type of machine can achieve a greater hourly capacity than the other. If a trenching machine with a yearly capacity of 500 km and an hourly laying capacity of 300 m of corrugated PVC pipe is compared with a trenchless machine whose capacity is 400 m per hour, the latter will be found to save 0.40 guilders per meter, or 17% of the total costs. Both calculations assume ideal working conditions.

The functioning of drains laid with trenching machines and trenchless machines

The effect of drainage is largely dependent on the degree of permeability of the soil close to the drains. Particularly if they have been laid with a trenchless machine, it depends whether or not this ground has been deformed or compressed, and to what extent an open structure has been created between the drain and the surface: in other words, to what extent the ground has been broken up. This, as we have already pointed out, is determined partly by the shape of the plough body.

If the ground around the drain was deformed or compressed when the drain was laid, the question is how long it will take for the structure and the permeability to return to normal.

It should also be remembered that when drains are laid with a digging chain, the trench walls and the excavated ground also suffer structural damage. This damage will be all the greater if the drains are laid in wet conditions (high groundwater levels).

With higher digging speeds, the risk of the soil getting deformed or compacted, will also increase; this applies particularly to wet plastic clay soils.

Experience in other countries

Generally speaking, little is known about the comparative efficiency of drains laid with the trenchless machines and those laid with trenching machines. Opinions differ greatly from one country to another, which is understandable in view of the different conditions under which drainage is carried out.
In Great Britain, where drains are generally laid in heavy soils, the drainage system is a combination of moling and subsoiling. There is in fact a vertical discharge to the drain whereby low permeability of the trench wall does not impair the efficient functioning of the drain.

In France drains are often laid in stony soils. As this causes a high degree of wear and tear to knives and chains, trenchless drainage is regarded as an economical solution for this type of soil.

In Austria, the "Bundesanstalt für Kulturtechnik und Bodenwasserhaushalt" (Federal Institute of Agricultural Engineering and Groundwater Management) at Petzenkirchen carried out a number of excavations on plots of ground where the drains were not functioning satisfactorily. From the resulting data it was concluded that — as with other methods — there are limits to the use of trenchless drainage. As far as one can see from the few investigations, these limits were due partly to mechanical factors and partly to the soil.

There were sufficient findings to show that trenchless drainage produced unsatisfactory results in plastic soils (with consistency limits, according to Atterberg, of between 50 and 80). In other types of soil few difficulties were encountered, provided the drains were not laid too deep.

In Germany experiments were carried out in 1971 under favourable conditions in the "Großbüttel" experimental drainage field in Schleswig-Holstein. The investigation showed that resistance to the flow of water to the drain decreased in time, which confirms an investigation in the IJsselmeer Polders. It should be mentioned that in both Großbüttel and the IJsselmeer Polders the maturity of the soil was an important factor. It was also found that in both the case of drains laid by trenching machines and of those laid by trenchless machines, the initial resistance was high, but had decreased by two-thirds a year later.

When drains are laid, the soil in their immediate vicinity is sometimes violently disturbed, which impairs permeability. This gradually improves. This is shown in the table below.
Permeability of the soil in the immediate vicinity of the drain in relation to time.

<table>
<thead>
<tr>
<th>Drainage system</th>
<th>Nov. '71</th>
<th>Mar. '72</th>
<th>Apr. '72</th>
<th>Nov. '73</th>
<th>Febr. '75</th>
<th>Apr. '75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trenchless PVC without a filter</td>
<td>0.034</td>
<td>0.049</td>
<td>0.065</td>
<td>0.108</td>
<td>0.142</td>
<td>0.198</td>
</tr>
<tr>
<td>Trenchless PVC with a filter</td>
<td>0.043</td>
<td>0.056</td>
<td>0.076</td>
<td>0.120</td>
<td>0.173</td>
<td>0.217</td>
</tr>
<tr>
<td>Digging wheel; clay pipes of 33 cm long</td>
<td>0.106</td>
<td>0.142</td>
<td>0.184</td>
<td>0.284</td>
<td>0.384</td>
<td>0.394</td>
</tr>
<tr>
<td>Digging wheel; clay pipes with a length of 50 cm</td>
<td>0.143</td>
<td>0.188</td>
<td>0.246</td>
<td>0.376</td>
<td>0.468</td>
<td>0.457</td>
</tr>
</tbody>
</table>

* To convert to the SI system (um/s), multiply the permeability values by 11.6

Permeability improved considerably over the years, but after trenchless drainage with the Nordhastedter Drörpfugl, the soil never regained anything like the degrees of permeability it had before it was disturbed, which was 0.5 m/day.

Experience in other countries shows that it is impossible to draw general conclusions because the conditions under which drainage is carried out vary so much from one country to another.

Experience in The Netherlands

During the last few years various investigations have been conducted in experimental drainage fields in The Netherlands with two objectives: to compare drains laid by trenchless and trenching techniques, and to try out various cover materials.

- These investigations show that trenchless drainage in certain kinds of soils causes more compression and deformation of the soil than trenching drainage. The soil recovers eventually, but it is a slow process. The use of trenchless drainage therefore involves a considerable risk for the land user.
- In experimental fields of clay and heavy sandy clay soil in the IJsselmeer Polders, drains laid with a trenchless machine were found to have a much lower discharge the first winter after being laid than drains laid with a trenching machine. This was also the case in subsequent years, although the disparity gradually decreased.
In 1973 drains were laid 135 cm deep with the trenchless machine in Friesland. The soil structure was 30 cm light sandy clay on 100 cm heavy sandy clay on light sandy clay to sand.

The first winter the discharge from the trenchless drains was about half that from the trenching drains. The reason given was that the soil had been deformed by the plough body. It was also found that the drains laid with trenchless machines had silted up more, which was ascribed to piping: i.e. an excessive vertical discharge of rainfall through the incision to the drain.

This can be prevented by ramming the top soil down thoroughly. The second winter the differences were more or less the same.

In investigations held in experimental drainage fields in Drenthe, where the soil was composed of peat on sand, no clear differences could be found between trenchless and trenching drainage. The drains were laid in the sandy subsoil.

Comparison of the advantages and disadvantages of drainage with trenchless and with trenching chain machines

- Under favourable conditions a trenchless machine laying corrugated PVC pipes at a depth of between 0.90 and 1.20 m can achieve a considerably higher capacity than a trenching machine.
- Drainage can be continued longer in spring with less damage to crops. This has the added advantage that drainage is carried out while the groundwater level is falling.
- Generally speaking, the number of days a trenchless machine operates under favourable conditions (dry topsoil and moist subsoil) are fewer than with a trenching machine.
- If drains are laid very deep, the trenchless machine needs a great deal of extra pulling force, and there is a greater risk of the soil around the drain being compressed and deformed.
- In wet conditions trenchless machines damage the structure of the topsoil much more than trenching machines, and their laying capacity is severely reduced.
- In hard, stony soils the digging chain machine has the disadvantage that the chain and knife are very subject to wear and tear. This can be partly remedied by cutting the earth first with a ripper. The trenchless machine has a definite advantage in this respect.
- Re-instatement work after trenchless drainage should not be neglected, especially if the plough lifts the earth well. Where trenching machines are used the earth can easily be put back with a scraper/grader or a rammer.
- It is difficult to check the depth of drains laid with a trenchless machine.
In regions where a porous fill material is used (for instance in Great Britain), a considerable saving can be made in this material with trenchless drainage because the annular space is considerably smaller.

In smaller areas (up to 10 ha) it is not worth using trenchless machines as the ratio of hours worked to transport costs is not favourable. This does not apply in the case of simple machines.

Crossing recently filled ditches often causes problems when a trenchless machine is being used, as the caterpillar tracks have insufficient grip on the loose ground.

Conclusions

- Trenchless drainage is a good solution in stony soils, since the chains and knives of a digging chain machine are subject to excessive wear and tear.
- Fewer hours on average can be worked with the trenchless machine since it can only be operated when the topsoil is reasonably dry.
- When drains are laid at considerable depth, the necessary pulling force rises excessively ($P = XD^3$).
- If the critical depth is exceeded, the soil around the drain is extremely compressed or deformed.
- The critical depth depends on the shape of the plough body.
- As regards the functioning of the drains, trenchless drainage is suitable for sandy soils but cannot as yet be recommended for sandy clay and clay.
- All the factors involved should be carefully considered before a trenchless machine is chosen. It should be borne in mind that its uses are, on the whole, more limited than those of a trenching machine.

References


NAARDING, W.H. A review on international experience with trenchless versus trenching drainage machines.


Fig. 1. Fairly narrow ripperleg with sharp front edge. The ripperleg is positioned at an angle of $90^\circ$ to the horizontal.

Fig. 2. The ripperleg is positioned at an certain angle to the horizontal. The ripperleg is concave; the front plate extends over practically the whole depth.

Fig. 3. The ground is lifted down to a certain depth; below this level the earth slides along the ripperbody.
Fig. 4. The "Willner" V-shaped plough body.

Fig. 5. The Y-shaped plough body.
Fig. 6. A winch is mounted at the front of the machine.

Fig. 7. An unsophisticated machine (Bruff TGI) towed by a winch on a tractor. The cable and block in front are visible.
the tractor on which the digging-chain or plough body is mounted

the digging-chain unit which can be mounted on the tractor

the plough body which can be mounted on the tractor

Fig. 8. A trenching machine and trenchless machine combined.
the tractor fitted with digging-chain and plough body

(Fig. 8 cont.)
Summary

Two types of soil disturbances may result at depth when using trenchless drainage ploughs, subsoilers and mole ploughs. The first, common at shallow depths, a loosening, fissuring disturbance ideal for the first two operations and secondly at great depths, a compressive, compacting disturbance suitable only for the latter operation. The working depth at which the transition between the two types of disturbance occurs, known as the critical depth, is dependent upon implement geometry and soil conditions. Increase in tine width and inclining the tine forwards increases the critical depth. Loosening the surface soil layers prior to deep tining increases the chances of loosening at depth. The use of shallow leading tines immediately ahead of the deep tine increases the critical depth without increasing the draught.

1. Introduction

Deep working rigid tined implements are in common use in drainage practice, examples being trenchless drainage machines, subsoilers and mole ploughs. The successful use of these implements is very dependent upon the way in which they disturb the soil. In trenchless drainage operations, the prime objective is to open up a slot to accept the drain pipe, without compacting or smearing the soil at pipe depth. Any such compaction would increase the water entry resistance and should therefore, be avoided. Successful avoidance depends upon loosening and fissuring the soil at depth. For effective subsoiling, loosening and fissuring are again required throughout the complete working depth. The requirements change when moling, where the objective is to form a stable compact channel at depth with loosened soil above.
The basic shape of implement used for all these operations is similar, being an inclined narrow tine, and yet the tine is required to deform the soil in different ways depending upon the need. This paper discusses the way in which tines disturb soil and highlights the major factors which influence the nature of the soil disturbance and the forces involved.

2. Soil disturbance with narrow tines

![Diagram of soil disturbance](image)

*Fig. 1. Soil disturbance caused by trenchless drainage machine working at relatively shallow (a) and great (b) depths.*

Two types of soil disturbance can occur with narrow tines, the type depending upon implement shape and soil conditions. This is illustrated in Fig. 1 which shows the disturbance caused by a trenchless plough working at 2 different depths in a uniform soil. At the shallow depth, the soil is displaced forwards, sideways and upwards throughout the whole working depth.
This type of disturbance causes fissuring and loosening and is termed crescent failure. At the greater working depth the trenchless plough causes crescent failure in the upper soil layers, but at depth, the soil moves forward and sideways only (lateral failure) and this causes soil compaction around the lower part of the tine. This change in the type of soil disturbance with increasing working depth is found with all narrow tined implements, including subsoilers and mole ploughs (see Fig. 2). The depth at which the transition from crescent to lateral failure occurs is termed the critical depth and is specific for the particular tine and soil condition. This critical depth represents the maximum working depth of that tine for satisfactory soil fissuring and loosening at depth. Any further increase in working depth would cause compaction at the tine base.

Fig. 2. Soil disturbance caused by a subsoiler and mole plough at relatively shallow (a) and great (b) depths.
To ensure minimum compaction and smear at depth, trenchless ploughs and subsoilers must always work above their critical depth. Conversely, the bullet on a mole plough must work below its critical depth to form the required compact channel. These drainage implements are required to operate at a given depth and whether their performance is satisfactory or not, will depend upon whether this depth is greater or less than their critical depth, under the prevailing conditions. An unsatisfactory performance can only be changed into a satisfactory one, if modifications can be made which will effectively change the position of the critical depth.

3. Factors influencing the position of the critical depth

The type of soil disturbance which occurs and hence the position of the critical depth, is dependent upon both the prevailing soil conditions and the implement geometry. The section of a narrow tined implement which controls the type of soil disturbance is the leading section at the working depth. There are two major implement factors which influence the critical depth position:

a) tine aspect ratio = \( \frac{\text{working depth}}{\text{tine width}} \)

b) tine inclination to the horizontal in the direction of travel (rake angle).

The smaller the aspect ratio and rake angle, the deeper the critical depth. Thus at a given working depth the wider the tine and the greater its forward inclination, the greater the probability of the critical depth being below the working depth.

The main soil factors influencing critical depth position are:

a) density
b) vertical confining stress resisting upward soil flow from depth (resisting crescent failure)
c) moisture content
d) texture and structure.
At any given moisture content, the lower the density and the higher the vertical confining stress, the shallower the critical depth. With constant density and confining stress values, increasing moisture content tends to decrease the critical depth.

Vertical confining stress can arise from forces both within the soil and on the surface. Wheels and tracks can impose confining stresses when positioned immediately above any failing soil. The internal confining stresses are dependent upon soil shear strength which tends to increase with decreasing moisture content. Severe surface drying, without a corresponding decrease in moisture content at depth, can result in the development of very high surface confining stresses which resist crescent failure, so effectively reducing the critical depth.

Table 1 shows for different rake angles and moisture conditions in a compact loam soil, the approximate aspect ratios at which lateral failure at depth becomes significant. It can be seen that crescent failure, over the whole working depth, continues to occur at higher aspect ratios with low rake angle tines than with high. As the surface layers become drier relative to the lower layers, wider tines at a given depth (smaller aspect ratios) are required to maintain crescent failure. Under soft wet plastic conditions the critical depth is near to the surface at almost all aspect ratios.

<table>
<thead>
<tr>
<th>Moisture state</th>
<th>Tine rake angle</th>
<th>Aspect ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friable throughout</td>
<td>90°</td>
<td>6 - 8</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>10 - 12</td>
</tr>
<tr>
<td>Hard dry surface layer, friable at depth</td>
<td>45°</td>
<td>6 - 8</td>
</tr>
<tr>
<td>Friable surface layer, just plastic at depth</td>
<td>45°</td>
<td>6 - 8</td>
</tr>
</tbody>
</table>
4. Implement design and field use aspects

Implement performance has been shown to be very dependent upon the position of the critical depth relative to the working depth of the implement. Every effort must therefore be made to get this relationship correct and the main factors that can be changed to achieve this are, tine width, tine rake angle and the surface confining stresses in the soil. A change in any of these factors, however, not only changes the critical depth position, it also influences the draught force. Wherever possible, the modification adopted should be the one which has the most desirable effect on the draught force, namely keeping it to a minimum. Results from soil tests in a compact sandy loam soil will be used to illustrate the effects of changes in tine width, rake angle and soil confining stress on draught and critical depth.

![Diagram showing change in tine draught with tine width and depth.](image)

**Fig. 3. Change in tine draught with tine width and depth.**

Figure 3 illustrates for a vertical tine, how the draught changes with increasing tine width at different working depths. The tine width, where the critical depth is coincident with the working depth is also shown. It
can be seen that the draught force increases with increasing tine width, but at a decreasing rate. The rate of increase is relatively small in the region where the critical depth is close to the working depth. Therefore, in situations where the critical depth of the tine is not too far above the working depth, increasing tine width will lower the critical depth to the required level, without too large an increase in draught. Tine width modifications can readily be carried out in the field.

The relationships between draught, tine width and rake angle are shown in Fig. 4 together with the transition points where the critical depth is coincident with the working depth. Reducing the rake angle of a tine, at a constant working depth significantly reduces the draught and also increases the critical depth. There is little further to be gained in terms of draught reduction by reducing the rake angle much below 45°. Changes in rake angle although not normally possible in the field, can be considered at the design stage.

![Diagram](image)

**Fig. 4.** Change in tine draught with tine width and rake angle.
Surface confining stresses are very dependent upon moisture status and therefore, in certain circumstances, it may be necessary to allow the soil to dry or wet before a satisfactory job can be done. An alternative procedure is to reduce the confining stresses in the surface by loosening, before the deep tining operation is carried out. The loosening can be done as a separate operation or performed at the same time as the deep tining. In the latter case, this is best done by positioning shallow working tines immediately ahead of the deep tine, to loosen the surface layers in the region where soil failure planes would develop if the deep tine were used alone (see Fig.5). The leading shallow tines should be far enough ahead of the deep tine so that they do not restrict the upward flow of soil from the deep tine, i.e. at a distance approximately equal to $1 - 1.25$ times the working depth of the deep tine. Relieving the confining stresses in this way increases the critical depth over a wide range of moisture conditions.

![Diagram](image)

**Fig.5. Position of shallow tines relative to soil failure planes created by deep tine alone.**

Table 2 allows a comparison to be made between the forces acting on a single deep tine and those on a deep/shallow tine combination in a compact sandy loam soil. It can be seen that the addition of the shallow tines has had no effect on the total draught. The force on the deep tine is considerably less when it is preceded by the two shallow tines than when it is work-
ing alone. If the surface loosening and deep tining is therefore carried out as a 2-stage operation, opportunities arise to reduce the force input required from the power unit. In trenchless drainage operations, the shallow tining could be done as the machine runs back empty prior to the next working run.

When soil loosening is required, deep working tines should always be positioned far enough behind wheels and tracks, to prevent the latter effectively increasing the confining stresses on the soil being failed by the deep tine. Any surcharging effect would tend to reduce the critical depth.

<table>
<thead>
<tr>
<th>TABLE 2. Draught forces of various tine combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tine combination</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>Two shallow tines</td>
</tr>
<tr>
<td>One deep tine</td>
</tr>
<tr>
<td>Two shallow tines</td>
</tr>
<tr>
<td>+ one deep tine</td>
</tr>
<tr>
<td>Tine rake angle</td>
</tr>
<tr>
<td>Working depth</td>
</tr>
<tr>
<td>of shallow tines</td>
</tr>
<tr>
<td>of deep tine</td>
</tr>
<tr>
<td>Tine width</td>
</tr>
</tbody>
</table>

5. Conclusions

a) Two types of soil failure can occur with deep working tines. At shallow depths a loosening, fissuring occurs (crescent failure) and at great depths, a compressive, compacting failure (lateral failure).

b) The working depth at which the transition between crescent and lateral failure occurs is known as the critical depth.

c) For minimum compaction in the region of the drain pipe in trenchless drain laying and for successful subsoiling, the tine must work above its critical depth. For successful mole draining the mole plough bullet should work below its critical depth.
d) The position of the critical depth is dependent upon tine geometry and soil conditions.

e) Increasing tine width increases the critical depth and increases draught.

f) Inclining the tine forwards to the direction of travel, increases the critical depth and reduces the draught.

g) Shallow leading tines ahead of the deep tine increases the critical depth without increasing the draught.

h) Loosening of the surface layers as a separate operation prior to deep tining reduces the total draught force compared with a single stage operation.

References


TRENCHLESS DRAINAGE

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Summary
The development of drainage ploughs is discussed as well as the plough designs and performances.

Introduction
In much the same way that drainage materials industry was revolutionized by the development of corrugated plastic tubing in the last decade, the drainage industry is now being revolutionized by the drainage plough. Van Schilfgaarde (1971) predicted a swing towards plough installation of subsurface drains, primarily due to reduced installation costs. The move to ploughs has taken place in the 1970's at a much greater rate than even he envisioned. This "trenchless" method of drainage is now on the way to becoming a principle means of installing subsurface drains. High-speed installation and low maintenance costs combine to make profitability the major factor in forcing the drainage plough to its position of increasing importance in the installation industry.

Several important developments during the past ten years have made trenchless drainage practical. The first of these was the application of the concept of corrugations in the walls of plastic conduits for maximizing structural strength per unit weight of material. The second was the development of the laser automatic grade control system. Corrugating the tubing wall provided strong, light-weight drainage conduit with the longitudinal flexibility needed for coiling, for handling in long lengths, and the flexibility needed for bending during installation. Development of automatic laser
grade control made it possible to install drains accurately to the proper depth and grade at the significantly higher speeds attainable by the plough. A third development was the adaptation of a prime mover capable of meeting the high draft requirements for trenchless drain installation. Such equipment was already available from within the heavy construction industry. A variety of both crawler and rubber tired vehicles are used with attachable ploughs. Self-propelled, single-unit ploughs are also manufactured that make use of available component parts from the heavy equipment industry.

Trenchless drainage concept

The plough-in method of drain installation has been termed "trenchless". In contrast, the trenching method involves both soil excavation and back-fill operations. The "trenchless" method places the tubing at a prescribed depth in an open channel beneath a temporarily displaced wedge or column of soil. The plough blade is designed to lift and split the overburden soil as it moves forward. The lifting action causes a deformation and disruption of the soil upward and outward at an angle on both sides of the plough blade (Fig. 1). The tubing is fed in behind the plough blade before the soil falls back around the tubing. In some areas, the split soil mound, which is formed at the surface, is pushed back down into place by running the crawler track back over the soil mound. In other areas, this method is not used. In such cases, the surface soil is re-levelled by other means or allowed to resettle naturally.

The two major questions associated with the plough-in technique are:

1. Can the tubing be laid on grade at the desired depth within acceptable limits;
2. Does the condition of the soil after installation allow unrestricted flow of water into the drain?

Plough design and operational characteristics, along with soil conditions, determine to a great degree how well these two requirements are met. Fouss et al. (1971) demonstrated that, in a silt loam soil, grades can be held to less than ±2 cm. However, the speed of installation and responsive-
ness of the grade control hydraulic system are key elements in determining how well grades are maintained. Some evidence has been obtained on reduced flow into ploughed-in drains, but the number of cases and the area involved is small compared to the large amount of tubing installed.

Fig. 1. "Trenchless" installation of subsurface drains. Lifting action disrupts and shatters soil at an angle outward and upward.

Drainage ploughs

There are now more than 15 manufacturers and distributors of drainage ploughs in the United States and Canada (Darbishire, 1977). Latest estimates place the number of ploughs in operation in North America at over 200. With the coming of each drainage season (spring and fall), the number of drainage ploughs increases. Often, the new plough contractor is a former trenching contractor who was not able to successfully compete with the ploughs in his area and was, thus, forced to join the ranks of "trenchless" drainage contractors. Speed of installation and low maintenance costs are the two factors mainly responsible for the change from trenching to plough-in drainage.

Early in the development period of "trenchless" drainage, the ploughs were used to install smaller diameter lateral lines and trenchers were used to place the main drain collectors. Currently, ploughs are being used to in-
stall both laterals and mains. Corrugated plastic tubing up to 10 inches I.D. is routinely ploughed-in to depths of six feet. In north-western Iowa and southern Michigan, plough installation of 12 inch tubing is anticipated for this coming spring (1978). Concrete mains as large as 16 inches I.D. have been installed by the "trenchless" method in Iowa.

Drainage ploughs consistently out-perform trenchers in rate of installation by a factor up to 10 to 1. For a ten-hour day, the installation of up to 50,000 feet of drain tubing per day has been reported. Installation of 20,000 feet per day on a routine basis is not uncommon. This compares to 5,000 or 6,000 feet per day for conventional trenchers.

Development of drainage ploughs

Serious use of ploughs for installing agricultural drains began in the 1960's. In the United States, the initial research was on the adaptation for lining a mole drain channel with a smooth-wall plastic liner (Fouss, et al., 1964). Equipment was developed that would form a cylindrical conduit from a flat roll of 15 mil. plastic (PVC), would interlock (zipper) the seam, and would place it in a mole channel formed with a modified mole plough. Results showed these liners held up for a period of up to four or six years, but failure by collapse eventually occurred. Although the flow capacity was severely reduced by this failure, the reduced channel still conducted water. These collapsed lines have continued to flow and to provided water table control on one test site for the 15-year period since installation.

Later research by the United States Agricultural Research Service (Fouss, et al., 1971) resulted in the construction and testing of a dual, long-beam "floating" type plough, together with the development of an automatic laser grade control system. Field testing of this prototype plough and grade control equipment demonstrated the feasibility of high-speed plough-in of corrugated plastic tubing to depths of up to 5 1/2 feet.

During this period, drainage plough technology advanced considerably. Several European ploughs were introduced into North America. These form the basis for most of the ploughs on the market in the United States and Canada today.
Fig. 2. The long-beam floating type plow seems to "float" because of the balance of forces on the plow.

Fig. 3. Plowing attitude and, hence, plowing depth is controlled by:
   a) raising or lowering plow-hitch point; or
   b) changing blade angle.
"Floating" plough principle

The term "floating" type plough comes from the fact that, as the plough is pulled through the soil, the soil drag forces on the blade are in balance with the tractor draft and plough gravity forces so that the plough seems to "float" through the soil (Fig. 2).

Ede (1961) conducted field trials on the "floating" beam plough in England. The "floating" plough has since become the standard in the industry. Ploughing depth is controlled by changing the attitude or angle of the plough. This can be accomplished by either raising or lowering the hitch point (Fig. 3a) or by rotating the plough blade (Fig. 3b).

Fouss et al. (1971) showed that changes in ploughing depth, in response to hitch height changes, were approximately linear, but not directly proportional. For example, his results showed that, for a change from one steady state flow position to another, a 4 cm vertical displacement of the hitch resulted in a 5 cm change in ploughing depth.

This type of a response is characteristic of all floating type ploughs. It is governed somewhat by plough blade design, but is influenced more by the soil drag forces on the blade as plough depth changes. These drag forces vary as some mathematical power of the depth. Draft curves for ploughs, developed by Jackson (1977) for clay, sand and silt are shown in Fig. 4.

The plough is also subject to change in depth as a result of changes in texture or soil consistency along the plough path, even though no change has been made in hitch-point elevation. Because of these variations in drag forces on the plough, grade control requires more than keeping the hitch-point height on a line which is parallel to the desired drain gradient. Information on both the elevation of the plough point and plough attitude is needed for precise control. Ideally, two detectors would provide the needed feedback information; however, both attitude and elevation can be monitored by proper positioning of one detector unit.

Most control systems in use on drainage ploughs today utilize only one detector for feedback and are of the on/off type. Fouss (1971) treated the subject of control systems and positioning of single detector units in detail.
For an on/off control system with one detector unit, he recommended a detector position of 0.833 times the long-beam length towards the rear of the plough from the hitch point.

The hydraulic system for operating the controls must be responsive and have a minimum time lag.

![Diagram showing typical drawbar-pull for various soil types and installation depths.]

Fig. 4. Drawbar pull required as a function of installation depth for various size drain tubes in different kinds of soil (Jackson, R.T., 1977).

Plough design

The "floating" principle is incorporated into the design of most drainage ploughs. However, the depth-gage wheel type plough can be used in areas where land slope is uniform and the ground surface is relatively smooth. Such a plough has been used extensively in the Imperial Valley, California, as shown in Fig.5 (Willardson, 1970).
Floating type drainage ploughs

There are at least five different types of ploughs produced or distributed in the United States and Canada that utilize the "floating" plough principle. Based primarily on the type of linkage and hitch-point location, drain tube ploughs can be categorized as follows:

I. Actual Hitch Point
   A. Movable
   B. Fixed

II. Imaginary or Virtual Hitch Point
   A. Double Roller
   B. Double Link System
   C. Tilttable Parallel Link System

The linkages of these plough types are illustrated in Fig.6.

The hitch points, real or imaginary, for all but the fixed-hitch-point plough are located near the front end of the tractor. This procedure brings the resultant force on the prime mover near the centre line of the tracks at the ground surface for the purpose of providing uniform load distribution.
ACTUAL HITCH POINT

Fig. 6. Plow types based on hitch-point linkage.
IMAGINARY OR VIRTUAL HITCH POINT

(Fig. 6 cont.)
on the tracks. The track load is increased by as much as 30 per cent of the normal tractor weight by the vertical component of the plough draft force. Optimum traction is attained by maintaining the track pressure uniformly under the entire track surface (Fig. 7). The forward hitch-point position and free-floating action also minimizes the backward tipping moment on the prime mover, which is a major problem for fixed-plough mountings or where ploughs are attached to the draw bar at the rear of the tractor.

Fig. 7. Uniform track pressure increases traction. The long-beam "floating" design is used to increase track load and give uniform load distribution.

The moveable hitch-point plough is shown in Fig. 8. The configuration used here utilizes a twin beam with each of the two beams attached to the rear of the dozer blade. The attitude of the plough blade with respect to the beam is manually adjustable by using the two turn-buckles shown at the rear of the plough. Grade control is achieved by moving the hitch point up or down with the dozer blade hydraulic system. The hydraulic cylinder at the rear of the crawler is for lifting the plough out of the ground only. During the plough-in mode of the plough, this cylinder is in the float mode. The hitch point is a "pin" connection; thus, the plough is mostly free of pitching action of the crawler tractor.
Fig. 8. Movable hitch point drain tube plow. This long, twin-beam floating type plow has its hitch point on the rear of the dozer blade (FOUSS et al., 1971).
The fixed-hitch-point plough utilizes a shorter beam than the other ploughs but achieves attitude control by changing the plough blade angle; the hitch remains fixed. The Hoes plough is an example of this plough type.

The concept of a roller-type floating plough with a virtual or imaginary hitch point was investigated by Ede (1961, 1965). The Badger plough, manufactured in England and distributed in Canada, makes use of this principle. The blade and tractor are connected through a pair of rollers which run on a curved, vertical track which is mounted on the rear of the tractor. The centre of curvature of this roller track, located near the front of the tractor, is the virtual hitch point.

The double-link plough utilizes two non-parallel links that provide depth control, combined with free-floating action. It is also a long-beam floating type plough with an imaginary or virtual hitch point. The rear link simulates plough rotation about the virtual hitch point and can be operated in a free-floating mode or with controlled constraint for attaining the desired load transfer to the tracks. The Zor and Krac ploughs are examples of this type of plough.

The parallel link system, with a forward-backward tiltable mounting, provides both plough depth and attitude control. The Barth and ADS ploughs are examples of this type of plough.

The pitching action of the tractor over uneven ground is a major problem for all trenchless methods. The problem is minimized, however, where the free-floating action of the plough is incorporated in the linkage design. The plough blade is thus nearly isolated from most of the pitching movements of the tractor.

Plough performance

As mentioned in an earlier section, the standard of plough performance is based on how well the tubing can be installed to grade and still leave the soil in a condition that allows water to move freely into the drain. Satisfactory results, based on these requirements, depend on a number of factors,
among which soil conditions, plough responsiveness, plough speed, and operator skill are of prime importance.

Soils vary from light sandy, to loam, to heavy clay, and from very dry to very wet. Prime-mover traction and soil compaction are more likely to be a problem in wet or high-clay soils. The occurrence of rocks constitute a serious problem in drain installation. It has been observed that ploughs perform better in rocky soils than do most trenchers. In areas where rocks are a problem, locations where rocks are encountered are flagged at the time of contact by the operator for later inspection and correction by the crew, if needed. Depending somewhat upon the hitch arrangement, a plough will tend to either push the smaller rocks aside or, where larger rocks are encountered, the plough will move sideways around the rock. If the plough is deflected upward a small distance by a rock, where slopes permit, an alert operator will make a small adjustment in grade from the point on and, thereby, not leave a hump in the line for later correction. Rocks as large as 100 cm in diameter have been lifted completely out of the ground as the plough passed through the soil.

It is well-known that mole drain ploughs compact soils. By association, there is a tendency to expect similar compaction with drain-tube ploughs. It is true there is a similarity between mole ploughs and drain-tube ploughs; but because of their very different blade designs, the compactive action on the soil is entirely different. The mole plough is designed to form a channel in the soil by radial compaction so that the mole drain will hold its shape for a long period of time. Consequently, the compaction of the soil outward from a central hole by a bullet-shaped plug is desirable and is a part of the design for moles. However, the drain-tube plough is designed to lift and disrupt the soil with as much disruption and as little radial compaction as possible.

Spoor (1976) described a model for soil disturbance and the accompanying compaction for sub-soilers. For a flat blade at a constant rake angle, his model shows loosened soil above some critical depth and compacted soil due to sideways soil movement below that depth. The model results were substantiated by laboratory tests.
Data are not available for compaction by blades with compound leading edge slopes. The sub-soiler model does not seem adequate for describing the effects of drainage plough blades. Drainage plough blades are designed to impart an upward movement to the soil from the blade cutting tip for some distance back and upward, thus minimizing compaction and creating a large amount of disruption to the soil as it is broken loose and heaved upward.

Irwin (1971) reported on measurements of soil density around ploughed-in drains. He found minimal compaction under and to the sides of the drain (<5 per cent). The unit weight of the soil was reduced by more than 15 per cent in the disturbed soil zone. The disturbed zone extended upward at an angle of about 45 degrees on either side of the drain.

Field investigations of trenchless drain installations were conducted in several different localities in the United States in 1977, under different soil conditions, to evaluate the immediate effects of ploughing around the tubing. In Kentucky, tubing was ploughed-in in a clay-loam soil at a depth of approximately five feet where the soil was extremely dry and in the same soil at another place where it was extremely wet. In the dry, clay-loam soil, the shape of the plough cut was precisely outlined to the exact shape of the plough point, with extreme fracturing and loosening of the soil above and outward at an angle of about 30 degrees from the vertical on both sides. In the wet soil, the cut was not greatly different. The fracturing was less evident, but the soil disruption was equally great. There was no measurable compaction under or around the tubing in either case.

In Iowa, at three different locations in a loose, well-aggregated black soil with a heavy light-coloured clay subsoil, the ploughed-in tubing became covered for a full 180 degrees over the top with 8 to 10 inches of loose, aggregated black soil. In this case, the well-aggregated and loose surface soil flowed freely down behind the plough blade and tubing boot. The drain was, thus, effectively blinded by a covering of highly-permeable, well-aggregated soil. Penetrometer measurements around the base and on each side of the tubing showed no measurable differences due to compaction.

The natural blinding action of the plough was observed to occur also in a sandy soil near Tifton, Georgia. The surface layer was a loose, dry sand which flowed down freely behind the tubing boot and covered the top of
the tubing. This is desirable where the surface material is highly permeable and stable, but it could cause siltation problems if the surface material is extremely silty or is very fine and uniform or if a filter is not used. With a filter, a covering of medium to coarse sand around the tubing could enhance inflow.

High-speed installation

The high speed of the trenchless drain plough has brought about a large increase in rate of installation of agricultural farm drainage. An example of the effect of the plough is the operation of drainage contractors, G. and R. Lazure, Quebec, Canada. Changing from a business built entirely on trenching in 1968 to an essentially full-plough operation in 1977, their annual installations increased from slightly less than 1 million feet to more than 15 million feet per year.

Contributing to their high production level is a well-managed organization where crew training and unique plough designs virtually eliminate lost time. The 15 million feet of tubing installed last year was accomplished in 32 work weeks with 8 ploughs operated by 6-man crews working 50 hours per week.

Their ploughs, which are of the double free-floating link type, are mounted on D8H crawler tractors. The basic plough blade is for 4-inch (or 3-inch) tubing; but has a removable attachment that can be added or taken off in less than three minutes in order to convert the plough blade to one that can install 6-inch or 8-inch tubing. Thus, they plough-in both mains and laterals. For the mains, an initial pass is usually made with the plough at about one-half the final depth. Following this initial cut, the tubing is ploughed-in to depths up to 7 feet with a D7F in tandem with the D8H. Their target for 1978 is 20 million feet of installed drains.
Fig. 9. Farm wagon built for stringing tubing from regular 250-foot rolls and big three-spool trailer with capacity of 15,000 feet.
Stringing tubing

Because of the high plough speeds, stringing of the tubing in the field prior to installation is a major item. To reduce both labour and material costs and to meet the high-speed stringing requirements of the plough jumbosized coils which are mounted on big-spool trailers have been developed. Fig. 9 shows a stringing wagon which is commonly used for handling the regular 250 foot tubing coils and the big three-spool trailer. Each spool, loaded at the factory, carries up to 5,000 feet of 4-inch tubing, making the total capacity of the unit 15,000 feet. In addition to the reduction in stringing time, more than 50 connections per load are eliminated, thus saving additional time and materials.

The future of ploughs

In a relatively short time, the trenchless method of drainage has come to the forefront as an effective and economical method of installing drains. Drain plough designers and engineers have done an excellent job in meeting the requirements of a new drainage method. Contractors are finding that maintenance costs are low, and the rate of installation gives a competitive edge that is shifting the industry from trenching to trenchless drainage. Whereas the drain tube plough started from a zero base a few short years ago, it is not difficult to imagine that the trenchless method will dominate the industry within the coming decade.

The rapid change envisioned is fraught with the possible danger of a decline in the quality of agricultural drainage. Shifting to a higher rate of installation requires improved procedures for maintaining accuracy of placement, both for drain grade and depth. While the concurrent gain in control technology may be adequate to ensure the required accuracy of installation, the means for ensuring acceptable performance in the field has not kept pace. Developing procedures for maintaining quality drain installations is a major challenge for drainage of the future.
References


Summary

The efficiency of field drainage demands particularly careful work. A survey of the laying quality has been recently held in France. The present paper gives a quick description of data handling and processing and then analyses the respective influence of various parameters, among which those relative to soil and machines appeared to be most important.

1. Introduction

The recent progress of field drainage in France can be explained first by a generalized mechanization and also by a more extensive information about it.

The mechanization development is linked with the cost lowering in constant francs, this lowering being itself correlated with the increase of laying speed.

One could then expect the laying quality to decrease if a certain number of recommendations or norms were not given to works consultants and applicants.

Because of this, the Ministry of Agriculture has edited a book of recommendations (Cahier des prescriptions communes, 1971) for drain works, referred to as "CPC" in this paper. In this document, among other rules, several tolerances were fixed, according to the laying technique (handmade, by excavator, by trencher, by trenchless machine).
In 1973 and 1974, the CTGREF (Ministry of Agriculture, Technical Center) held a quality survey to estimate the respect of CPC recommendations.

It was found that too severe tolerances could not be respected without considerable increase of costs.

However, the results were alarming: a high number of negative slopes and laying errors did appear.

In 1976, presuming that no quality increase had occurred, and searching for more recent and objective data, the CTGREF held a new quality survey in whole France, which gave data for a more refined analysis.

This paper briefly describes the measurements, presents the data analysis and summarizes the conclusion of it.

2. Effects of a bad laying of drains and collectors

Effects of a negative slope

A negative slope is schematized on Fig. 1.

![Fig. 1. Negative slope of a drain.](image)

It is clear that such a situation enables a stagnation of water at the end of a drainage period; this area, when the soil is drying, attracts crop roots and, thus, clogging by roots.
In addition, the slope change lowers the mean water velocity and provides sedimentation of solids transported (loam, fine sand, roots), and thus inner clogging.

Finally, the flow under pressure is a factor of drain instability.

Effects of a laying error

A laying error provides an increase or a decrease of the drain slope. In the second case, the effects are similar to those of a negative slope, though less important.

Case of the collectors

Particular care must be observed for collector laying, these pipes being the major organs of the drainage layout. Thus, collectors must formally present neither negative slope nor laying error.

3. Quality survey

The quality survey consisted in checking the profiles of several drains on each site. In order to obtain homogeneity among different sites, it has been decided to check about 200 metres on each site, with one point per metre. In order to check the depth of pipes, the soil surface elevation was measured every fifth metre.

In view of avoiding the risk of errors, the pipe was made visible before measurement. In the case of trenches, checking was made just after laying. In the case of trenchless machines, it was necessary to extract the backfill with an excavator. The levelling was made with a level combined tacheometer. The sighting pole had a mobile shoe (Fig.2).

For each drain, several informations were handled, among which the type of machine, the control system, some soil characteristics (texture, rock content, water content, stability, terrain aspect), and the machine velocity. These data were recorded in an explicative data file.
4. Data analysis

The analysis involved the three following steps:

- pipe slope draft;
- creation of an explicated data file, from the descriptive parameters of laying quality;
- variance analysis of this file, combined with the explicative data file.

The two last steps will be developed:

- the second one is in fact an automatic notation of the drain laying quality. The criteria were relative to underlayings, negative slopes and laying errors.

The underlayings, i.e. the points where the drain bottoms was less than 0.80 m deep (according to the trench drainage CPC), could be detected every five meters; the total number of such points was counted.
A negative slope was counted any time a point was more than 3 mm below the immediate downstream point. The length of the negative slope was estimated as the distance between the highest downstream point and the first upstream point at the same level. The amplitude of the negative slope was estimated as the difference between this level and the level of the lowest point in the considered area.

The negative slopes were classified into seven classes, according to the importance of their amplitude. One counted for each drain the number of negative slopes of each class, and their total number. A special count in terms of presence or absence of negative slope, was made for the first five meters of each drain, because of their importance and the hand-laying of this part.

The evaluation of laying errors implied existence of a reference pipe slope design. In the absence of such a draft for most projects, it was decided to estimate it practically and theoretically, from the level data. A least-squares method was used to adjust the levelling to an optimal line having at most one slope change. The theoretical design was thus composed of two half straight lines, the slope of which was necessarily positive.

The laying errors were then detected and classified in five classes determined from a tolerance depending on the mean slope (according to the trench drainage CPC). For each drain, the number of laying errors of each type was counted.

The third step analysed the data file for each drain, involving explicative data from field observations and mean slopes, and explicated data obtained at Step 2.

The treatment was a variance analysis, executed for each couple explicative datum - explicated datum. When the sample size was large enough, additional treatments were performed for files reduced to a given value of an explicative variable, for testing the influence of a given parameter, with respect to another.

The general results of this analysis are listed and commented thereafter.
### Results of the Variance Analysis

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<th>Negative SLOPES within First 5 Meters</th>
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<th>Amplitude of Negative SLOPES</th>
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**Legend**

- non significant test
- 5 significant test
- 1 highly significant test
5. Results

The results of the 1976 survey (9500 levelled points) are not much different from those of the 1973-74 survey (3850 levelled points) as well for the negative slopes as for the laying errors. The main difference lies in the fact that the first survey involved few sites held with use of trench-less machines and of laser control systems.

The first analysis of the 1976 survey results shows that the main problems are:

- negative slopes at the beginning of drains (downstream, which means near the junction with the collector)
- laying depth often too small
- high number of negative slopes
- high number of laying errors.

The variance analysis (see above) allows to precise what parameters have major influence.

Influence of machines and control systems

The results do not provide much difference between the two types of machine, as well as for the negative slopes as for the laying errors.

The control system by poles or rotating laser give a similar quality which appears better than that obtained by other systems.

It seems that the linear laser system provides negative slopes, which is paradoxal. The use of it is probably at the origin of these results.

The radio control system provides the highest number of laying errors.

Influence of machine velocity

For trenchers, the increase of velocity results in a decrease of quality. The phenomenon is less apparent for trenchless machines, but there was lack of high speed machines during the survey.

Influence of soil

The more the slope is important, the smaller the number of negative
slopes; however, the number of laying errors increases with the slope. The operator is probably less careful in this case.

The soil moisture has also an influence: the number of negative slopes is almost the same in wet and in dry conditions; but the number of laying errors increases with wetness.

It is not possible to conclude about the part played by the stone content, because of the small size of the sample and of the particularly dry period in 1976.

About texture, the best laying is obtained in loamy soils, followed by clay soils and then sandy soils. The number of negative slopes is more important in sandy soils (instability of trench bottom; generally flat topography, high speed of machines due to a smaller resistance).

Topography

It is paradoxal that the number of negative slopes is higher in regular topography. This result can be explained only by a more careful work in difficult conditions.

As a conclusion, it appears that the drain laying quality, especially characterized by the number of negative slopes and laying errors and by the laying depth, is not mainly influenced by the type of machine and control system, but by the physical soil conditions (slope, moisture, texture, stone content, topography) and by human parameters depending on the draining staff and first of all the machine driver. The results given in the present paper show that the survey of drain laying quality must be now a major task for drainage consultants and applicants, but also that contractors must do an important effort of staff training, especially to make them understand the consequences of their work. Machine constructors have also to play a part by designing equipment able to make the driver's task easier. Finally, it would be emphasized that the objective character of the survey and of the data analysis gives conclusions for the french conditions only.

References

A method was developed to predict the additional flow resistance to drain pipes due to the technique of laying drain pipes.

For the trenchless drainage technique the flow of soil around the body that is forced through the soil, is assumed to be a sequence of steady state situations in which the streamlines are the sliding lines to be described according to Prandtl. From the such known stream lines and an assumed displacement, a relation is derived between the deformation of the soil, the friction angle and the distance to the body.

A relation between hydraulic conductivity and deformation was derived by means of cores placed in a triaxial apparatus. When the friction angle is known, the reduction in hydraulic conductivity and the change in radial flow resistance can be determined.

For the traditional drainage technique, the change in dry bulk density due to settling of the loose soil with which the trench is filled up is estimated from the relation between change in density and density of the original soil in situ. From a relation between density and hydraulic conductivity the reduction in conductivity due to the change in dry bulk density can be obtained. The change in radial flow resistance then can easily be calculated.

The predicted hydraulic conductivity in the deformed zone respectively in the trench in a silt loam and a silty clay loam (marine deposits) was compared with the hydraulic conductivity in these zones derived from measured drain discharges, heights of water table and known hydraulic conductivities in the various, undisturbed layers. There appeared to be a reasonable agreement between the predicted and measured hydraulic conductivity.
APPLICATION OF OPERATIONAL RESEARCH DURING THE EXECUTION OF DRAINAGE SYSTEMS

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Lelystad, The Netherlands.

This article will be published in the Proceedings of ICID 10th Congress, Athens 1978, and therefore only an abstract follows.

Abstract

The operational aspects of subsurface drainage in the IJsselmeerpolders in The Netherlands are analyzed with the help of a network. Further attention is paid to investigations of installing a subsurface drainage system. Especially the activity "laying pipes" has been followed in detail to collect data for optimizing execution and planning purposes in general. For planning costs of the whole subsurface drainage system these data are very valid. A specification of drainage costs is given at the end of the report.

Introduction of this type of operational research may be a good help in tropical areas for large-scale irrigation projects combined with composed drainage system.
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DRAINAGE INSTALLATION PROBLEMS IN THE SAN JOAQUIN VALLEY, CALIFORNIA, USA

William R. Johnston, Westlands Water District, Fresno, California, USA

Summary

The area of the San Joaquin Valley, California, U.S.A., which has a subsurface agricultural drainage problem is described, as are the proposed solutions to the problem. The rate in which drainage problems have developed over the past ten years is tabulated for the 600,000 acre (240,000 hectare) Westlands Water District.

The costs and benefits of subsurface agricultural drainage in the San Joaquin Valley are described and compared with expected crop yield decrements due to not providing farm drainage after the ground water rises within five feet of the ground surface. Estimates indicate that the average benefit from drainage is about $150 per acre ($375 per hectare) which is approximately five times greater than the annual cost of a drainage system.

Specific problems pertaining to drain envelopes and pipe materials; trenching; and backfilling during the installation of subsurface drainage systems in unstable soils with an extremely high ground water table are also discussed.

The area

The great central basin of the State of California is one of the most intensively farmed and productive agricultural areas of the world. The southern half of this basin, the San Joaquin Valley, as shown on Figure 1, comprises about eight million acres (3.2 million hectares) most of which are devoted to irrigated agriculture. About 20 per cent of the irrigated area which is located in or near the Valley trough now has, or is projected to develop, high water tables and saline ground water (6,000 to 15,000 mg/l total dissolved solids) conditions sufficient to damage or destroy agricultural productivity.

On-farm drainage systems which are necessary to alleviate this problem were initially installed in parts of the Valley during the early 1940's, but system installations have been limited to about 50,000 acres (20,000 ha)
Figure 1. California, U.S.A. Showing location of San Joaquin Valley and Westlands Water District.
because of the lack of adequate drainage disposal facilities. Discharge and recirculation of saline drainage effluent to irrigation canals or natural channels degrades the water for downstream reuse.

The projections of expected future conditions in Table 1 show that, within the next 50 years, almost 900,000 acres (364,000 hectares) of irrigated land in the San Joaquin Valley will require subsurface drainage in order to maintain a high level of agricultural productivity. The soils in the Valley which require drainage are generally stratified heavy clay and silty clay alluvium, basin rim and basin soils - all of which have a subsoil that is rather unstable when saturated.

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<td>2060</td>
<td>1,053</td>
<td>426</td>
<td>746</td>
</tr>
<tr>
<td>2070</td>
<td>1,078</td>
<td>436</td>
<td>788</td>
</tr>
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<td>2080</td>
<td>1,097</td>
<td>444</td>
<td>823</td>
</tr>
<tr>
<td>Ultimate</td>
<td>1,142</td>
<td>462</td>
<td>941</td>
</tr>
</tbody>
</table>

* San Joaquin Interagency Drainage Program, Progress Report No. 2, August, 1977
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The "Area Requiring Drainage" is defined as that area where a perched watertable occurs within five feet (1.5 meters) of the ground surface. Most of the 1,142,000 acres (462,000 hectares) that are expected to ultimately require drainage presently (1977) have a watertable within 20 feet (6.1 m) of the ground surface. It is assumed that some of the area requiring drainage will never be drained directly with an on-farm drainage system because of individual landowners on-farm practices, preferences, and economics. However, it is estimated that about 75 per cent of the area will eventually be drained in order to maintain a stable agricultural economic base. The increasing need for food and fiber will place a greater importance on maintaining the long-term productivity of such lands. Inasmuch as the drainage
Figure 2. General layout of the Westlands Water District Drainage Collector System.
problems within California span a large area which traverse several levels of government, irrigation districts, drainage districts, and other political subdivisions, it becomes obvious that the need to ultimately collect and dispose of 500,000 to 600,000 acre-feet (617 million to 740 million cubic meters) of saline drainage effluent annually will require a major coordination effort between all of the drainage problem areas.

Westlands Water District

Westlands Water District, a political subdivision of California, covers approximately 600,000 acres (240,000 hectares) of prime farm land in the San Joaquin Valley between the foothills of the Coast Range on the west and the Valley trough on the east, as shown on Figure 1, is a part of this larger Valley drainage problem area. It is estimated that about one-half of the Westlands Water District area will ultimately need subsurface agricultural drainage facilities. Currently, more than 200,000 acres (80,000 hectares) of land within the District have a perched watertable that is less than 20 feet (6.1 meters) below the ground surface. The following tabulation shows the growth of the areas affected by the perched watertable in the District.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>feet</td>
<td>acres</td>
<td>ha</td>
<td>acres</td>
</tr>
<tr>
<td>0-5</td>
<td>12,300</td>
<td>4,980</td>
<td>34,900</td>
</tr>
<tr>
<td>5-10</td>
<td>57,000</td>
<td>23,070</td>
<td>81,200</td>
</tr>
<tr>
<td>10-20</td>
<td>89,400</td>
<td>36,180</td>
<td>89,100</td>
</tr>
<tr>
<td>158,700</td>
<td>64,230</td>
<td></td>
<td>205,200</td>
</tr>
</tbody>
</table>

The above data shows that between 1967 and 1976 there was a 46,800 acre (18,930 hectare) increase in the area with a watertable of 10 feet (3 m) or less. The Bureau of Reclamation, a Federal government agency, is presently constructing an open outlet channel called the San Luis Drain to transport saline drainage water from Westlands Water District for initial disposal to the Kersterson (holding and regulating) Reservoir. Eventually, the drainage water will either be diverted from the Kersterson Reservoir to the western Sacramento-San Joaquin Delta-San Francisco Bay estuary by gravity or will be disposed of by pumping over the Coast Mountain Range to the Pacific Ocean.
Figure 3. Typical on farm drainage system and pump sump layout.
If found feasible, the saline drainage water will be used in wildlife management and/or for cooling electric generating plants before final disposal.

Westlands Water District has assumed the responsibility to collect the saline subsurface drainage effluent from each farm and transport it to the Bureau of Reclamation's San Luis Drain. The District's Drainage Collector System, which is currently under construction, consists of open-joint collector drains and closed carrier pipelines. The District's drainage system functions both as subsurface drain lines as well as a carrier of subsurface drainage water from the privately owned on-farm drain systems by gravity to the concrete-lined San Luis Drain. The collector drains discharge by gravity into closed pumped sumps or directly into the carrier lines.

One one-farm drain connection to the District's Drainage Collector System is permitted for each 160-acre (65 hectare) parcel. The connecting point is sufficiently deep to allow the on-farm drains to be 6 feet (2 m) deep and still discharge into the District drains by gravity.

Figure 2 and Figure 3 illustrate the general layout of the Westlands' Drainage Collector System and a typical layout of an on-farm system.

A contract to install about 115 miles (185 kilometers) of the District collector drains and 30 miles (48 kilometers) of carrier pipelines was awarded in June 1975. However, after installing the carrier pipelines and only 36 miles (58 kilometers) of collector drains, the contractor abandoned his work because of difficult field conditions and installation problems typical for the Valley soils.

These problems will be discussed in this paper.

Economics

Drainage costs

The cost of a subsurface drainage system will, of course, vary with the particular needs of an area. The average cost of plastic tubing installed for on-farm drainage with a gravel envelope, at depths of approximately 7 feet (2.1 meters) in the San Joaquin Valley is as follows:
Drain Diameter

<table>
<thead>
<tr>
<th>Inches</th>
<th>Centimeters</th>
<th>Unit Cost in Dollars (U.S.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>10</td>
<td>0.90</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>1.50</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>2.00</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>3.25</td>
</tr>
<tr>
<td>12</td>
<td>30</td>
<td>4.00</td>
</tr>
</tbody>
</table>

In order to compare the costs and benefits for agricultural land in the San Joaquin Valley, a typical drainage system in Westlands Water District will be used as an example.

A typical on-farm drain system, shown in Figure 3, contains approximately 150 feet of drain per acre (45 meters of drain per hectare). The costs of such a system would be approximately $160 per acre ($400 per acre). If it is assumed that such an on-farm drainage system can be financed for a period of 20 years at an average interest rate of 9 per cent, the annual equivalent capital cost is approximately $17,50 per acre ($43.75 per hectare). The cost of the District's collection facility is estimated to be approximately $300 per acre ($750 per hectare) served when completed. The District has obtained a 40-year interest-free loan for the construction of the drainage collection system. The equivalent annual cost for the District's drainage system is approximately $7.50 per acre ($18.75 per hectare). The District also must pay the United States Government $0.50 per acre-foot ($0.41 per 1000 cubic meters) of irrigation water delivered for the use of the San Luis Drain and other related facilities. With an average water requirement of about 3 acre-feet per acre (9250 cubic meters per hectare), the annual drainage disposal cost will be about $1.50 per acre ($3.75 per hectare). Assuming the operation and maintenance of the District's Drainage Collector System and the on-farm drain systems costs are $3.50 per acre ($8.75 per hectare) the estimated total annual cost will be about $30 per acre ($75 per hectare).

Benefits of drainage

When a saline ground watertable rises into the crop root zone, a decline in crop yield can be expected. This decline is due both to the high water-
table and the resultant increased salinity in the crop root zone. The range of expected decline in crop yield, when no on-farm drainage is provided, is shown in Figure 4, which compares the per cent of relative crop yield decrement to time after saline watertable raises to within 5 feet (1.5 meters) of the ground surface.

![Figure 4. Expected crop yield decrement due to no on-farm drainage provisions after ground water raises to a minimum of 5 feet (1.5 meters) below ground surface.](image)

It is quite apparent that if drainage is not provided, when needed, the crop yield will be reduced by as much as 20 per cent in a very few years. It would quickly be uneconomical to cultivate land with this reduced productivity. It could be assumed that the agricultural value of the land would soon be greatly reduced or lost entirely.

Obviously, the landowner or farmer receives the primary benefit of the continued productivity of the soil and the sustained land values resulting from the timely installation of a needed drainage system. This direct annual benefit from the investment in irrigated agriculture should, in fact, be equal to the rate of return for an equal capital investment elsewhere and should probably approximate 10 per cent of the value of the land and improvements when it is producing a maximum crop yield. Since the present value of the agricultural land in the Westlands Water district averages approxima-
I. rely $1500 per acre ($3750 per hectare), the annual drainage benefit can then be estimated to be $150 per acre ($375 per hectare). This indicates that the primary benefits received by the landowner from the timely installation of a complete drainage system that has an annual equivalent cost of $30 per acre ($75 per hectare) are five times greater than the annual cost of the system. This amounts to an annual rate of return on the drainage investment of approximately 30 per cent.

Additional benefits are realized by local and regional economies by having sustained employment levels and maintenance of a stable economic base. Also, because of this continued farm production, the farm suppliers and manufacturers of farm-related equipment and machinery will enjoy full employment and constant industrial production while satisfying the material and equipment needs of the farmer. The farm product processor is also able to maintain a high level of employment and plant capacity in handling and preparing the food and fiber for shipment to the merchant and the consumer. The consumer is benefited by a continued supply of food and fiber at reasonable prices when commodities are grown locally or domestically in abundant quantities. When the consumer's demand for any commodity exceeds the available supply, goods are transported long distances or imported - usually at higher prices to satisfy the demand. Increased imports to satisfy the commodity needs of a nation can contribute to foreign trade deficits. These deficits, if prolonged, will eventually affect the stability of a nation's currency. Therefore, the beneficiaries of sustained agricultural productivity through the installation of on-farm drainage systems are farmers, farm suppliers, processors, manufacturers, merchants and, last - but not least - consumers.

Material problems

The need to provide subsurface drainage for an extensive area of farm-land in the San Joaquin Valley of California and many other areas of the world to protect agricultural productivity means that it is most important to design and construct the best drainage facilities possible. Good construction is necessary to maximize the life of the facilities and to minimize maintenance problems once the facilities are completed. Even though there have been many recent improvements in regard to the type of materials and equip-
ment used in the installation of subsurface agricultural drainage facilities, there are still many problems needing research and development work to assure the installation of an economical, efficient, trouble-free drainage facility—particularly under adverse construction conditions.

Pipe

There are three basic types of pipe used for subsurface drain construction in the San Joaquin Valley: 1) concrete pipe, 2) clay tile, and 3) corrugated plastic drain tubing. For many years concrete and clay were the predominant materials used to construct drain conduits.

One problem with concrete is that under high sulfate soil and water conditions corrosion of porous concrete drain tile can take place. The most prominent among aggressive salts which affect concrete in the San Joaquin Valley and many other arid areas of the world are sulfates of sodium, magnesium and calcium. These salts, which are sometimes known as white alkali, react chemically with the hydrated lime and hydrated calcium aluminate in cement. These reactions are accompanied by considerable expansion and disruption of the concrete. Dense concrete containing cement which has a low content of tricalcium aluminate is highly resistant to this sulfate attack and has been used widely in the manufacture of concrete pipe installed in drainage facilities. Good quality clay drain tile are, for all practical purposes, immune to the corrosive action of soil and water sulfates. However, clay drain tile have recently become relatively scarce and expensive.

Today, the most small diameter drain conduits are flexible plastic corrugated tubing. Plastic tubing appears to be well suited for agricultural drainage when properly manufactured and installed. However, there are certain problems in its manufacture that still need attention. The latest developments in tubing design provide suitable openings for water inflow and adequate structural strength to withstand the forces placed on the tubing when properly installed to depths of 8.0 feet (2.4 meters). It is still not uncommon, however, to have tubing delivered to the field with excessive variation in wall thickness. This minimizes the structural strength of the tubing and leads to collapsed drains. In addition, tubing seam ruptures, cracks or splits result in poor drainage installations.
Envelope

Two types of envelope materials are generally used in agricultural drainage at various locations around the world -- natural graded gravel or sand materials and synthetic fabrics of several types. In many areas the use of an envelope material does not appear to be necessary for good drainage. Where a gravel envelope is required, more often than not, it is needed to facilitate the drain installation and to provide a structural base for the drains. It is also beneficial in reducing the convergence of flow as the ground water moves from the less permeable saturated soil into the more permeable gravel envelope material and then into the perforations or openings in the conduit.

Gravel and sand drain envelopes are used extensively in the San Joaquin Valley for the above reasons and because of the heavy unstable soils in which the drainage problems occur. However, the high cost and, at times, the unavailability of the native sand or gravel make it imperative that an adequate substitute be developed. To date, none of the synthetic envelope materials available provides the stability needed in adverse installation conditions, but some show promise as "filters".

Installation problems

Both trenching and trenchless installation techniques are used to install on-farm drainage facilities in the San Joaquin Valley of California. Even though there are more trenching machines used because of their versatility, there are some serious problems related to the difficulties of installing good drainage systems with either technique.

Trenching and backfilling

Chain type trenchers, in optimum soil conditions, have a greater digging capacity than bucket type trenchers. The bucket type trencher is more versatile in some of the adverse soil and water conditions that are encountered during the installation of subsurface drains. Some clay soils become quite sticky when the water content is near saturation. The sticky clay ad-
heres to the chain of the chain type trenchers, stopping the trenching op-
eration. It then becomes necessary to decrease the stickyness of the clay
soil being excavated by spraying water on the chain and raising the water
content of the soil in contact with the chain. The spoil (excavated material),
under these conditions, is little more than a slurry and becomes almost un-
manageable, particularly during the backfill operation. If it is placed in
the trench immediately, it will dry as a mass. If it can be allowed to dry
before backfilling the trench, then it is like trying to fill the trench
with large bricks. It is questionable if either situation promises the in-
stallation of a good drainage system. Bucket type trenchers usually perform
better under adverse digging conditions.

In unstable soils, it is usually important to backfill the trench imme-
diately behind the trenching machine during the placement of the drains to
insure that the drains remain on line and grade. This is especially impor-
tant when the trench extends into saturated soil and the drain is being
placed below the watertable.

The weight of the soil adjacent to the excavation bears on the soil
stratum at the level of the bottom of the excavation; and, if the bearing
capacity of the saturated subsoil is not great enough to support the weight,
the bottom of the trench will bulge upward, causing the drain to be pushed
off grade. When the trench extends into sand, the bottom is ordinarily stable
as long as the water level inside the trench is no lower than the ground
water outside the trench. However, as soon as the water inside the trench
is lowered by the installed drain, an upward seepage of water is created.
If the difference in water levels is excessive, the bottom will heave, then
become quick, and sand boils will appear. Gravel envelope material can be
lost in these sand boils, as its weight is insufficient to stabilize such
material. To adequately stabilize this condition, it is sometimes necessary
to use gravel as large as 3-inch (7.5 cm) in diameter as a drain envelope
to stabilize the trench. The problems just described were all encountered
by the contractor when installing 10 to 24-inch (25 to 61 cm) diameter con-
crete pipe at 8.0 to 12.0 feet (2.5 to 3.7 meters) depths for the Westlands'
Drainage Collector System with a very large and heavy wheel type trenching
machine.
Trenchless installations

The trenchless method of installing drainage tubing requires a much higher draft force than the trencher method of installing drains. These forces rise sharply as the width of the shank and the depth of the installation increases. Therefore, drains installed by this method are limited to 4-inch (10 cm) diameter and a depth of approximately 8.0 feet (2.5 meters).

Envelopes

When installing a gravel envelope around corrugated plastic drain tubing, the placement of the gravel in the trench in relation to the bends in the tubing appears to be an important factor. Temporary stretching of the tubing occurs where the tubing is bent to make the vertical turn at the bottom of the trench. The corrugations on the top of the tubing are compressed and those on the bottom are expanded during such curvature. If the expanded corrugations are filled with the envelope material as the machine makes forward progress and the tubing becomes parallel to the bottom of the trench, the top portion of the tubing must also expand since the lower portion cannot return to its original shape if the corrugations are full of gravel. The timing of placement of the gravel envelope is, therefore, quite critical. Gravel must not be placed around the tubing until it is on proper grade and alignment. It appears that when a synthetic fabric envelope is placed around the tubing before the gravel envelope is placed around the tubing, the synthetic envelope will eliminate this problem because the gravel envelope material is prevented from moving in between the tubing corrugations.

Another problem occurs when insufficient amounts of gravel envelope material or a synthetic envelope is used without gravel. The tubing, being buoyant, has a tendency to float when submerged prior to the trench being properly backfilled. This can cause problems in both alignment and grade, and may greatly reduce the efficiency of the drain line. The synthetic envelope materials presently available, while capable of acting as a filter, do not provide adequate weight to overcome the buoyancy of plastic tubing prior to backfilling. Under these conditions the trench must be backfilled simultaneously with the placement of the drain and envelope material.
When a subsurface drain is installed with trenchless equipment, the placement of the gravel envelope can be hampered when the soil is saturated and the resultant hydrostatic head is high. The opening in the soil created for the tubing and the gravel envelope will rapidly close as the semi-fluid soil tries to flow into the opening, thus restricting the flow and proper placement of the gravel. The severity of this problem has been decreased by one contractor in the San Joaquin Valley by placing a power auger in the opening around the tubing, which forces the gravel into the open space provided for it, thereby overcoming the hydrostatic pressure of the soil.

Tubing stretch

Polyethylene tubing will stretch under tension during installation. Excessive stretching can cause transverse slots in the tubing to become quite wide, thereby allowing the gravel envelope and native soil to migrate into the tubing, causing the drain to become blocked. Stretching of the tubing also decreases its resistance to deflection. Stretching appears to be attributed to several other factors in addition to improper placement of the gravel envelope material. One such item is having the drainage machine speed exceed the rate at which the gravel envelope material will flow freely into the trench around the drain line. Another is using crushed rock that will create more friction than well rounded gravel and cause tubing to stretch more at the same installation speed.

It is essential that the amount of stretch be minimized and one way to know the amount of stretch that is occurring is to lay the tubing on the ground ahead of the drain trencher, rather than to carry it on a reel on the machine. However, in hot weather the temperature of black polyethylene tubing increases as it lays in the sun. The tubing then has much less resistance to stretching and its resistance to deflection can be reduced up to 50 per cent when the temperature of the plastic reaches the vicinity of $120^\circ$ to $140^\circ$F ($50^\circ$ to $60^\circ$C). The tubing stretch can be substantially reduced or eliminated by the installation of a pair of tubing drive sprockets along with the proper use of gravel envelope installation methods. If the perimeter of the prockets is driven at the same rate of speed as the forward progress of the trencher, stretch of the tubing is eliminated.
After the proper materials and installation techniques for the anticipated construction conditions are selected, a rigid inspection program must be carried out during construction. Many maintenance problems can be attributed to the careless attitude of a workman and it is essential to strive for a quality drainage system, rather than try to compromise with some lesser degree of workmanship.

Maintenance

Crop roots can be a problem even in drains placed to 8-foot (2.5 m) depths. Plant roots that enter drains in sufficient quantities cause plugging. Root plugging problems are minimized in the San Joaquin Valley by periodically blocking the outlets and injecting a copper sulfate solution through an air vent in the end of each drain line and allowing the solution in the drain for two to four days before placing the line back into service.

In areas where magnesium or iron oxides are present, incrustations of these materials can occur and close the perforations or openings in the drain lines. These incrustations can be removed by injecting a 2 per cent solution by weight, of sulfur dioxide and water through a vent or riser at the upstream end of the drain.

The drains must also be sealed for a period of two to four days so that the contact time is adequate to allow the sulfur dioxide solution to dissolve the deposits. Care must be taken, however, because the relatively unstable sulfurous acid \( \text{H}_2\text{SO}_3 \) also reacts with any available oxygen as well as with metals to produce varying amounts of sulfuric acid \( \text{H}_2\text{SO}_4 \), which will dissolve some synthetic envelope materials. A comparison of drainage flows prior to and after treatment will provide an estimate of the benefits from the cleaning operation.

The effluent discharged from the drains following any chemical treatment will contain chemical residues, acid in varying states of dilution and water with a very low dissolved oxygen content. The effluent should be monitored and diluted if necessary to prevent damage to fish and wildlife and/or to prevent problems for any potential downstream use of the water.
Conclusion

The materials and installation methods used in the construction of subsurface drainage systems on agricultural land have improved substantially during the past decade. However, research and experimentation must be continued to develop alternative materials and to improve equipment, so that agricultural drainage systems can continue to be provided within the economic means of the farmer. It has been demonstrated that the proper and timely installation of drainage systems will sustain agricultural productivity, which benefits everyone.

There does appear to be several general areas where continued improvement is needed, particularly in the design and production of materials for, and the construction of drainage systems. They are:

1. The specifications and standards necessary to produce good materials and installation procedures;
2. The quality and uniformity of the manufactured materials; and
3. The reliability of contractors or workmen building drainage systems.

In addition, two specific problems relating to the installation of drainage systems in the San Joaquin Valley of California need additional attention. They are:

a) The economic production of a synthetic envelope material which will serve as a suitable replacement for graded gravel or sand; and
b) The manufacture of a drainage machine suitable for installing large size 12 to 21-inch (30 to 53 cm) drains in high watertable conditions.
Summary

As the pressure to grow more food increases worldwide, so does the need for drainage and, in turn, the demand for information and technology. The present status of knowledge and technology is considered generally adequate to meet short-term needs of drainage design and implementation in developing countries. The disappointing results of many newly irrigated and drained areas should not primarily be attributed to an insufficient data base but, rather, to a lack of understanding of the broad interrelationships between the various technical components and of the role of institutional factors. Therefore, the development of new and advanced theories and methodologies is not of immediate concern. It is the application of what is available that is inadequate. Thus, short-term research priorities should be directed toward constraints in the transfer of information. Since most technical information is generalizable to a fair degree, these constraints are primarily in the adaptation and acceptance of technology and concepts. Adaptation related to irrigation practices and related activities which govern drainage systems in dry areas rather than to drainage technology itself. Acceptance, or adoption, refers to the farming community as well as to higher decision-making levels.

Long-term research needs cover a much wider area. In fact, they relate to most aspects of drainage investigations, rationalization of designs and implementation. In addition, long-term research should be increasingly directed to broad optimization programmes of water management.

Effective research programmes at the local level call for national as well as regional and interregional coordination, guidance and support.

1. Increasing scale of drainage

Drainage programmes are on the increase in both the humid and arid regions of the world, whether in high-income areas or developing countries. The objectives are the same in all cases - to protect the quality of the land and to grow more food. In traditional drainage countries, such as The
Netherlands, United Kingdom, Germany, and the United States, old drainage systems are being replaced, or remodelled, with systems that are more finely attuned to the requirements of present-day intensive crop production. According to the American Soil Conservation Service, about 30 per cent of the USA's "Prime farmlands", or 110 million acres, is land with a natural wetness problem that has been solved by drainage. FAO (1977) estimates that 52 million hectares of irrigated land in developing countries will need to be drained in the 1975-1990 period to control waterlogging and salinity. In the same period some 26 million hectares of rainfed land will profit from the improvement or introduction of simple on-farm drainage systems. The total cost is estimated at about 14,000 million dollars.

Countries that have only recently embarked on substantial drainage programmes are found primarily in regions where water development schemes have resulted in the increased availability of irrigation water. This, in turn, has led to higher deep percolation losses from canals and on-farm application resulting in rising groundwater levels. It is clear that most of the world's irrigated land will eventually be in need of watertable control to prevent waterlogging and soil salinization. At present large-scale activities are being developed in such Near Eastern areas as Iraq's Mesopotamian Plain, Egypt's Nile Delta and Valley, Syria's Euphrates Valley, Pakistan's Indus Basin and Iran's Khusistan Basin. Drainage problems are also developing in irrigated areas in Hungary, Roumania, California's San Joaquin Valley, Arizona's Salt River Valley and Mexico's Mexical Valley.

New drainage activities are not, however, limited to irrigated land; they are also found in the wetlands. In North Africa, Latin America, India, Korea and many others, surface and subsurface systems are planned and implemented as pressure for higher production on rainfed land grows.

Though recent drainage programmes in developing countries are of considerable magnitude, there are still vast areas that are in the process of degradation due to waterlogging, salinity and erosion. In practice, drainage is often considered a necessary evil in irrigation projects and, worse, it is left out of many irrigation schemes or postponed till an unspecified later date, which is usually after serious damage has already been inflicted. Drainage is often too expensive for traditional production patterns in developing countries and requires changes that deeply affect the farming communi-
ty. In the institutional field, numerous arrangements are needed to adjust irregular patterns and shapes of holdings, bring in needed expertise, organize and initiate research and maintenance programmes, etc. In spite of these and similar constraints, indications are that drainage is being increasingly looked upon as an integrated part of the modern package of tools in agricultural production, and as a must if land is to be cropped to its productive capacity.

2. Needs of technology and expertise in developing countries

As drainage programmes grow in number and scale, so does the need to make site-specific drainage criteria and design parameters available in a timely manner. Since most developing countries are not traditional drainage countries, local experience is limited and there is not sufficient time and manpower to build up this expertise through research, experimentation and gradual application on practical scales. It is common practice, therefore, to use concepts, criteria and technology from areas that are similar to the project conditions. Testing their local applicability is usually initiated but insufficient research coordination, shortage of competent staff and changing emphasis in research elements often lead to premature termination of research programmes and inconclusive results.

When transfer of technology has been carried out, the benefits of drainage in terms of improved soil moisture conditions, reduced soil salinity and better crop yields are often disappointing. Thus the question arises as to what extent this may be due to the inadequacy of the available technology or to problems in transfer. It is noted, in this connection, that drainage and water management projects in developing countries are mostly located in areas that are characterized by traditional cropping patterns on a subsistence basis, by a need for improvement in farmers' skills and understanding of water management; and furthermore, by weakly developed institutions such as extension services, limited credit facilities, fertilizer availability, seed quality and storage capacity. To obtain higher production, improvements must be made in all these fields, not only in drainage and water management.
Therefore, we should expect crop yields and capital intensity of farms to increase only gradually over the years. The sensitivity of production to refined control of surplus water will increase correspondingly. For the time being, however, this sensitivity is relatively low and some flexibility in the precision with which drainage design parameters and criteria are established is considered acceptable. It should be expected that adjustments in the drainage intensity will be introduced in the course of the years, as the level of water management increases and agricultural output expands.

3. Status of knowledge and technology

An analysis of the present state of affairs regarding available information and knowledge will imply the selection of a criterion to assess their adequacy. Within the context of the FAO's development programmes and objectives such a criterion is unlikely to be of a strict academic nature. Rather, the question is whether information that has been developed over the years in the world as a whole satisfies present short-term needs of improvement and development projects. This question of short-term adequacy is briefly examined below for a number of drainage problems and elements. No attempt has been made to be complete or to deal with the details.

It is shown that the technology and the information are available in sufficient quantity to satisfy short-term needs of developing countries, i.e. to make rational designs for most wet and salty areas. However, a substantial number of newly irrigated and drained areas has been less successful than hoped for, and there have been outright failures. It has often been claimed that these projects have been designed on the basis of inadequate information and that the result would have been better had more time been allocated for further studies. There are strong indications, however, that this is not necessarily so in all cases and that, in fact, insufficient or insufficiently precise data is seldom the real cause of the problems. Rather, it is unawareness of the effects that changes in the water regime, brought about by water development and irrigation, may have. It is also a lack of understanding of the broad interrelationships between the various technical components, as well as between these and non-technical factors. Amongst these latter, the
impact of deficient farmers' skills and institutional arrangements for on-farm water use is of great importance. Most of the problems presented so far can be avoided if the right questions are asked at the right time.

3.1 Drainage theories

The theories of groundwater and surface waterflow are well established for a wide range of conditions and are universally applicable. In fact, equations are available which are considerably more precise than the data on the soils and hydrologic conditions that are used in the calculations. Difficulties do occur in the application of theories, but these stem mostly from the inability to simplify heterogeneous field conditions to known models. Only in special situations will there be a need to conduct research at the base prior to project design.

3.2 Investigation methods

Field and laboratory methods to survey and analyse local project conditions, in particular soils, hydrogeology and climate, are known and available. They are insufficient to diagnose the problems and to design solutions. The information developed, however, is frequently not as precise as would be desirable from a design point of view. This is due to the heterogeneity of the conditions, particularly of the soils, rather than to the investigation methods applied. A greater density of the observation network will usually lead to higher precision. This, however, is costly and the network density is limited for practical and economic reasons. An initially lower level of precision in pre-design investigations may be acceptable if, through the introduction of drain performance tests on sample areas of several acres, additional information can be developed, and so improved designs obtained during the first part of the construction phase. In so doing the project implementation may be considerably advanced.

3.3 Criteria and design parameters

Agronomic criteria for drainage refer to the water regime that should be effected in the rootzone of the crop. In practice, they relate to depth,
duration and frequency of water ponded on the ground surface and to the position and fluctuation of the watertable. For groundwater, more specifically, they refer to watertable levels that are not to be exceeded, or that may be exceeded over specified distances and duration and with specified frequencies. Clearly, the criteria are highly dependent on crop, growth stage, season and soils. They are also closely linked to the amount and frequency of damage that is economically acceptable.

The available information is considerable for both humid and irrigated areas and this permits us to express the criteria in a quantitative form for most conditions. However, crop response cannot always be predicted with a high measure of precision and opinions differ on specific values. As an example, some engineers consider it acceptable that the watertable rises into the upper 50 to 100 cm after each irrigation, for periods of 2 to 5 days. Others base designs on the criterion that the watertable should not exceed, in any part of the growing season, a level of 1.0 or 1.5 metres below the ground surface. In humid areas with storm rainfall and resulting watertables occasionally close to the ground surface, the criterion is expressed as a rate of fall of the watertable. Opinions differ, however, on the optimum drop rate for different crops in difficult growth stages.

Obviously, more data is needed to further specify the criteria. However, it is felt that the existing information and expertise is sufficiently usable in the meantime, to permit the design of systems in short-term project development. This conclusion does not apply to such specific drainage problems as those of some tropical peat soils, acid-sulphate soils, paddy fields and tropical mud flats, information on which is particularly deficient.

These uncertainties of agronomic criteria as well as of the limitations in investigation programmes have a direct bearing on the determination of such design factors as the specific discharge rate, drain depth, leaching rate, capacity of drains and drain spacing. In addition human and institutional conditions will have a profound impact on water management and thus drainage design. A typical example is the drain depth which, in irrigated areas, is often set at 2 m for field drains. It might be agreed that, from a strictly technical viewpoint, a depth of 1.5 m would be acceptable. Shallower drains, however, bring about an increased sensitivity to deficient
water management and, consequently, to a higher risk of waterlogging and salt accumulation. Present tendencies are for deeper rather than shallower drains, particularly in capital intensive cropping areas.

Another example is the design discharge rate in irrigated areas. This parameter is primarily influenced by deep percolation irrigation losses and by leaching requirements. The deep percolation losses, in turn, depend very much on such factors as system management and operation, farmers' understanding of irrigation and salinity, land preparation, methods of irrigation, functioning of users' organizations, etc. Most of these are hard to express in quantitative terms and, moreover, may show changes in the course of time. As a result, the design discharge rates that are selected in practice, if translated in a steady-state value, vary from about 1 to 4 mm per day, the difference being more closely linked to the concept and experience of the designer than to physical conditions.

It would not be difficult to make a long list of items on which available knowledge is inadequate. Such a list, however, is likely to refer to specific problems rather than to the conditions that are commonly found in development or rehabilitation projects. For these latter, the available information is considered adequate in a short-term context.

3.4 Drainage materials

The performance of drain pipes, whether made of clay, concrete or plastics, can be reliably predicted for most soil types. On drain envelopes, however, there are still questions to be answered, and conditions that require a filter are also not yet well defined. Granular filters can be designed to match the soil on the basis of existing knowledge. However, their cost may be high if sieving is needed. Most other filter materials do not match the soil and their performance cannot usually be predicted with complete confidence.

Since the interpretation of results of laboratory research to field conditions is difficult, field research may be indispensable in some new areas for safe technical and economic designs.
3.5 Installation methods

Pipe drains are mainly installed by trenching machines in irrigated areas, and by both trenching and trenchless machines in humid areas. Whilst trenching techniques are basically applicable anywhere, some engineers harbour reservations about trenchless techniques on layered soils if the discharge of water depends heavily on the hydraulic conductivity of the trench backfill. Questions have also been raised about possible compaction around the drain pipes, particularly in soils of higher clay content. It appears that more research is needed to enable designers to predict the performance of drains laid with trenchless techniques more precisely. Methods using trenching machines, on the other hand, are considered widely applicable.

The installation of tubewells for drainage has become a familiar technique in important new drainage areas which include large tracts in India and Pakistan. Problems of corrosion of well materials, particularly in areas of salty groundwater, have been partially solved through the introduction of such materials as fibreglass and asbestos cement. Here again, more research is needed but the available technology is adequate for the installation of tubewells in the short run.

3.6 Specific problem areas

What was said in the above refers to a kind of "standard" conditions in humid arid zones, which are characterized by the absence of specific problems. Examples of specific problems are the drainage of paddy fields, mud flats, tropical peats, acid-sulphate soils, and some vertisols. Though some information is available, considerable research may be needed in each of these prior to the design of optimum solutions.

4. Constraints in the transfer of technology

The application of existing knowledge on drainage to new areas has been and still is slow. Degradation of land through waterlogging, erosion and salinity is widespread and continuing. The processes and factors that play a major role in the transfer of information and technology may be grouped as
a) generalization, b) adaptation, and c) adoption.

4.1 Generalization

Most technical information is generalizable, i.e. it can be directly used in or adjusted to new conditions. As observed in the previous section, the drainage theories are universally applicable. The investigation's methods permit to identify and characterize the physical conditions to most areas with sufficient accuracy to predict drain performance. Most criteria and design parameters are site-specific. However, since there is considerable scope for interpretation and extrapolation, they may be considered as partially generalizable as well. This does not apply in full to drain envelope materials where performance cannot always be predicted with complete confidence.

4.2 Adaptation of technology

Available technology in water management is not often used by farmers because they believe it does not apply to their specific physical and other production conditions, the cost is too high, the required energy source is not available, the foreign currency component is too high, or credit facilities are lacking. Thus there is a need to adapt known technology to the specific physical and socio-economic conditions of a project area. This applies particularly to on-farm irrigation which is governing some critical drainage design parameters and which has several components in common with drainage systems. However, whilst on-farm irrigation systems, once constructed, are operated by farmers, drainage systems rarely are. Once installed, the drainage system needs only periodic maintenance by either the farmers or contractors. An exception may be where drains serve as supply ditches in the irrigation season or where surface drains need to be annually reconstructed. Consequently, appropriate technology in drainage has a different function and should primarily serve to reduce installation cost while maintaining quality and performance. As an example, drainpipe laying machinery has become rather sophisticated, but is commonly used since the alternative of execution by hand labour appears impractical and offers few economic advantages. The digging and maintenance of ditches, on the other hand, is still often being done by
hand labour. Furthermore, clay or concrete drain pipes are normally being manufactured locally since this requires only simple and inexpensive equipment. Drain envelope materials are mostly found or produced locally as well as auxiliary structures such as inspection pits, silt traps, drain outflow structures, etc. Simple tools and techniques are also of considerable importance in such surface drainage activities as land forming, and construction of small farm drains and control structures.

4.3 Adoption

Adoption of new drainage concepts and techniques by the local farming community as well as by project and higher decision-making levels, meets with constraints that are similar to those met in broader water management schemes. These constraints are institutional, legal and socio-economic in nature. Almost universally, farmers and administrators are reluctant to invest in drainage improvement as long as there are doubts about returns or as long as waterlogging is not noticeably present. To make drainage pay, traditional cropping patterns may need to be changed. Credit may not be easily available. Drainage normally requires a group of farmers to cooperate in a rather specific sense and perhaps sacrifice land. Comparatively little research has been done so far on the identification of specific factors that interfere with the rate of acceptance of drainage concepts and considerable gaps exist in knowledge and understanding in this area.

In conclusion, transfer of research results in drainage to development areas does not generally meet with major constraints of generalization and adaptation. However, adoption of drainage concepts and technologies is still slow and research is needed to obtain improvement.

5. Research needs and priorities

5.1 Short-term research

It appears that it is not the development of new and advanced technology that is of concern in the short run. Rather, it is the application of what is known. Since most of the information is generalizable, a survey of the
local project conditions will basically be sufficient to prepare the designs of the drainage systems. In practice there is often a need for field experiments or for performance tests to check the designs as well as to build experience and confidence. It was shown, however, that there are still specific topics and problem areas on which available knowledge is limited and which should be given priority in short-term research programmes. In this respect particular mention was made of drain envelope materials in relation to soil type and a number of special problem soils.

Considerable short-term research is also needed on the adaptation of technology, the development of appropriate technology, and on constraints to its acceptance by the farming community. Research emphasis in these areas should be on the factors that govern the need of drainage and drainage intensity rather than on the actual techniques of drainage. These factors are found particularly in irrigation practices.

With regard to the adoption of concepts and technology, research is needed into farmers' responses to constraints which result from the prevailing water codes and regulations, social organization patterns and local decision-making processes, problems of leadership and status patterns, problems of coordination and integration of institutions from the project formulation level down to farmers' organizations, the flow of information between research stations, advisory services and farmers. Research is also needed on the possible changes in the social system, skills, working and living conditions that result from irrigation and drainage improvement projects. These factors have not yet been subjected to intensive and systematic research at the required scale. A major, coordinated effort, which takes into account the rather unique position of drainage and water management in agricultural development would appear to be justified. This position is primarily characterized by the large, non-recurrent, capital investment needed for water systems and by the fact that water management facilities are largely beyond the control of the individual farmer.

5.2 Long-term research

It has become apparent that there are many issues – relating to almost all aspects of drainage – that require further study in the long run.

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Research should be conducted on the further improvement of present methods and techniques as well as on the development of new technologies, methods and methodologies for the optimization of technical designs and the effective operation and maintenance of drainage systems. Some examples are: crop response to specified watertable fluctuations and soil salinity regimes in various types of soil; economics of drainage; methods of characterization of soils and deeper strata in relation to drainage; low cost methods of drain installation; effects of trenchless drain installation on permeability of soil around the drains; design criteria for vertical drainage in humid areas; design discharge rates in relation to rainfall patterns, soils, irrigation and salinity; and, the mechanism of salt transport in soils. These and related subjects deal with a further rationalization of technical drainage designs. Drainage research, however, should also - and increasingly - be oriented to broader programmes of optimization of water and agricultural management. In addition, long-term research is also needed on the transfer of technology which includes complex problems of a socio-political and legal nature, educational programmes, institutional models, etc., as related to on-farm water management.

6. Implementation of research

Most of the short-term research is site-specific and calls for work at the field and project level. Various programmes are at present being carried out in the countries that have important drainage and irrigation programmes. Their number, however, is too small to adequately cover the needs, and the methodologies used differ from one country to another and sometimes even from one area to another within the same country. Results, therefore, are difficult to compare and are not systematically collected and disseminated to other users. Feedback from the field to research centres is highly inadequate or often lacking altogether. Longer-term research is both site-specific and includes work at the base that could be done anywhere. Here again, however, new development projects would benefit considerably from a systematic and coordinated effort.
It appears that action is needed at both local and international levels. At the local level there is a need to involve research institutes and university faculties in actual field work, and to do so in cooperation with extension services, project administration and planning agencies. This would make sure that research is directed to problems whose solutions are of direct importance to agricultural development. The effectiveness of such programmes would be further enhanced by the participation of research and training organizations from countries with highly developed water management systems.

Action at the national, regional and interregional levels is needed to coordinate the field programmes and standardize methodologies, to collect and disseminate information, to organize the training of staff and to provide financial support. It is considered that water management centres at this level, functioning as focal points for these tasks rather than as research institutes, are urgently needed.

References


SUMMARY

An adequate body of theory is available to predict the behaviour of drainage systems. This theory, however, has not been packaged in a manner that makes its application as convenient or pertinent as it could be, in part because of a lack of data relating a certain degree of drainage to economic returns.

For rainfed areas, the effectiveness of drainage probably should be evaluated in terms of the soil water content of the rootzone and/or the surface soil, rather than the height of the water table. For irrigated areas, the primary concern is removal of excessive salts. In the latter case, the interaction between irrigation management (and cropping pattern) and drainage requirements must be recognized. Furthermore, in both cases, the drainage facilities must be designed with due regard for the natural drainage rate.

Finally, the impact of drainage is not restricted to the farm; in some cases, the off-site effects are important and may even dominate.

INTRODUCTION

Since the pioneering work of Hooghoudt some forty years ago, and that of his predecessors, a tremendous body of new drainage theory has become available. We now have a host of equations that describe, with various reasonable assumptions, the flow of water through soils and to drains. Notwithstanding this body of knowledge, practical drainage design more often than not is still based on guides derived from experience rather than on analytical formulations. The step from theory to practice still is a formidable barrier.
Here I shall make a few remarks about analytical solutions of transient watertable problems; consider some aspects of unsaturated flow; briefly address drainage design criteria; and, finally, call attention to certain aspects of water quality.

Analytical solutions

Whereas the usefulness of steady-state analyses is readily granted, the situations most commonly encountered in the field are better described by non-steady formulations. The best known and most frequently used solution for the typical problem of a falling watertable over parallel drains is based on a linearized version of the differential equation resulting from the Dupuit-Forchheimer assumptions,

$$K \frac{\partial}{\partial x} \left( h \frac{\partial h}{\partial x} \right) + R = f \frac{\partial h}{\partial t}$$  \hspace{1cm} (1)

where $K$ represents the saturated hydraulic conductivity; $f$ an assumed constant drainable pore space, $R$ precipitation and $h$ the hydraulic head referred to the impervious layer; $x$ is used to represent the horizontal coordinate and $t$ is time. Linearization yields, with $\bar{h}$ an assumed constant depth of the water-bearing stratum,

$$K \bar{h} \frac{\partial^2 h}{\partial x^2} + R = f \frac{\partial h}{\partial t}$$  \hspace{1cm} (2)

The resulting Fourier series solution for $R = 0$ is often referred to in the USA as the Glover equation (Dumm, 1954). If a correction is made for convergence near the drain by means of Hooghoudt's equivalent depth (van Schilfgaarde, 1963; Moody, 1966), the results obtained are entirely adequate as long as the flow above the watertable can be ignored and the equation is used for a single drawdown event. Tapp and Moody (Dumm, 1964) later modified the Glover equation somewhat to the solution now used routinely by the U.S. Bureau of Reclamation by using a 4th degree parabola initial watertable in place of a horizontal watertable, as originally assumed. However, the same problem has been solved without linearization, i.e., without the assumption...
that the depth of the water bearing stratum stays constant during drawdown. This writer (1964) presented the solution

\[ t = \frac{fS^2}{9KD_e} \frac{m \left( 2d_e + m \right)}{m \left( 2d_e + m_0 \right)} \]  

where \( t \) is the time required for a mid-spacing drop in watertable from \( m_0 \) to \( m \) above the drain axis, \( d_e \) the equivalent depth below the drain axis, and \( S \) the drain spacing. Equation (3) reduces, in the limit as \( d \to 0 \), to the Boussinesq equation,

\[ t = \frac{2fS^2}{9K} \frac{m_0 - m}{m_0 m} \]  

as it should (Raats and van Schilfgaarde, 1974). The initial condition implied in both Eqs. (3) and (4) is an elliptically shaped watertable. Thus a simple-to-use solution has been at hand for some time that avoids the restriction introduced in the Glover equation through linearization, and the substantial errors that result for relatively large drawdowns.

The most useful application of falling watertable theory, however, considers a sequence of recharge events. Werner (1957) and Maasland (1959, 1963) applied the principle of superposition to intermittent but regularly periodic recharge events as may be visualized from irrigation. Krayenhoff van de Leur (1958) and van Schilfgaarde (1965) considered the more general case of arbitrarily distributed precipitation. Because the principle of superposition requires linearity, Eqs. (3) and (4) above, cannot be used for this purpose; the authors cited used an appropriate, if mutually different, starting point in each case. Similarly, direct use of the modified Glover equation (Dumm and Winger, 1964) introduces a systematic error, resulting in over-conservative spacing recommendations, because of the forcing of the initial condition for each recharge impulse. McWhorter (1977) discovered this problem and represented a corrected solution.

The U.S. Bureau of Reclamation routinely uses the concept of periodic yearly recharge patterns from irrigation in its drainage design. As just pointed out, one can find fault with the detail of the procedure, but the principle is sound. A key assumption concerns the amount of deep percolation

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following each irrigation. In a recent study by the U.S. Bureau of Reclamation (unpublished), it was demonstrated by a linear programming technique that the farmers' choice of cropping pattern could have as large or larger effect on the annual drainage volume from an irrigation district as the irrigation management for a fixed cropping pattern.

In rainfed agriculture, drainage design based on the probability distribution of rainfall and consequent deep percolation seems not to be practiced. A number of research studies (e.g. Vaigneur and Johnson, 1966; Wiser et al., 1974; Skaggs, 1977) have demonstrated the potential, but application by action agencies or consulting engineers has not been encountered. We shall return to this point later.

Flow above the watertable

All of the equations and techniques discussed so far consider only saturated flow bounded by a watertable. This clearly imposes a major limitation. There have been numerous studies in which the total flow system was considered, while in others an intermediate approximation was used. As to the latter, the simplest device still is to lower the effective impervious layer by an amount equal to the thickness of the capillary fringe, whatever way one wishes to define it. With respect to the former, most workers have chosen to resort to numerical solutions of Richards' (1931) equation for unsaturated flow. Skaggs and Tang (1976), for example, analytically determined the position of the watertable as a function of time for a range of geometries and compared the results based on the Richards' equation with those obtained from Eq. (1), with and without a convergence correction, and with and without a capillary fringe; they derived a (variable) drainable pore space from the steady-state moisture characteristic. McWhorter and Duke (1976), on the other hand, chose to adapt the Glover equation by making a fairly involved correction for flow above the watertable and water storage in that zone, while retaining in part the non-linearity of the differential equation. In part, this was accomplished by replacing the factor $Kn/f$ in Eq. (2) by an analytically derived expression that takes account of the volumetric rate of drainage from the region between the soil surface and the
watertable as the watertable drops. Their procedure, as expected, results in a substantially faster rate of watertable drop than does use of the Glover equation. Even if the Glover equation is corrected by increasing the thickness of the aquifer by the estimated thickness of the capillary fringe, it still results in a somewhat slower rate of drop than determined from more rigorous procedures. This and similar studies are significant in that they provide an estimate of the magnitude of error introduced by the simpler analytical tools that ignore the flow above the watertable. They have a serious limitation, however, in that in principle they do not lend themselves to superposition. A further, and possibly more severe, limitation is that the soil parameters required are expensive to determine and may vary widely over short distances. On the other hand, since probabilistic - or dynamic equilibrium - evaluations generally will call for computer computation in any case, it is certainly possible to develop families of tabulated or plotted solutions for classes of situations that take into account all pertinent soil hydrologic variables.

Drainage criteria

From the foregoing brief discussion, I conclude that we have adequate analytical tools to describe the behavior of the watertable, or even the time course of the water content in the rootzone. Lacking is a sufficient data base to interpret such calculations in terms of the economic return from a drainage system. Wiser et al. (1974), for example, calculated the frequency of flooding for prescribed periods and related these results to published yield responses of alfalfa to make an economic analysis. As they pointed out, they had no basis for assessing damage due to watertable rises that did not reach the surface. Young and Ligon (1972) calculated how long watertables were expected to be above certain levels for given recurrence intervals, drain spacings and hydraulic conductivities at a location in South Carolina. They also related watertable height directly to soil water content. They left to the reader, however, the interpretation of these data in terms of crop response.

Possibly we tend to forget that the watertable, a convenient criterion for purposes of measurement and calculation, has no particular significance
when it comes to plant growth. Duke (1973), among others, explicitly proposed that drainage design be based on adequate aeration. He used the relationships between relative saturation, matric potential and hydraulic conductivity proposed by Brooks and Corey (1964), and assumed that the equivalent depth of a capillary fringe, \( w \), as calculated (Myers and van Bavel, 1963) from

\[
w = (1/K) \int K(z)dz
\]  

integrated from the watertable to the soil surface, could be used to estimate the zone in which gaseous diffusion was insufficient to maintain plant roots. The main point is simply that attempts have been made repeatedly to provide better indices for the effectiveness of a drainage system, but to my knowledge, these concepts have not yet been packaged to be of direct use to practising designers.

Under irrigated conditions, an important criterion for drainage design is the predicted salinity in the soil solution. It has been customary to express this criterion in terms of a leaching requirement (LR) which is derived by imposing on the leaching fraction (LF) the restriction that the soil solution leaving the rootzone cannot exceed a prescribed value. The LF simply states that, at steady-state, the mass of salts removed from the rootzone through drainage equals that brought in with the irrigation water (USSL Staff, 1954):

\[
LF = \frac{V_d}{V_i} = \frac{C_i}{C_d}
\]  

Here \( V \) and \( C \) stand for volume and concentration, and the subscripts \( i \) and \( d \) for irrigation and drainage water. The LR, then, becomes

\[
LR = \frac{V^*_d}{V^*_i} = \frac{C^*_i}{C^*_d}
\]  

where the asterisks distinguish the desired, or required, conditions from those actually encountered. To determine numerical values for \( V^*_d \), the USSL used to advocate somewhat arbitrarily that \( C^*_d \) could be taken equal to the concentration of the saturated soil extract at which a 50 per cent reduction
in crop yield was obtained in field experiments with artificially salinized waters that utilized high leaching fractions. Such experiments tend to result in uniform salinity throughout the rootzone.

More recently van Schilfgaarde et al. (1974) proposed that, although these recommendations were safe, they led to unnecessarily high LR's. Briefly, the reasoning is as follows: Under quasi-steady-state conditions, salinity profiles are not uniform; they tend to take on an S-shape, with the salinity near the surface about equal to that of the irrigation water, but increasing asymptotically to a maximum at the bottom of the rootzone. The plant root system is able to extract water from the soil solution with minimal ill effects until its concentration reaches a maximum peculiar to the crop. This maximum can be approximated from existing data on crop tolerance to salinity by extrapolation to 100 per cent yield reduction. Maas and Hoffman (1977) recently summarized many of the existing data in a table of coefficients A and B for the equation

$$Y = 100 - B(S_e - A)$$ (8)

where $Y$ represents relative crop yields and $S_e$ the electrical conductivity of the saturation extract in mmho/cm (1 mmho/cm = 0.1 S/m). Thus for $Y = 0$,

$$S_e^* = A + 100/B$$ (9)

and, with appropriate units, the value in Eq.(7) for $C_d^*$ (with concentrations expressed in electrical conductivity) would be $S_e^*$ adjusted from saturation extract to field water content ($S_w^*$). In the absence of specific data, this correction may be taken as

$$S_w^* = 2 S_e^*$$ (10)

Application of this concept will result in a reduction in LR from earlier recommendations by a factor of 3 to 4. It should be stressed that this concept is based on reasoning supported by limited data and requires further verification before it can be advocated with confidence. There is no question, however, that LR's can be reduced below those generally advocated.
A change in LR should translate directly into a change in drainage requirements. However, a number of other variables enter in before a drainage criterion can be established for design purposes. Among them is the need to distinguish between natural drainage rate and the additional drainage required through a man-made drainage facility—frequently a difficult task, especially in new lands to be developed for irrigation. Also important is the effect, mentioned before, of a change in cropping pattern. Here we call special attention, however, to the close interrelation between irrigation management and drainage need. Even if the above postulate on LR is proven fully justified, one must take account of both special and temporal variability, not to mention the farm operator. With infrequent irrigation, both the matric and osmotic components of water potential will fluctuate significantly during an irrigation cycle and the steady-state concepts outlined must be adjusted accordingly. With most irrigation systems, the areal uniformity of water intake deviates substantially from the ideal, and a leaching fraction that is barely adequate on the average will be inadequate on some part of the field. Thus drainage design must be seen as an integral part of the development of a total water management plan.

It does not follow that one should ignore the possibility of more efficient irrigation practices and consequent reduced drainage requirements. On the contrary, there are often good reasons, including the conservation of water and energy resources and the savings in costs, to design and operate systems to take full advantage of the potential.

Environmental considerations

Agricultural water management, while primarily concerned with on-farm conditions and crop production, clearly impacts the environment off-site. It must be viewed as an important component of total natural resource management. Only a few observations will be made here that relate directly to the subject matter of this conference.

The implications of the above discussion of LR and irrigation practices are often more significant in terms of downstream effects than for the farm operator. Extensive studies in the Colorado River Basin, for example, have
shown that the most cost effective approach to maintaining or improving water quality in terms of salinity downstream starts with the improvement of on-farm water management. Two processes are especially important. When the leaching fraction is reduced, independent of irrigation water quality, there is a shift from soil mineral dissolution to salt precipitation. Thus changes in drainage rates (i.e., irrigation practices) will affect the total amount of salt in solution that must be managed. Secondly, in some instances drainage waters displace saline groundwaters, thus adding disproportionally to the river's salt burden. Alternative choices for amelioration, such as desalting or disposal of drainage waters, carry heavy costs. Another type of situation is illustrated by the Central Valley in California. Since drainage water disposal out of this mountain-ringed basin would involve a tremendous capital investment even if it were socially acceptable, any method that reduces drainage volumes substantially without endangering crop production would pay high dividends; in this instance, evapotranspiration by plants is a viable alternative to exporting for disposing of a substantial part of the waste water.

Two brief illustrations put these considerations in perspective. The Wellton-Mohawk Irrigation and Drainage District in Arizona historically receives about $640 \times 10^6 \text{ m}^3/\text{yr}$ of irrigation water, delivered in open canals through a pump lift of about 55 m. This water is used to irrigate about 26,000 ha and results in some $270 \times 10^6 \text{ m}^3/\text{yr}$ of drainage water pumped from nearly 100 wells at an average salt concentration of above 3,000 mg/l. To meet an agreement with Mexico relative to the quality of water delivered, there were two extreme options: a desalting plant requiring $370 \times 10^6 \text{ kwhr/yr}$ that would spill about $50 \times 10^6 \text{ m}^3/\text{yr}$ of brine to the ocean, blending the remaining waters to the agreed concentration; or increased irrigation efficiency to technically feasible but extremely difficult to obtain levels, also spilling about $50 \times 10^6 \text{ m}^3/\text{yr}$ (one-fifth the current drainage volume) to the ocean. The implications are clear. The final solution is expected to be a combination of the two extremes.

In the Central Valley, we have proposed that drainage return flows be separated from irrigation water supplies and, in a concentration range of 0.5–0.9 S/m, be reused to irrigated tolerant crops. We speculate that after
this use, the new drainage waters might well still be used to produce biomass from halophytes that can be used to produce methane or other industrial products. The first step alone would substantially reduce the disposal problem. Alternatives include reductions in irrigated areas, selling the drainage water for industrial use such as cooling towers, or constructing a massive central drain outlet. This proposal should open up a wider range of options, and probably more acceptable ones, than the more direct implementation of greatly improved irrigation efficiencies.

Finally, there is an area of concern where drainage engineers and soil physicists can provide a useful service. As regulatory control over water resources increases, it becomes more important to show definitive relations between land and water management practices and drainage water quality. Failure to establish such relationships may well result in unwarranted restrictions. This challenge requires, as a starting point, that attention be given to flow paths and travel times, and not just potential distributions and gross discharge rates. Existing potential flow theory, in principle, can provide the needed answers. However, the otherwise useful approximations, such as the Dupuit-Forchheimer approach, cannot be used. Jury (1975) made a start in this direction and Raats (1977) expanded on this problem analysis.

Epilogue

Not much will be gained from further refinement of existing drainage theory or from development of new solutions to abstractly posed problems. The challenge ahead is to imaginatively apply the existing catalogue of tricks to the development of design procedures that are convenient and readily adapted by practicing engineers. This calls for better definition of drainage design criteria and, no doubt, expansion of the data base for crop response as well as trafficability. It will require expression of such criteria in terms of recurrence intervals. This, in turn, will be facilitated by the increasingly greater availability and capacity of computers. Thus the advantages van Schilfgaarde and others claimed in the past for closed analytical solutions have been (partly) dissipated.

Closely related is the need to consider drainage problems as part of a total water management scheme. The recent drought has emphasized that need
in The Netherlands; water quality concerns have driven it home in the Western USA. Challenging opportunities await us in devising means to better use our dwindling natural resources worldwide. Drainage specialists will play an important role in meeting these challenges, but only if they can put drainage in the proper perspective.

References


CONSTRUCTION AND MAINTENANCE TECHNIQUES FOR SUBSURFACE PIPE DRAINAGE SYSTEMS IN IRRIGATED LANDS

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Summary
Installation of subsurface drains in irrigated lands requires specialized trenching machines capable of excavating a suitable trench to depths of at least 3.7 meters. Trenching machines should also be capable of installing a designed, well-graded gravel envelope which will provide adequate permeability for convergence, prevent fines in the base material from moving into the envelope and drain line and provide the required bedding support for corrugated plastic drain tubing. One of the more complex problems in drainage of irrigated lands is establishing a stable drain trench when saturated, unstable soils are encountered. Stabilization of drain trenches can be accomplished by using a coarse gravel bedding, installing a system of well points, or installing a temporary dewatering drain below the grade of the permanent drain. Backfilling the trench after the drain tubing has been installed must follow some type of backfilling technique that will insure consolidated backfill to the original ground surface. After the drain has been completed the effectiveness and quality of installation should be evaluated by flushing or pulling a torpedoshaped plug having a diameter 1-inch less than the drain diameter through the drain in a manner that will not affect the installation or efficient functioning of the drain. A TV camera can be used after the drain is in place to observe obstructions, determine tubing deflection, and condition of the water inlet perforations. Periodic inspection and maintenance are essential for keeping the drains from plugging with roots and from bacteria. Cleaning equipment consists of high pressure jetting equipment and high speed auger type cutting heads. Copper sulfate can be used to kill roots and sulfur dioxide gas or safe sulfuric acid in pellet form can be used to reduce iron bacteria.

Introduction
Agricultural drains have been installed before man's recorded history (Maierhofer, 1967). Some ancient systems were simple, some were elaborate,
but few were entirely successful. Part of man's trouble with drainage systems has been due to lack of understanding of the physical and technical problems involved in designing and constructing the systems, and part has been due to neglect of the completed system. Drainage is not yet an exact system science and probably never will be, but as man learns more about the complicated plant-soil-water relationships and develops better subsurface drain design, construction, and maintenance techniques, drainage systems will become more economical, successful, and permanent.

A. CONSTRUCTION TECHNIQUES

Most of the existing literature on subsurface drainage covers the investigation, location, and design of these drainage systems, but there is only limited information about construction and maintenance techniques. After the designer is satisfied with the design of a drainage system, the design and construction requirements are turned over to the drainage contractor who has the responsibility of installing drains that control the watertable as the designer planned, have the minimum maintenance problems and last forever. Few people watching a smoothly operated drain installation realize that the drainage contractor must be a highly skilled, experienced person, who through his own mistakes or the mistakes of others has learned how to handle all types of problems from dealing with an irate farmer to installing drains in unstable material that perform as designed. As any drainage contractor knows, there will be a new problem as well as old problems every day so he has learned to "hope for the best, but expect the worst" each morning when he starts his equipment.

Equipment

Installation of subsurface drains in irrigated lands requires specialized trenching machines capable of digging to depths of at least 3.66 meters (12 feet). For drainage of irrigated lands economic drain depth ranges from 2.1 to 3.0 meters (7 to 10 feet; Christopher and Winger, 1975), so the designers will try to keep the average depth within this range. Trenchers that dig only to 2 meters (6.5 feet) cannot install satisfactory drains.
without removing the overburden soil down to within 2 meters of the bottom grade of the trench. For areas of high watertable, this amount of scalping will place the machine on unstable material and it will not be able to operate. Therefore, only the larger machines especially designed for deep drains are suitable for installing drains in irrigated lands. For general drain installation, where all types of soils and cementation problems are encountered, the so-called conventional trenchers will do satisfactory work. These consist of the ladder- and wheel-type trenchers capable of maximum sustained speeds in uncemented materials at depths of about 2.5 meters (8 feet) of about 122 to 150 meters per hour (400 to 500 feet per hour). For medium-to-heavily cemented materials the large wheel-type trencher performs the best. The teeth and sometimes the entire bucket on the ladder-type trencher will break off when boulders or a section of heavily cemented material are encountered. Both the ladder- and wheel-type trenchers will function fairly well in unstable soil as long as the surface will support the weight of the trencher and the trencher can be kept in motion. If either type of trencher stops in unstable material the unstable material caving against the shield can cause the drain pipe or tubing to be pushed out of alinement and grade. Prices for the larger type wheel- and ladder-type trenchers with a laser grade control system, shield, and gravel hopper but not continuous backfilling equipment, are in the range of $175,000 to $225,000.

The larger chain-type trenchers are capable of installation speeds of 180 to 250 meters per hour (600 to 800 feet per hour) at depths of about 2.5 meters (8 feet) in uncemented, friable material. However, any large rocks or cemented material will damage the fastmoving teeth and in most cases will break the chain. Also in unstable materials the chain-type trencher churns the supersaturated material to a consistency so that the digging teeth will not remove the material from the trench, and grade and alinement requirement cannot be maintained. Many contractors who install thousands of meters of plastic drain tubing annually in all types of material are equipped with both the large wheel-type and the large chain-type trenchers, and each machine is used where it functions the best and most economically. Some drain contractors build their own trenchers, usually starting from one of the commercial-type trenchers and adding the features they believe will assist them in installing better and more economical drains. This is an ex-
pensive project, but the contractor can sometimes develop a trencher that does function better than the commercial trenchers. However, there are probably more inventor contractors that go out of business because of debts than those that succeed.

There are a large number of plow-type machines that are operating throughout the world. These plow-type machines install the drain tubing without the necessity of excavating the material from the trench. Many are capable of high speeds, and can install pipe up to 2 meters (6.5 feet) deep. This type of machine performs satisfactorily only in the more sandy, lighter textured soils, free of rocks and cemented materials. In soils high in silt and clay with high moisture content the plow shoe will form an almost impermeable seal underneath the drain tubing. This type of machine installs an economical drainage system per meter of drain line but on a hectare basis the completed drainage system will cost about the same as conventional trenching machine installation, because the more shallow installation depth results in additional tubing and envelope material.

All drain-installing equipment must have a method of placing some type of envelope material around the drain. The designer will specify the type of envelope material required and the contractor must equip his machine to place the material. There is some disagreement on what materials should be used to surround the pipe or tubing, but research studies indicate that a designed, well-graded gravel envelope produces the most water, prevents fines in the base material from moving into the envelope and drain line and provides the required support for corrugated plastic drain tubing (Winger and Ryan, 1970). Synthetic envelope materials are being used where the source of gravel is limited and expensive. They are appropriately called "filter materials" because that is their sole function. When used in sand and gravel base materials with little or no silt or clay, the synthetic materials are satisfactory. However, when used in soils containing silts and clays they eventually develop a "filter-cake" which in time prevents the ground water from entering the pipe or tubing. Also, when synthetic materials are specified around plastic tubing the trenching machine should be equipped with buckets only a few inches wider than the outside diameter of the tubing and a shoe to form a properly shaped bed for the tubing so it will have adequate support.
When gravel envelopes are specified, the trencher must be equipped with a shield which includes a gravel hopper that is capable of providing a continuous flow of gravel around the tubing. For unstable soils that flow upward when the overburden pressure is removed, the gravel must be placed completely around the tubing or pipe before it leaves the protection of the shield. For all subsurface drains where a gravel envelope is used, the trenching equipment and the method employed in excavating the trench, laying the drain pipe and placing the gravel envelope material should be such that the in-place gravel is in contact with undisturbed soil at the sides and bottom of the trench.

When excavation at the bottom of the trench is in very unstable material, the trenching equipment should be capable of excavating to additional depths to provide for installing stabilizing material. The material used for stabilization should be hard, dense, and durable rock of sufficient size and gradation that it will establish a bedding for the gravel envelope material and drain pipe. Since the material cannot be run through the gravel hopper because of its size, it must be placed in the trench by a backhoe or frontend loader.

Besides the trenching and laying equipment, the contractor should have a backhoe or drag line to excavate and place the outlet pipe, excavate the trench when large boulders are encountered; install the pipe or tubing at road, lateral, and canal crossings; and set manholes. When the gravel is placed at convenient locations along the drain line the contractor will also need a front-end loader to move the gravel from the storage site to the machine. He can have his gravel hauled from the gravel pit to the site and dumped at convenient locations, or he can build special gravel trucks that use auger-type equipment to place the gravel directly into the gravel hopper. This procedure saves gravel, keeps out unwanted clay and silt, and permits the machine to continue without stopping to have the hopper filled. In unstable, swampy areas half-track trucks work very well for keeping the gravel hopper filled.

The drainage contractor should also have a bulldozer to backfill the trench, to scalp when required, and pull the trencher through unstable areas. A pick-up or extra truck is needed to distribute pipe and tubing, haul equipment, and move the crews.