Some Recent Research on Land Drainage

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It is agreed that a key requirement for the improvement or reclamation of saline and alkali soils is good drainage [1, 7, 12]. The purpose of my report is to present results of some recent soil physics research on drainage, done at my school, Iowa State University, Ames, Iowa, USA. This report might be considered a follow-up of the one I presented at the Sodic Soils Symposium, sponsored by UNESCO and by the International Soil Science Society, at Budapest, Hungary, Aug. 10—15, 1964 [6]. That symposium was directed by SZABOLCS, one of the co-leaders of the present symposium. The research I shall briefly report is: 1. removal of sodium salts by different methods of application of water, 2. drainage of stratified soils, 3. drainage of land underlain by an artesian aquifer, 4. improvements in the theory of the piezometer method for assessing soil drainability, and 5. depth of moisture penetration in soil due to irrigation water advancing over the soil surface.

1. Sodium salts removal by several different methods of application of water

a) Salt removal by the diffusion process alone

Several methods for removal of the salts, sodium chloride (NaCl), sodium bicarbonate ($NaHCO_3$), and sodium sulfate (Na_2SO_4) from soil have been tried in our laboratory [3]. A first experiment was done to see whether the diffusion process alone could remove much salt when fresh water is ponded on soil underlain by an impermeable stratum that prevents downward water movement. In our experiment we ponded distilled water to a depth of 15 cm on a layer of silt loam soil initially free of sodium salts. To this soil, after first air-drying it, we added a sodium salt at a rate of 5 grams of salt per 100 grams of dry silt loam. The soil-salt mixture was then packed to a depth of 25 cm in replicated plastic tubes of diameter 4 inches (10 cm). Each tube of a replicate contained only one of the three sodium salts. After the soil-salt mixture was packed, it was water-saturated for a week with distilled water to allow ionic interchange to occur. When the soil was water-saturated an additional 15 cm of ponding water was applied. Evaporation was prevented;

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drainage was also prevented; temperature was kept constant, 20 °C. To see how much salt diffused into the surface water, electrical conductivity measurements were made [12] of samples of the ponded surface water. These measurements were made once a week for 120 days.

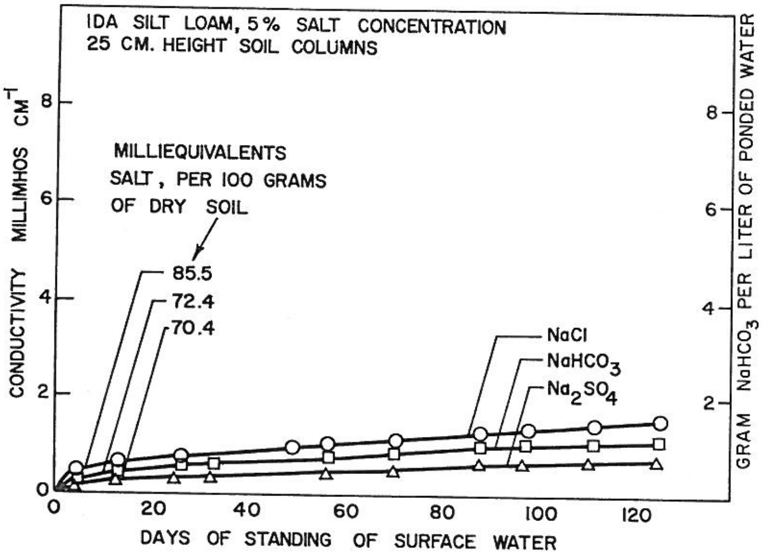
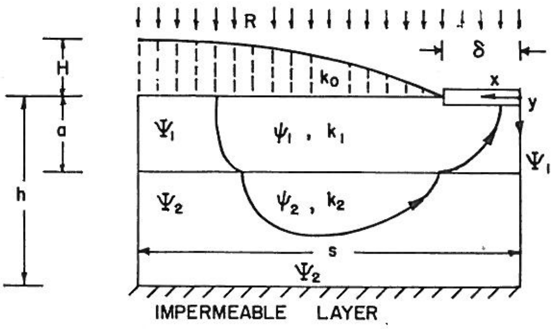


Fig. 1
Diffusion of salt in soil, into ponded water

Figure 1 shows how each of the three salts diffused into the ponded water. The numbers 85.5, 72.4 and 70.4 on the figure are the milliequivalents per 100 gm of air-dry soil for NaCl, $NaHCO_3$ and Na_2SO_4, respectively. We see that the amount of salt that diffused into the ponded surface water was in proportion to the milliequivalents of salt in the soil. From the electrical conductivity measurements we found that, after 120 days, less than 15 per cent of the salt in the soil, for any one of the salts, diffused into the water. Thus, we concluded that the process of salt diffusion alone into fresh water is relatively ineffective for removing sodium salt from this silt loam soil, and by inference from other soils.

b) Salt removal by intermittent leaching

When there is deep natural drainage and there has been no previous irrigation to build up a water table to approach the soil surface, one might expect that a large continuous application of one or even two meters of leaching water would do an efficient job of leaching. However, Amemiya, and others [1], and Wilson and others [14] have shown that intermittent leaching applications of small quantities of water are more efficient than large single applications. Nielsen, and others [9], showed that "leaching" in the unsaturated state was more efficient than leaching in the saturated state. Laboratory experiments we did [3] bear out the conclusion that several small applications of leaching water remove more salt from soil than one large application of the same total amount. This is evident from the following example: When $NaHCO_3$, initially at a concentration of 5 grams of salt per



BOUNDARY CONDITIONS :

1.	$\Psi_1 = \Psi_0$	$0 \leq y \leq a$,	$x = s$
2.	$\Psi_1 = \Psi_0$	$0 \leq y \leq a$,	$x = 0$
3.	$\Psi_1 = \frac{\delta - x}{\delta} \Psi_0$	$y = 0$,	$0 \leq x \leq \delta$
4.	$\Psi_1 = \frac{x - \delta}{s - \delta} \Psi_0$	$y = 0$,	$\delta \leq x \leq s$
5.	$\Phi_1 = \Phi_2$	$y = a$,	$0 < x < s$
6.	$k_1 \frac{\partial \Phi_1}{\partial y} = k_2 \frac{\partial \Phi_2}{\partial y}$	$y = a$,	$0 < x < s$
7.	$\Psi_2 = \Psi_0$	$a \leq y \leq h$,	$x = s$
8.	$\Psi_2 = \Psi_0$	$y = h$,	$0 \leq x \leq s$
9.	$\Psi_2 = \Psi_0$	$a \leq y \leq h$,	$x = 0$

Fig. 2
Geometry and boundary conditions for seepage into stratified soil

100 grams of a sand-soil in a vertical column 25 cm long and open to the atmosphere at the bottom, was leached by water, steadily applied at 10 cm of head, we found that 57.5 cm water were needed to reduce the salinity from 5 per cent to 0.28 per cent. On the other hand, for the same column, and for the same initial salt concentration, it took only 15.4 cm (1/3 to 1/4 as much) of water to reduce the salinity to the same 0.28 per cent level, when the water was applied intermittently in 14 applications, each of 1.1 cm height ($14 \times 1.1 = 15.4$). Further examples can be found in BAKR [3], where some new possible leaching methods, tested in the laboratory, are also presented.

2. Drainage of stratified soils

In many reclaimed arid irrigated areas, the water table approaches the soil surface after a certain time, and a drainage system is required. We have recently derived drain spacing formulas for stratified soils that is, for soils of layers of different hydraulic conductivities. The problem is represented for a two-layered soil in Figure 2.

In the figure excess irrigation water at an average rate R (mm per day, say) seeps downward along streamlines, one of which is shown, to a "strip

$$H=\frac{2Rs}{\pi k_1}\left\{\ell n\frac{1}{\sin\frac{\pi r}{2s}}+\Sigma\frac{1}{m}\left(\coth\frac{m\pi a}{s}-1\right)\left(\cos\frac{m\pi r}{s}-\cos m\pi\right)\left[1-\frac{e^{\frac{m\pi a}{s}}}{\sinh\frac{m\pi a}{s}}\cdot\frac{1}{\frac{k_1}{k_2}\coth\frac{m\pi(h-a)}{s}+\coth\frac{m\pi a}{s}}\right]\right\}A$$

$$A=\left[1-(R/k_o)\right]^{-1}$$

$$m=1,2,\cdots$$

Fig. 3

Drain spacing formula for stratified soil

drain" of width σ which is shown in the upper right of the figure. The strip drain is, analytically, shrunk to a line sink. Then, an equipotential surface about this line sink is identified with a drain tube of radius r, running half full.

Stream functions ψ_1 and ψ_2 and potential functions $\varnothing_1$ and $\varnothing_2$ arise in the problem for the layers of conductivity k_1 and k_2. A k_0 layer may be considered as suggested by WESSELING [13], if this "layer" is taken to be the soil in the water table arch. The boundary conditions needed to solve the problem are indicated in the figure. The formula for the drain spacing as finally derived for the layers of conductivity k_0, k_1 and k_2 is shown in Figure 3 [11]. This formula can be put in nomographic form for practical use, and TOKSÖZ [11] who has spent a number of years in land reclamation projects over the world, has prepared for me three examples from practical situations, to present here.

Figure 4 shows for $k_1 = k_0 = 1.2$ meters/day and for $k_2 = 0.6$ meters/day, and other parameters as shown, that the drain spacing $2s$ is given by $2s = 92.4$ meters.

Figure 5 shows a nomograph for the examples 2 and 3. Example 2 has the same parameters as the example 1 except that k_2 is equal to $2k_1$ instead of 0.5 k_1. By having k_2 equal to $2k_1$ instead of 0.5 k_1, the drain spacing becomes 156 meters instead of 92.4 meters. That is, quadrupling the conductivity of the lower layer has changed the spacing from 92.4 meters to 156 meters.

Example 3 has the same parameters as example 1 except that k_1 is now equal to 0.5 k_2. This change in k_1 results in a drain spacing of 43.2 meters rather than the 92.4 meters of example 1.

The nomographs may also be used for ditch drain spacings. The H of

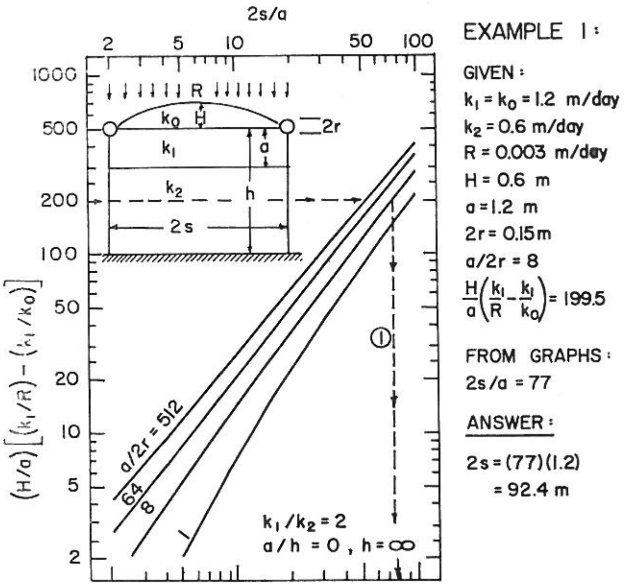


Fig. 4

Nomograph of drain spacing formula, example 1 (TOKSÖZ, [11])

Figure 2 is then measured from the level of the water in the ditch and the width of the ditch is taken equal to $2r$.

3. Drainage of land underlain by an artesian aquifer

We have seen that an impervious soil layer prevents downward leaching of salts. Downward leaching can also be prevented by upward seeping water due to artesian pressure. We have studied this artesian problem and I will show three of our recently published flow nets [5].

Figure 6 is a flow net for steady rain water and artesian water seeping into a drain tube. In arid regions the rainfall rate R would be the average application rate of excess irrigation water. A piezometer at the right of the figure measures the water pressure in the aquifer. This piezometer water level gives the height the water would stand without drainage and if there is no

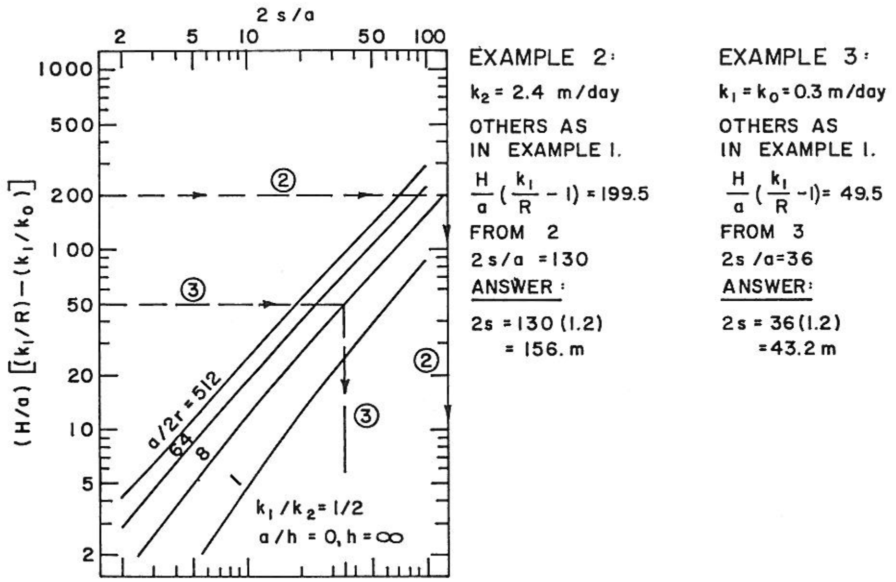


Fig. 5

Nomograph of drain spacing formula, examples 2 and 3 (TOKSÖZ [11])

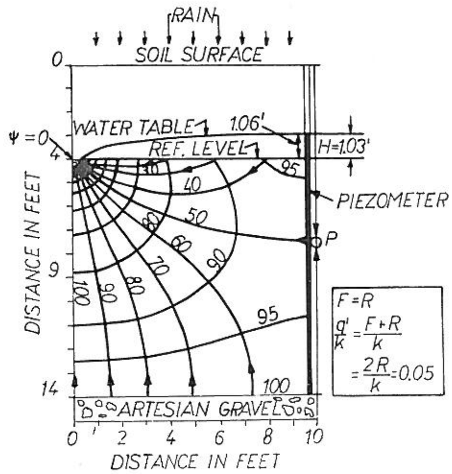


Fig. 6

Flow net for rain and artesian water seeping into a drain tube

excess irrigation water, that is, if we have R = 0. With R greater than zero (R > 0) the soil water table will stand higher than the piezometer water level.

Figure 7 shows a flow net for $R = 0$.

Figure 8 shows a flow net for a submerged drain tube located 8 feet below the soil surface and for an artesian pressure head that almost reaches the surface. For a large piezometric pressure as shown in the figure, the drain tubes must be very close together to keep the soil water table low. The soil water table could also be kept low, and at less expense, by relieving the artesian pressure by the pumping of wells sunk into the aquifer.

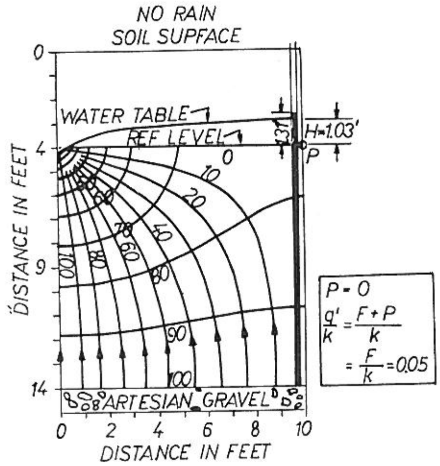


Fig. 7
Flow net for zero rainfall

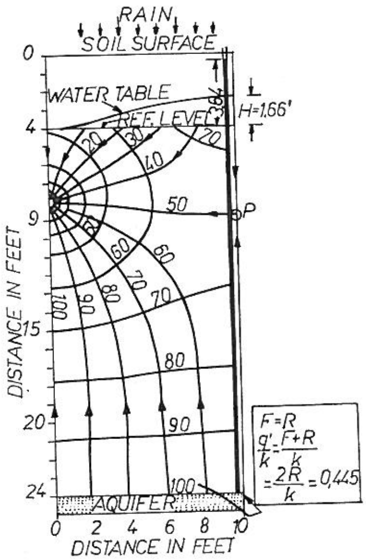


Fig. 8
Flow net for a submerged drain tube

4. Improvements in the theory of the piezometer method for assessing soil drainability

In the piezometer method for measuring hydraulic conductivity (see [8]) one augers out a cavity below the base of a vertical tube sunk into the soil below the water table. The rate of rise of ground water in the tube is observed and is converted to hydraulic conductivity by means of a shape factor S occurring in a ratio S/a where a is the radius of the piezometer tube.

In the piezometer method, the geometrical factor S/a was originally determined by use of electrical analogs. Recently, SMILES and YOUNGS [10] used the piezometer method in a soil anisotropy problem where they needed accurate values of the geometrical factor S/a. YOUNGS [15], also using electric analogs, found that some of LUTHIN's earlier shape factors S differed by several per cent from his (YOUNG's) analog values. To determine which values were correct we have derived theoretical formulas for S/a [4]. These formulas do not depend on electric analog experiments. We obtained the solution for S/a as an infinite series. The series converges fairly rapidly. So far, we have used 70 terms of the infinite series to approximate its value.

Figure 9 shows at the left a theoretically computed flow net for the piezometer problem. At the right of the figure the geometrical shape factor S/a is plotted against 1/N where N is the number of terms used in the theoretical infinite series. Experimental values of S/a as obtained by YOUNGS and LUTHIN are shown on the "y" axis of the graph corresponding to N = ∞. We see that YOUNGS' value is even more accurate than LUTHIN's. We checked a number of other values of the extensive tables of YOUNGS [15] and found that his

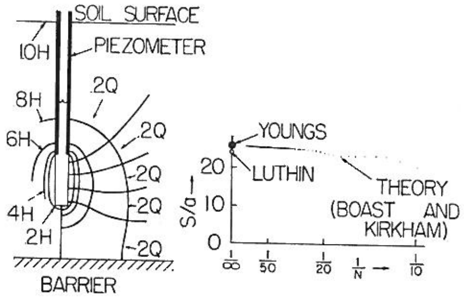


Fig. 9
Flow net (left) and S/a values (right) of piezometer method

values agreed with the theory. YOUNGS' tables are a valuable addition to the piezometer method.

The theory used in the last paragraph for testing the work of LUTHIN and YOUNGS was not simple. Figure 10 shows the geometry of the problem. An expression had to be found for the hydraulic head ∅ at all points in the soil water flowing into the piezometer cavity; and this expression had to satisfy the boundary conditions, namely, the hydraulic heads and velocities

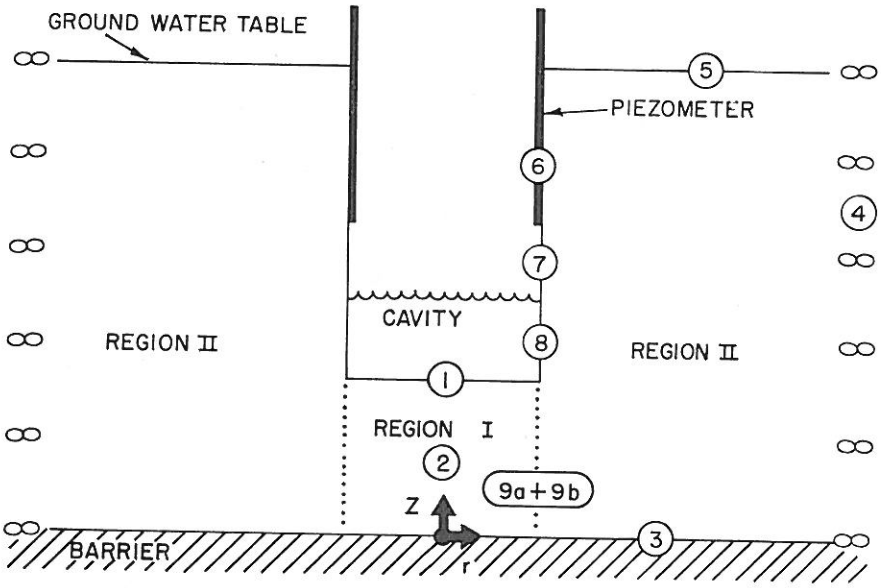


Fig. 10
Geometry for analyzing the piezometer problem

on the boundaries of the flow region. To get the expression for the hydraulic head Ø, we divided the flow region into two regions, region I and region II. There are 10 boundary conditions if we count 9a and 9b separately.

We cannot discuss all the boundary conditions. However, Figure 11 shows how we dealt with boundary conditions 6, 7, 8 and 9. Each of these

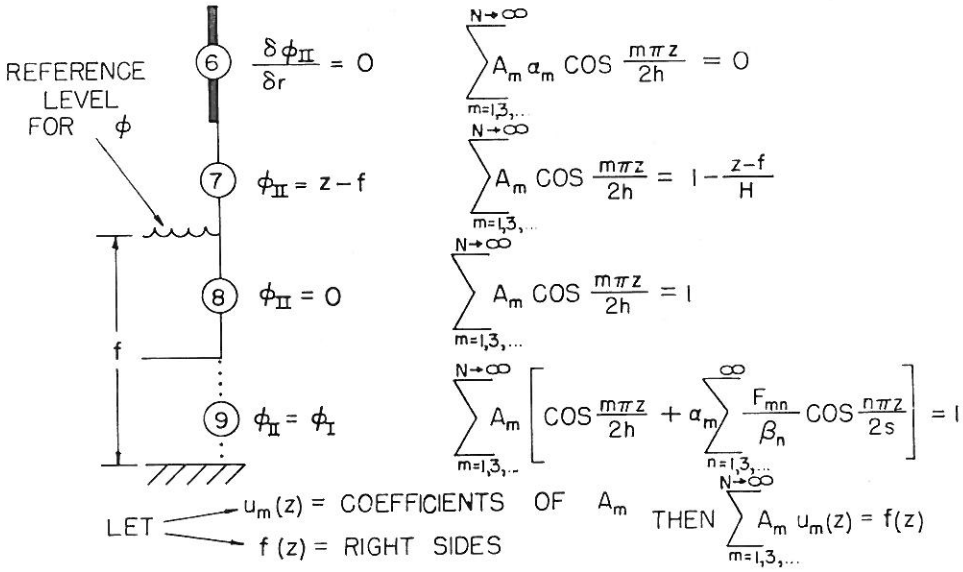


Fig. 11

Equations of boundary conditions 6, 7, 8 and 9, of the piezometer problem

conditions gives rise to an equation shown at the right. For definition of all the symbols we refer to BOAST and KIRKHAM [4]. The key to the solution of the problem consisted of learning how to compress the four equations into a single equation shown at the bottom right, and in learning how to compute the constant A_m shown there. We did learn how to compute these constants and they were used as we saw in Figure 9 in testing the values of the shape factors S/a of LUTHIN and YOUNGS for the piezometer method of assessing soil drainability.

5. Depth of moisture penetration in soil due to irrigation water advancing over the soil surface

Finally, I shall speak about the depth of vertical penetration of irrigation water when an irrigation stream advances over the soil surface. We see that this topic is related to drainage, when we recognize that salts will not leach below the depth of water penetration.

Figure 12 [2] illustrates the water penetration problem. The symbol C represents the average depth of irrigation water for a distance of advance x from the flooding origin 0. At a point D, a distance s from 0, the water will penetrate a distance y/f (f is the porosity) which is obtained from the theory, as is also the distance x.

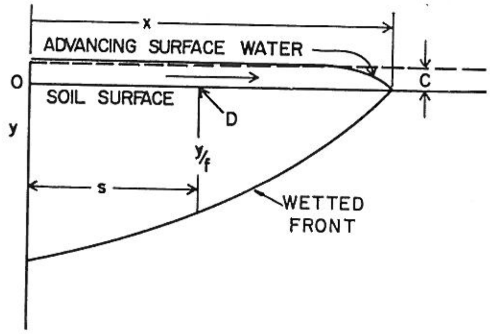


Fig. 12

Depth of wetted front in the soil due to advancing surface irrigation water

Figure 13 gives the theoretical (eq. 62 of ASSEED and KIRKHAM) and experimental advance of the wetted front for a Webster silt loam soil. The soil is contained in a laboratory test model, 203 cm long. The experimental points

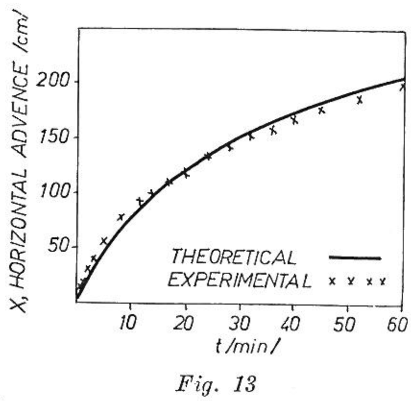


Fig. 13

Advance of surface irrigation water, theoretical and experimental. Webster soil $y = At^{1/2} + Bt$; $A = 0.48$ (cm) (min)$^{-1/2}$; $B = 0.034$ (cm) (min)$^{-1/2}$; $C = 1.1$ cm; $Q = 35$ cm^3/min; $L = 1.9$ cm; $q = Q/L = 18.42$ cm^2/min. No surface roughness; $S = 0\%$

show good agreement with the theory. To apply the theory to the field, we have supplied sixty curves and examples [2].

Some other of our recent studies pertinent to this conference, but not cited above, are listed at the end of this report. Reprints may be obtained from me or my University, upon request.

Summary

Some recent theoretical and laboratory research at Iowa State University, Ames, Iowa, USA is reported under the headings: 1. removal of sodium salts from soil by different methods of application of water, 2. drainage of stratified soils, 3. drainage of land underlain by an artesian aquifer, 4. improvements in the theory of the piezometer method for assessing soil drainability, and 5. depth of moisture penetration in soil due to irrigation water advancing over the soil surface. Some studies not included under these headings are referred to in a literature list separate from that of the five subjects.

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