateau tops 1-2% slope	3% slopes and steeper
Drain spacing	40 metres	80 metres
Drain depth	80 cm	80 cm
Permeability aids	Moling	Moling
Permeable backfill	Normally used	Normally used

In some areas skeleton tile systems up to 200 m spacing have given satisfactory drainage. The excellent stability of the soil seems to make it an ideal moling soil.

vii) Recommended drainage treatment

As existing.

viii) Farming

Mainly cereals with some roots.

ix) Land capability class

Class 2.

Paper 1.13

RECLAMATION OF PEATS AND IMPERMEABLE SOILS

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Summary

The paper deals with the design and development of drainage techniques and equipment for the reclamation of peats and impermeable soils.

Blanket peats up to a depth of 0.5 m are usually ploughed to get a satisfactory peat/subsoil mix and an increase in surface strength. Drainage may also be required, depending on the permeability of the subsoil. Where the depth of peat lies between 0.5 m and 1 m, drainage is usually limited, by economic considerations, to surface grading to open collector drains. Where the peat depth exceeds 1 m, the "tunnel plough" or the "gravel tunnel" machine may be used to install an intensive drainage system at an economic cost.

Impermeable soils (K-values 0-0.1 m/day) require some form of subsoil disruption. Mole drains can be successfully installed on cohesive soils whose plasticity and shear strength characteristics are suitable. However there are no reliable criteria available for the selection of suitable mole drainage soils and investigations to establish an adequate classification system are urgently required. Soils unsuitable for mole drainage are subsoiled, ripped or have a system of "gravel-filled moles" installed. In the reclamation of all impermeable soils, particular attention is paid to surface grading to eliminate ponding and reduce depression storage to a minimum.

1. Introduction

A land drainage survey of Ireland (Galvin, 1969) showed that the major drainage problems in the country were Seepage and Springs (38%), Impervious Soils (33%) and High Water Tables (24%). Minor problems accounted for the remaining 5%.

The seepage problems usually occur in the free-draining regions and are generally solved by the application of conventional design principles. The biggest problem attaching to seepage investigations is that, due to our

complex glaciations, many aquifers are discontinuous. As a result borehole pumping or the installation of a deep drain may occasionally result in the lowering of water pressure over a portion of the area rather than from the whole area. Water table problems are also solved by the application of established drainage principles and it is only where the hydraulic conductivity of the soil demands an uneconomic drainage intensity that problems arise.

Our reclamation efforts over the past number of years have therefore been concentrated on the investigation of impermeable peats and soils and on the design and development of drainage techniques and equipment for the economic reclamation of the materials.

2. Peatland drainage

General

Irish peatlands are generally divided into two major categories, blanket bogs and raised bogs (Barry, 1954). The blanket bogs cover extensive areas along the western seabord where the annual rainfall averages 1,400 mm, and also extend over high ground elsewhere, e.g. on the Wicklow mountains near the East coast. The total area of blanket bog is estimated by Hammond (1975) at about 870,000 hectares of which about 8,000 hectares are being developed for fuel production. The average depth of the deeper blanket bog is about 2.5 m and it is relatively uniform in composition throughout the profile. However, there are also extensive areas of shallow blanket bog varying in depth from 100 mm to 1 m. These areas are often adjacent to existing mineral farmland and are therefore a first priority for reclamation in a farm development programme.

The raised bogs are largely located in basin-type situations in the centre of the country where the annual rainfall is about 850 mm. The total area is estimated at 500,000 hectares. Of this, 100,000 hectares have already been cut over for fuel production and a further 60,000 hectares are in the process of fuel harvesting. In contrast to blanket bogs, raised bogs frequently exhibit in section a distinct sequence of peat types that reflects

the changing environmental conditions under which they developed, from a low-moor stage, represented by reed-fen or woody-fen peat to raised bog. This develops above the influence of the groundwater and is characterised by the presence of peat derived from sphagnum, cotton grass and related species. During fuel harvesting, different peat types are exposed and the reclamation of the bog at any particular time depends on the degree of cutting that has taken place and on the underlying subsoil if the peat is less than a metre in depth.

Reclamation methods

The reclamation methods vary depending on peat type and local drainage conditions. Four very important considerations are:

a) depth of peat,
b) hydraulic conductivity of peat,
c) hydraulic conductivity of subsoil and
d) general surface slopes.

The latter is especially important where the hydraulic conductivity of the peat is low. Adequate surface drainage prevents large-scale surface ponding and reduces depression storage to a minimum. In this way the percentage runoff is maximised and the infiltration minimised thus resulting in the smallest possible addition to the water table for any given rainfall. This is especially so in the case of impermeable peats whose infiltration capacity is often exceeded for substantial periods by the rate of rainfall. Additional advantages, stemming from well-graded surfaces, are very much improved surfaces for sillage harvesting and a decrease in grassland poaching. Experimental trials on a peat cut-away showed very clearly that poaching always started at a minor hollow and spread from there (Galvin, 1972).

Blanket peats

The hydraulic conductivity of blanket peat varies from place to place but is generally of the order of 10 mm per day in the undrained condition. The reclamation methods used are conditioned by the depth of peat and the nature of the underlying subsoil. Where possible the subsoil is invariably

mixed with the peat in order to strengthen the finished surface and improve its trafficability. Experience has shown that a mixture of equal depths of peat and subsoil gives satisfactory results.

Where the peat is up to 200 mm deep, basic reclamation involves ploughing to a depth of about 400 mm. This provides satisfactory mixing and sufficient loose material for subsequent surface grading. It also usually results in the disruption of any pan that may have formed under the peaty layer However, if the pan occurs at a depth greater than 400 mm, provision must be made for its disruption either by subsoiling or by deeper ploughing. Where the subsoil is sufficiently permeable and where a high water table does not occur (this happens frequently on hill-land) no internal drainage is required apart from occasional water course to trap surface flow and intercept springs However, where the subsoil is impermeable a system of internal drains is needed and is based on the hydraulic conductivity and other physical characteristics of the subsoil.

Details of the variety of drainage installations to cater for the reclamation of impermeable soils are discussed later.

For peats varying in depth from 200 mm to 500 mm, ploughing to a depth of 0.4 m to 1 m (deep ploughing) is needed to obtain satisfactory mixing, surface strengthening and sub-surface disruption. Deep ploughing is a relatively expensive operation and since the overall expenditure on reclamation is limited to approx. £850 per hectare, the combination of deep ploughing and piped drains can only be accommodated where the required drain spacing is greater than 40 m. Where the subsoil is permeable and a high water table does not occur, deep ploughing used in conjunction with intensive surface grading (aimed at eliminating all local depressions and hollows as far as possible) is normally sufficient. Where the subsoil is impermeable or where a high water table occurs, the peat/subsoil mixture must be stable and its permeability such that it can be drained at a spacing of 40 m or greater. If this does not obtain the scheme is considered uneconomic.

Where the peat depth exceeds 0.5 m, subsoil mixing is excluded on the basis of economics. For depths ranging from 0.5 m to approx. 1 m, the provision of a satisfactory internal drainage system is generally economically infeasible. However peats of this depth often occur on sloping land and in

the absence of a high water table, satisfactory reclamation can be attained by careful surface grading, combined with occasional surface water catchment drains. This system can also be successfully applied to deeper peats under the same conditions. For blanket peats deeper than 1 m and affected by a high water table, a drain spacing of between 1 m and 4 m is required due to the basic impermeability of the peat. The drainage system involves the installation of main collector drains strategically placed in natural hollows along the contours. The provision of the intensive system of internal drains (at the 1 m to 4 m spacing) is another problem. Conventional piped drains could be used but the costs involved would be completely unrealistic especially in view of the fact that blanket peat even when intensively drained is by no means an ideally trafficable medium. Ordinary mole drains are unsuccessful as they collapse within a very short period. In the circumstances two methods have been developed aimed at providing reasonably good water table control at an acceptable expenditure.

One of these methods (Armstrong, Burke & Quinn, 1960) involves the excavation of a tunnel section (380 mm deep × 280 mm wide) at a depth of approx. 800 mm. The excavated peat is extruded from the top of the machine and can be deposited on the bog surface as a ribbon of peat or macerated by activating a PTO-driven macerator on top of the tunnel plough. This machine was originally developed in 1959 and used with varying degrees of success until the early sixties. It has since been re-designed by Burke and Grubb (1978) and is now a far more effective machine. There is one major difficulty involved in the use of this plough. It works on the basis of extruding a band of peat and therefore tends to fail when the plough encounters a section of bogland that is either too slurried to allow for proper extrusion or too fibrous in relation to its shear strength. However, a system for measuring the vane strength of the peat prior to tunnelling using a modified field vane has been devised. This method has been developed by measuring the vane strength of peats that have been successfully and unsuccessfully tunnelled and from these figures an empirical method for determining the suitability of a bog for tunnel drainage has been devised by Burke & Grubb (1978). In the recent past, very profilic rooting systems have been obtained by using the tunnel plough for forestry drainage. The big advantage has been the

aeration provided at the 400 mm - 800 mm depth and also the space provided in and around the tunnels for root development and proliferation. The Forestry Departments in Ireland, and Northern Ireland have been very impressed by the results and are considering using the tunnel plough drainage system as far as possible in future blanket peat plantations.

Because of difficulties associated with the tunnel plough in the early sixties a more positive drainage system was developed for blanket peat in 1963. The method involved the installation of a band of gravel (approx. 100 mm × 80 mm) on a layer of polyethylene at a depth of approx. 800 mm. A prototype machine to install this drain was developed by Burke and McCormack in 1969. After further trials and experience this machine has been redesigned by Burke and Grubb and will be used on commercial drainage installations in 1978. This method involves the installation of approx. 25 cubic metres per hectare of 16 mm clean single-sized gravel chippings as a series of gravel bands at a spacing of 3.5 m. This is the minimum spacing justified by existing economic considerations and gives acceptable water table control on grassland during the summer months. It is always combined with as much surface grading as feasible within the monetary constraints of each job as the elimination of depression storage is particularly important on schemes where the water table was close to the surface before drainage.

Raised bogs

The reclamation of raised bogs follows the same general principles outlined for the blanket peats. However, as many of these peats have been cut away to varying degrees, the permeability and strength of the peats exposed at the different depths varies as also does the depth of the water table below the surface. The sphagnum peats are soft and have strength characteristics similar to those found in blanket peat, and must be treated accordingly. The fen peats, however, are stronger and can provide an ideally trafficable medium, without mixing with the underlying subsoil. They are also more permeable and as the wood content increases the hydraulic conductivity can increase to 1 or 2 m per day. These peats are obviously very valuable and are used for arable cropping with minimum drainage. A disadvantage is that under an arable system, surface shrinkage usually amounts to 50 mm yearly so that a depth of 2 m to 3 m is required for continuing arable production.

3. Drainage of impermeable soils

The impermeable soils referred to in the context of this discussion are those with K-values ranging from 100 mm per day to almost zero. Irish soils of this type are derived from boulder clays formed from a variety of glaciated parent materials. Because of this, they are often very variable in composition and the fine (clay size) particles contain an appreciable percentage of finely ground non-expandable minerals (Mulqueen & Burke, 1967). Many of these soils have been overconsolidated under the heavy overburden of ice and in some cases the bulk density can reach 1,620 to 1,650 Kg/m^3. Some of the soils occur under raised or blanket bogs but where the depth of overlying peat is less than 0.5 m the efficiency of the drainage method used is directly related to the efficiency of subsoil drainage.

Under Irish climatic conditions these impermeable soils are not suited to tillage operations. Apart from their sticky nature they are usually stoney and completely unsuited to continuous cropping. In these circumstances they are invariably used for grassland and as such there is a limit on the reclamation expenditure that can be justified by the expected returns from efficient grassland farming. As of now the optimum returns result from intensive dairying and as previously stated the maximum justifiable expenditure is approximately £850 per hectare. This figure includes cultivation, reseeding and any necessary fencing, etc. required to bring the land into full production. The spacing of conventional drains is therefore limited to a minimum of approximately 30 m by these economic factors and the required drainage intensity for soils with K-values less than 100 mm per day cannot be accommodated by conventional drainage systems.

In a situation as outlined, where conventional drainage methods cannot provide an economical system, the approach must be to alter the subsoil (improve its hydraulic conductivity and reduce its water holding capacity) so that a satisfactory system can be provided with more widely-spaced piped drains. The traditional methods of achieving this have been the installation of mole drains or by subsoiling. The former enables one to provide a very intensive drainage system by substituting moles for the conventional pipes but this requires a soil in which the moles remain stable over a sufficiently long period. Subsoiling works on the principle of disrupting the subsoil to such an extent