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Predicted and Measured Drainable Porosities for Field Soils

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ABSTRACT

EXPERIMENTS were conducted on large field cores to determine the relationship between drainage volume and water table depth for five soils. The measured drainage volumes were less than predicted from the soil water characteristics for three soils, but were in good agreement for the other two. Drainable porosities were calculated from both theoretical and experimental drainage volume-water table depth relationships by assuming that the unsaturated zone is essentially 'drained to equilibrium' with the water table. The experimental drainable porosities thus obtained were less than predicted.

Drainable porosities for drainage in two-dimensions were calculated from experimental results for one-dimension by assuming an elliptical water table profile. These results gave nearly constant drainable porosities for the layered soils and a variable drainable porosity for Wagram, a homogeneous, sandy soil.

INTRODUCTION

The drainable porosity or specific yield is one of the basic input parameters in conventional methods for predicting water table drawdown. Drainable porosity is usually defined as the volume of water per unit area that is released when the water table falls by a unit distance. In drainage design it is conventionally assumed to be constant and treated as a soil property. Childs (1960) and Taylor (1960) have shown that drainable porosity is not constant but depends on water table depth as well as other factors. Duke (1972) presented a closed form expression for specific yield in terms of water table depth and the parameters in Brooks' and Corey's (1964) relationship for the soil water characteristic. An equivalent drainable porosity can be obtained by continuous measurement of water table depth and drain outflow as suggested by Taylor (1960) and used by Hoffman and Schwab (1964). Methods were recently presented (Skaggs, 1976) for determining the hydraulic conductivity — drainable porosity ratio from water table drawdown measurements. However, outflow measurements needed for an independent determination of drainable porosity are relatively difficult, and it is usually more convenient to calculate this property from the soil water characteristic by methods such as those used by French and O'Callaghan (1966) and Duke (1972).

The purpose of this paper is to compare drainage volumes and drainable porosities measured for vertical drainage in large undisturbed soil cores with values predicted from the soil water characteristics. The measured relationships between drainage volume and water table depth are then used to predict outflow volumes and effective drainable porosities for two-dimensional water table drawdown to parallel drains.

PREDICTION METHODS

The concept of drainable porosity or specific yield has been discussed in two recent works which have resulted in several methods of defining the property. Dos Santos and Youngs (1969) defined the specific yield in terms of the fluxes across the soil surface and the water table, and the time rate of change of the water table height. They considered the effects of rainfall and evaporation and defined bulk and virtual specific yields which could be determined from drain outflow and water table measurements. Raats and Gardner (1974) defined global specific yield as the ratio of the time rate of change of the total volume of water in the profile to the time rate of change of the volume below the water table. To evaluate the drainable porosity by this definition requires knowledge of the water table position and the soil water content distribution above the water table or the distribution of the fluxes at the boundaries.

The drainable porosity was calculated herein by assuming that the water table recedes slowly such that the vertical hydraulic gradient above the water table is zero and the unsaturated zone is essentially 'drained to equilibrium' with the water table at all times. That is, it is assumed that the water content distribution at any time is the same as that which would result if the water table was stationary at a given position and the profile drained to equilibrium. Then for one-dimensional (vertical) flow, the volume drained per unit area, V_d, when the water table drops from the surface to depth y_1, may be expressed as,

$$V_d = \int_0^{y_1} (\Theta_o(y) - \Theta(y))\, dy, \quad \ldots\ldots\ldots\ldots \quad [1]$$

where $\Theta_o(y)$ is the soil water content prior to drainage, usually assumed to be constant and equal to the total porosity, and $\Theta(y)$ is the equilibrium water content

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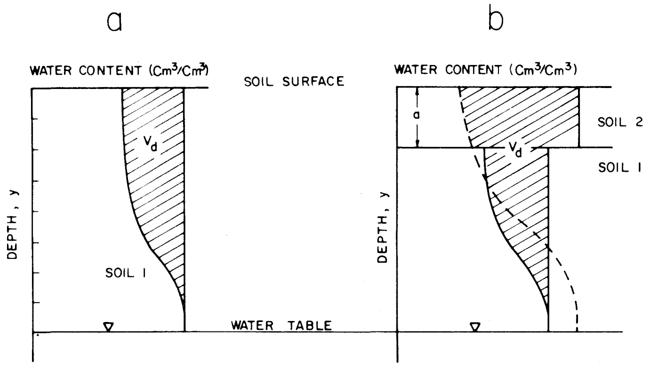

FIG. 1 Soil water distribution for a uniform soil [a] and a layered soil [b] drained to equilibrium to a water table. The broken curve in [b] represents the soil water distribution for a uniform soil 2.

distribution which is obtained from the soil water characteristic for a water table depth of y_1. The water content distribution and V_d are shown schematically in Fig. 1a for a uniform soil.

The drainable porosity, f, may be determined at depth y_1 by considering a drop in the water table of Δy,

$$f(y_1) = \frac{V_d(y_1 + \Delta y) - V_d(y_1)}{\Delta y} \qquad [2]$$

Therefore f(y) can be graphically calculated for the one-dimensional case by plotting V_d versus y and determining the slope at the desired depth. For a constant Θ_o and a 'drained to equilibrium' zone above the water table, the shape of the soil water profile is preserved. Raats and Gardner (1974) showed that, for profile preserving flows, $f = \Theta_o - \Theta_s$, where Θ_s is the water content at the surface ($y = 0$). In field situations Θ_o is probably less than the saturated water content because of air entrapped when the water table rises.

For layered profiles Θ_o and $\Theta(y)$ are obtained from the soil water characteristics for the respective layers; the drained volume for a layered profile is schematically shown in Fig. 1b. If the V_d versus y relationships of the soils in the top layer, $V_{d_2}(y)$, and in the bottom layer, $V_{d_1}(y)$, are first determined from the soil water characteristics, V_d can be easily computed for the layered soil as follows. For water table depths less than the depth, a, of the top layer,

$$V_d(y) = V_{d_2}(y) \qquad [3]$$

For greater depths,

$$V_d(y) = V_{d_2}(y) - V_{d_2}(y-a) + V_{d_1}(y-a) \qquad [4]$$

When the soil is layered the slope of the V_d versus y relationship, and thus the drainable porosity, will be discontinuous at the depth of the layer interface and equation [2] will not be valid at that point. However f can be defined for all the other depths as discussed above.

For drainage in two-dimensions, depth to the water table and the soil water distribution above the water table vary with the horizontal distance, x, from the drain (Fig. 2). If the water table falls from the surface to a known position $y = y(x)$ the average depth (volume per unit area) of drainage water leaving the profile may be expressed as,

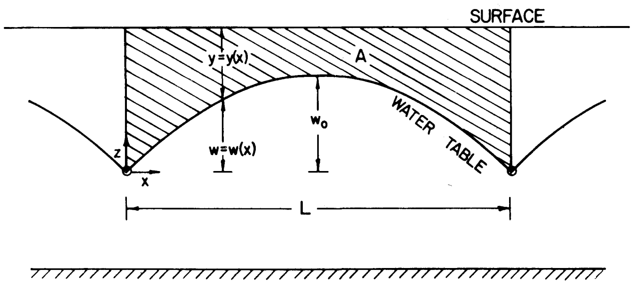

FIG. 2 Schematic showing the water table shape during drainage.

$$\overline{V}_d = \frac{1}{L} \int_A (\Theta_o - \Theta(x,z))dA, \qquad [5]$$

and the average depth of the water table by the equation,

$$\overline{y} = \frac{1}{L} \int_{x=o}^{L} y(x)\, dx, \qquad [6]$$

where L is the distance between drains, A is the cross-sectional area between the water table and the soil surface from $x = 0$ to $x = L$ (Fig. 2) and $\Theta(x,z)$ is the soil water content at position (x,z). The drainable porosity for the two-dimensional case may then be defined as,

$$f = \frac{d\,\overline{V}_d}{d\overline{y}}, \qquad [7]$$

which may also be written,

$$f = \frac{d\overline{V}_d/dt}{d\overline{y}/dt}, \qquad [8]$$

where t is time. Since we have assumed that the unsaturated zone is always drained to equilibrium with the water table, equation 8 may be interpreted as the ratio of the time rate of change of the air volume above the water table to the time rate of change of the soil volume above the water table (i.e., the rate of change of the unsaturated soil volume) and is equal to the global specific yield defined by Raats and Gardner (1974).

In order to approximate the effect of the horizontal variation of water table depth during drainage porosity, one may assume the water table to have an elliptical shape given by,

$$w^2 = 4\, w_o^2\, (x/L - (x/L)^2 \qquad [9]$$

where w is the height of the water table above the drain, w_o is the water table height at a point mid-

TABLE 1. PHYSICAL PROPERTIES OF THE SOIL CORES.

Soil type	Number of cores	Total core length	Depth		Bulk density	
			Plow layer	Subsoil	Plow layer	Subsoil
Cape Fear l.	2	0.80 m	0 - 0.30 m	0.30 - 0.80 m	1.42 g/cm^3	1.45 g/cm^3
Goldsboro s.l.	2	1.05	0 - 0.25	0.25 - 1.05	1.65	1.70
Portsmouth s.l.	1	1.00	0 - 0.25	0.25 - 1.00	1.55	1.60
Rains s.l.	2	1.15	0 - 0.25	0.25 - 1.15	1.64	1.71
Wagram l.s.	3	0.84 Uniform over total length			1.48	1.48

way between the drains, and x is the horizontal distance from the drain. Assuming a 'drained to equilibrium' profile, the pressure head at each point is known and the water content, $\Theta(x,z)$, can be obtained from the soil water characteristic for any midpoint water table elevation, w_o. Then the amount drained from the profile, V_d, for a given w_o can be obtained from equation [5] by numerical intergration.

An alternative method for determining $\overline{V}_d$ makes use of the $V_d(y)$ relationship obtained for vertical drainage from equations [3] and [4] from experimental measurements that will be discussed in the next section. For a given midpoint water table elevation, w_o, the water table depth at specified x/L increments (e.g. x/L = 0.0, 0.1, 0.2, ..., 1) can be determined from equation [9]. The air volume or volume drained at each x/L position can be obtained from the $V_d(y)$ relationship for one-dimensional drainage. Then the average depth of water drained from the two-dimensional profile, $\overline{V}_d$, can be easily calculated from the equation,

$$\overline{V}_d = \sum_{i=1}^{N} \frac{(V_d(y_i) + V_d(y_{i-1}))}{2} (\frac{\Delta x}{L}) \quad \ldots\ldots\ldots\ldots\ldots\ldots [10]$$

Where N is the number of increments from x/L = 0 to x/L = 1 and y_i is the water table depth at each x/L position. The average water table depth, $\overline{y}$, for a given midpoint water table elevation, w_o, can also be calculated numerically from equation [6]. Then drainable porosity for two-dimensional drainage can be determined by plotting $\overline{V}_d$ versus $\overline{y}$ and taking the slope of the $\overline{V}_d(\overline{y})$ relationship (equation [7]).

EXPERIMENTAL METHODS

Experiments were conducted to determine the drainable porosity of five soils and the results compared to calculated values obtained from the soil water characteristics. Large undisturbed soil cores 0.51 m in diameter and approximately 1 m long were collected from five mineral soils. The cores were obtained by forcing empty 16 gauge metal cylinders into the soil with an anchored hydraulic jack arrangement. The cores were brought into the laboratory and sealed to metal bases filled with coarse gravel. The soil type, core length, and some of the physical properties of each of the soils are given in Table 1. The results of water movement studies on cores of the Wagram soil were previously reported by the authors (Wells and Skaggs, 1976).

Prior to initiating the experiments, the water table was raised to the soil surface and then drained to a position near the bottom of the core. Then the water table was again brought to the surface by raising a constant head (Mariotte type) reservoir connected to the core base. The reservoir remained in a place until inflow had ceased, a procedure which required approximately 1 to 2 days. The top of the core was covered to prevent evaporation and the test was initiated by lowering the constant head reservoir to a depth of 0.1 m. The reservoir was held at that elevation until drainage ceased; the drainage volume was measured; and the reservoir lowered to the next 0.1-m increment. This procedure was repeated until the water table reached the bottom of the core and resulted in an experimental relationship between the volume of water drained and water table depth. Drainage was assumed to have ceased when the total drainage in a 24 h period was less than 1 cm^3. For the 0.51 m diameter columns, this corresponds to a depth of 0.005 mm. Tensiometers were installed in the Wagram columns at vertical increments of 0.10 m. Drainage was assumed to have ceased in this soil when the maximum difference in hydraulic head above the water table was less than 5 mm of water.

The soil water characteristic was determined for both the plow layer and the subsoil of each soil. Small undisturbed soil samples were collected from depths of 0.15 and 0.5 m in the immediate vicinity of each core site. The samples were saturated by soaking for at least 48 h and the drainage branch of the soil water characteristic determined by the pressure plate methods described by Richards (1965). Triplicate samples were used for each determination.

RESULTS AND DISCUSSION

Vertical Drainage

Soil water characteristics for the two layers of Rains soil and for the Wagram soil are plotted in Fig. 3. The

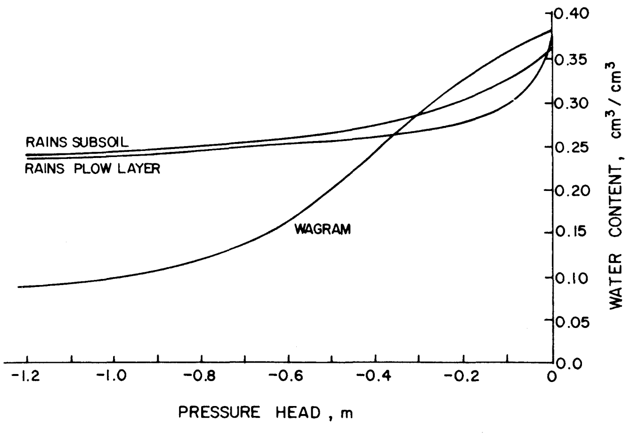

FIG. 3 Soil water characteristics for the two layers of Rains sandy loam and for Wagram loamy sand.

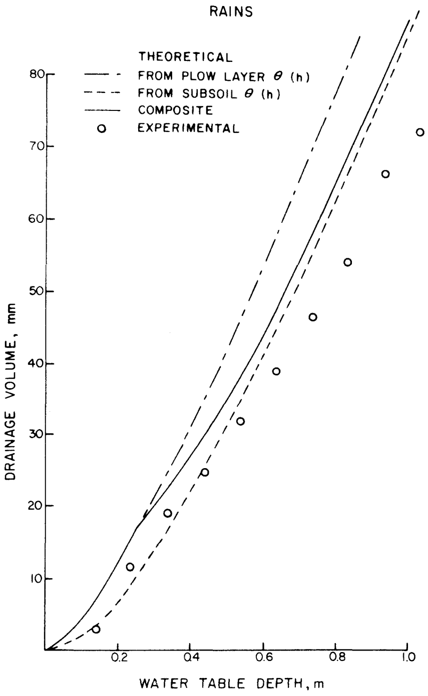

FIG. 4 Measured and predicted drainage volumes for vertical drainage in Rains sandy loam.

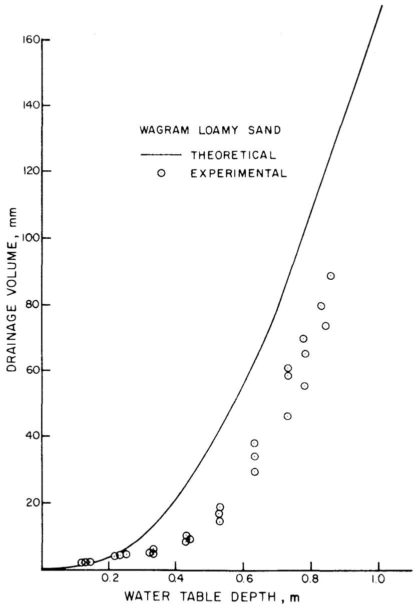

FIG. 5 Measured and predicted drainage volumes for vertical drainage in Wagram loamy sand.

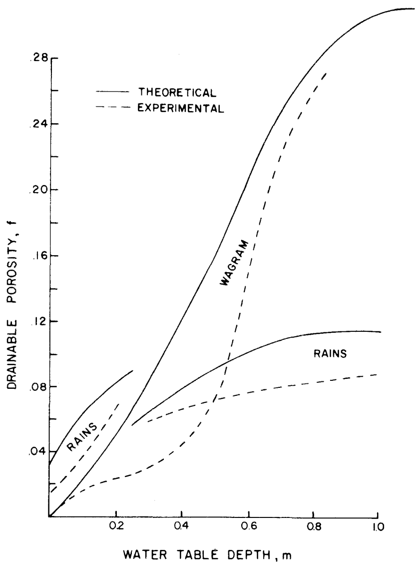

FIG. 6 Measured and predicted drainable porosities for vertical drainage of Wagram and Rains soils.

saturated water contents for Rains were 0.370 and 0.365 for the surface and subsoil layers respectively. Theoretical drainage volume-water table depth relationships are plotted in Fig. 4 for homogeneous soils made up of each layer of the Rains soil and for the two-layered composite. As noted earlier, the slope of this relationship is equal to the drainable porosity for one-dimensional drainage in the vertical direction and is discontinuous at the layer interface. Experimental values for the drainage volume at various water table depths are plotted as discrete points in Fig. 4. The predicted drainage volume was about 30 percent higher than measured for all water table depths.

Theoretical and measured drainage volume — water table depth relationships are plotted in Fig. 5 for the single-layered Wagram soil. Although the measured and predicted volumes were about the same for depths less than 0.20 m, predicted volumes were considerably higher for water table depths greater than 0.3 m.

Theoretical and measured drainage volumes are tabulated for all five soils in Table 2. Although there was good agreement between the measured and predicted relationships for the Cape Fear and Portsmouth soils, predicted drainage volumes were greater than measured for the Wagram and Rains soils as discussed above and for the Goldsboro soil for water table depths greater than 0.5 m. The difference for the Goldsboro soil could have been due to an increase in the bulk density and a corresponding change in the soil water characteristic with depth. However this could not explain the differences for the Wagram and Rains soils which had nearly uniform subsoils. The differences in measured and predicted volumes for these soils is attributed to the entrapment of air during rise of the water table prior to the initiation of drainage. Air entrapment for transient water table rise experiments was previously discussed by the authors (Wells and Skaggs, 1976). While the amount of air trapped is probably dependent on the initial and boundary conditions under which water moves into the profile, soils will rarely be completely saturated in field situations. However the samples used to determine the soil water characteristic were small (approximately 40 mm dia. x 10 mm deep) and,

TABLE 2. MEASURED AND PREDICTED( ) DRAINAGE VOLUMES FOR VERTICAL DRAINAGE IN LARGE SOIL CORES.

	Drainage volume in mm (mm^3/mm^2)				
			Soil		
Water table depth	Cape Fear	Goldsboro	Portsmouth	Rains	Wagram
0	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
0.1 m	4.3 (3.5)	1.6 (0.8)	2.0 (1.3)	2.2 (4.5)	1.8 (1.4)
0.2	9.5 (8.5)	4.5 (2.5)	5.5 (4.5)	8.0 (13)	4.0 (4.0)
0.3	18 (15)	8.0 (5.7)	10 (7.0)	17 (20)	5.0 (10)
0.4	24 (21)	12 (11)	14 (12)	23 (27)	8.2 (21)
0.5	27 (28)	17 (18)	18 (17)	30 (35)	15 (38)
0.6	33 (33)	22 (26)	23 (23)	37 (44)	28 (56)
0.7	39 (40)	28 (36)	28 (29)	44 (54)	50 (79)
0.8	45 (46)	34 (45)	33 (36)	52 (60)	71 (106)
0.9	— (51)	39 (56)	39 (43)	60 (77)	— (136)
1.0	— (59)	43 (66)	45 (51)	60 (94)	— (167)

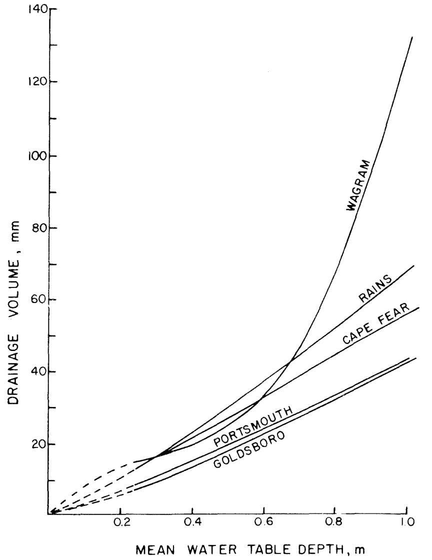

FIG. 7 Mean drainage volume vs. mean water table depth for an elliptical water table profile and a 1 m drain depth.

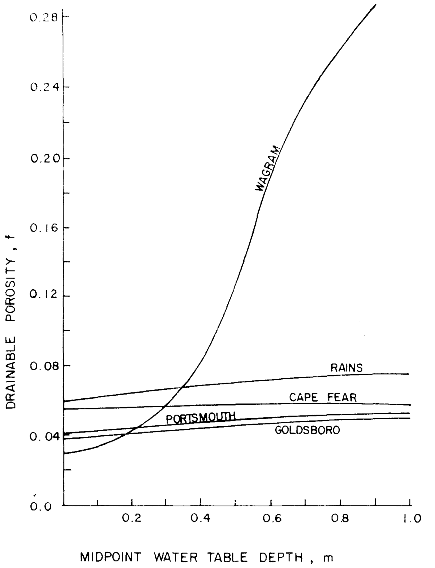

FIG. 8 Drainable porosities for two-dimensional flow assuming an elliptical water table profile and a 1 m drain depth.

under standard procedures, care is taken to insure that the samples are initially saturated. Probably better results can be obtained by using relatively large samples for the determination of the soil water characteristic. Furthermore, the samples should not be saturated under suction but wetted at a relatively rapid rate. Under these procedures, air will be entrapped and the resulting soil-water characteristic will be more representative of natural conditions than if procedures designed to insure saturation of the samples are used.

Predicted and measured drainable porosities were obtained for vertical drainage by graphically determining the slopes of the drainage volume-water table depth relationships. Drainable porosities are plotted in Fig. 6 for the Wagram and Rains soils and are tabulated for various water table depths in Table 3 for all 5 soils tested. As expected from the V_d relationships, the predicted f values are higher than measured at nearly all water table depths. For the homogeneous Wagram soil, the predicted value ranges from 0.0 when the water table is at the surface to a nearly constant value of 0.31 for a water table depth of 1 m. Unfortunately the Wagram cores were not long enough to determine experimental f values for depths greater than 0.8 m. Note that the measured drainable porosity was always less than predicted although there was fair agreement for water table depths greater than 0.6 m.

As noted earlier the theoretical drainable porosity for the Rains soil is discontinuous at the plow layer-subsoil interface. Experimental values also indicate a discontinuity, but because of the nature of the measurements, the location of the discontinuity was not precisely defined. A smooth curve drawn through the experimental data indicates a reduction of drainable porosity from 0.068 at a water table depth of 0.2 m to 0.060 at 0.3 m. Again the experimental values were less than predicted for all water table depths on this soil. It is interesting that drainable porosity (both measured and predicted) for vertical drainage is much less dependent on water table depth for Rains than for Wagram (Fig. 6). In fact, the dependence of f on water table depth was small for depths greater than about 0.4 m in all soils tested except Wagram (cf. measured values, Table 3). This is apparently due to the fact that the loam and sandy loam soils are well aggregated with some large pores, worm holes, etc., that drain at relatively low suctions as shown in Fig. 3 for both layers of Rains. Once these large pores are drained, the soil water content changes slowly with pressure head and the drainable porosity is almost constant with water table depth. In contrast, the Wagram loamy sand

TABLE 3. MEASURED AND PREDICTED( ) DRAINABLE POROSITIES FOR VERTICAL DRAINAGE IN LARGE SOIL CORES.

Water table Depth	Cape Fear	Goldsboro	Portsmouth	Rains	Wagram
0 m	0.035 (0.030)	0.01 (0.0005)	0.015 (0.01)	0.014 (0.030)	0.000 (0.0)
0.1	0.052 (0.046)	0.022 (0.015)	0.025 (0.02)	0.036 (0.064)	0.02 (0.02)
0.2	0.06 (0.09)	0.030 (0.026)	0.040 (0.04)	0.068 (0.083)	0.024 (0.05)
0.3	0.076 (*)	0.040 (0.045)	0.040 (0.03)	0.060 (0.065)	0.028 (0.084)
0.4	0.055 (0.04)	0.04 (0.065)	0.045 (0.045)	0.066 (0.080)	0.040 (0.140)
0.5	0.04 (0.06)	0.055 (0.075)	0.050 (0.06)	0.072 (0.092)	0.092 (0.172)
0.6	0.055 (0.062)	0.055 (0.090)	0.050 (0.065)	0.076 (0.102)	0.154 (0.210)
0.7	0.058 (0.062)	0.055 (0.100)	0.052 (0.065)	0.080 (0.110)	0.240 (0.250)
0.8	0.062 (0.062)	0.050 (0.100)	0.054 (0.07)	0.084 (0.115)	0.260 (0.300)
0.9	— (0.063)	0.045 (0.100)	0.057 (0.07)	0.086 (0.115)	— (0.31)
1.0	— (0.063)	0.045 (0.100)	0.058 (0.07)	0.088 (0.115)	— (0.31)

*Not defined because $V_d(y)$ function discontinuous at layer interface.

has a single grain structure with few large pores. It has a 'typical' soil water characteristic (Fig. 3) in which the water content changes rather rapidly and in a nonlinear fashion for pressure heads greater than about - 1.0 m. Thus the drainable porosity is very dependent on water table depth.

Two-Dimensional Drainage

Plots of the drainage volume, $\overline{V}_d$, versus the mean water table depth, $\overline{y}$, for the elliptical profile described by equation [9] are given in Fig. 7 for all five soils. The volumes were computed numerically by assuming a drain depth of 1 m and a 'drained to equilibrium' condition above the water table. The volume drained for a given water table depth, $\overline{V}_d$, was obtained from equation [10] by determining the position of the water table at horizontal increments of $\Delta x/L = 0.1$ from equation [9] and the volume drained from the experimental relationships given in Figs. 4 and 5 and Table 2.

This general shape of the volume-depth relationship for Wagram is as expected and results in a drainable porosity which is variable with water table depth (Fig. 8). However, results for the other four soils are somewhat surprising. The relationships for drainage volume versus mean water table depth plotted in Fig. 7 are nearly linear and the resulting drainable porosities (Fig. 8) are almost constant. This is in contrast to the f values for vertical drainage (Table 3) which show considerable variation with depth for small water table depths. Keep in mind, however, that we have assumed an elliptical profile shape, so even when the midpoint depth is small, the water table depth at the drains ($x=0$) is 1.0 m. The intergration process (equation [10] tends to average the volume drained for small water table depths near the midpoint with that drained for larger depths nearer the drain. The results essentially mask the effect of a variable drainable porosity at small water table depths. This is not the case for Wagram because the one-dimensional drainable porosity varies over a much wider range of water table depth (Fig. 6).

The results given in Figs. 7 and 8 are subject to the assumption of the elliptical profile shape given by equation [9] and of a 'drained to equilibrium' unsaturated zone. However, an analysis of solutions for combined saturated-unsaturated flow during drainage to parallel ditches (Skaggs and Tang, 1976) indicate these assumptions are reasonable for field situations. The dotted sections of the curves in Fig. 7 are due to the transition of the water table profile from initially horizontal, with a mean water table depth of zero to an elliptical shape with a mean depth of about 20 cm when the water table intercepts the surface at $x = L/2$. The actual shape of the relationships in this range will depend on the water table movement during the transition and the dotted sections should be treated as approximations only.

We have arbitrarily chosen the drain depth to be 1 m. However, calculations for larger drain depths also resulted in nearly constant, although somewhat higher, f values for all but the Wagram soil. For example, when the drain depth was assumed to be 1.5 m for the Rains soil, the f values varied from 0.065 for a midpoint water table depth of 0 to 0.079 for a midpoint water table depth of 1 m. These values are compared to a range of 0.059 to 0.075 (Fig. 8) for a 1 m drain depth. The results given in Fig. 8 are somewhat comforting to those who find it desirable to assume f constant when making drawdown calculations. However, this assumption will be hazardous for many soils as clearly demonstrated by the results for Wagram. An estimate of the drainable porosity and its dependence on water table depth can be made from the soil water characteristics of the profile layers using the methods given herein. The characteristics should be measured on relatively large samples without provisions to insure initial saturation so that air entrapment will be reflected in the results obtained.

SUMMARY AND CONCLUSIONS

Experiments were conducted on large field cores to determine the relationship between drainage volume and water table depth for five soils. The measured drainage volumes were less than predicted from the soil water characteristics for three soils but were in good agreement for the other two. Drainable porosities were calculated from both theoretical and experimental drainage volume-water table depth relationships by assuming that the unsaturated zone is 'drained to equilibrium' with the water table.

Drainable porosities for two-dimensional water table drawdown were calculated from experimental results for one-dimensional flow by assuming an elliptical water table profile and a drain depth of 1 m. These results gave nearly constant drainable porosities for the layered soils and a variable drainable porosity for Wagram, a homogeneous sandy soil.

The results of the study yielded the following conclusions.

1 The volume of water drained from a profile when the water table is lowered from the surface to a given depth and allowed to reach equilibrium may be considerably less than that predicted from the soil water characteristic. The difference is attributed to air entrapment when the water table rises to the surface prior to drainage. As a result, drainable porosities calculated from the soil water characteristic may be higher than actual values.

2 Drainable porosities for two-dimensional drainage are less dependent on water table depth than for one-dimensional flow. Although, in general, drainable porosity should still be considered dependent on water table depth, the assumption of a constant drainable porosity appears to be reasonable for four of the five soils examined in this study.

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