REFINING THE DEFINITION OF FIELD CAPACITY IN THE LITERATURE

By M. H. Nachabe,[1] Member, ASCE

ABSTRACT: The normalized water content calculated with the simple algebraic equation $\Theta_{fc} = (q_{fc}/K_s)^{1/n}$, where $q_{fc} = 0.05$ mm/day and K_s = hydraulic conductivity, can be used to estimate field capacity. The water content calculated with this relationship is close to the water content at 1/3 bar matric potential for all soils. It is suggested that the concept of "field capacity" be refined by relating it to the mobility of soil moisture (drainage flux). Field capacity should not be characterized solely by a particular drainage time, because the time to reach field capacity depends on soil properties, but also on the initial water content and water depth in the soil.

INTRODUCTION

Water content at field capacity, or simply field capacity, is an important concept in agricultural engineering, hydrology, and soil physics. Field capacity determines the water available for evaporation and transpiration of crops in simulation models in agriculture. Typically, field capacity is reached within a few days of drainage after infiltration (Linsley and Franzini 1972). This drainage period allows gravity water to drain from the soil, leaving the remaining soil water available for the slow processes of evaporation and crop water uptake. Colman (1947) attempted to rationalize field capacity in relation to water retention in soils. He performed a laboratory procedure on 120 California soils to show that field capacity is approximately equal to the water content at 1/3 bar matric potential. After this work, the water content at 1/3 bar matric potential became a standard definition of field capacity in many textbooks (e.g., Linsley and Franzini 1972). Miller and Klute (1967) suggested that field capacity is reached when the downward drainage flux becomes very slow. This last definition relates field capacity to the mobility of soil moisture while recognizing that drainage does not cease completely. Nevertheless, there is no consensus among hydrologists as to what is considered a very slow drainage flux.

The descriptions "very slow" and "a few days" are qualitative and leave two questions unanswered. First, what is the relationship between the time to reach field capacity and simple soil properties? Also, what is a reasonable value for the magnitude of this very slow drainage flux? To answer these questions, the dynamic of soil drainage is used to show analytically that for most soils: (1) the drainage flux at field capacity can be considered 0.05 mm/day; (2) the water content at this drainage flux is close to the water content at 1/3 bar matric potential; and (3) the drainage period to reach field capacity depends on soil properties, the initial water content, and the initial water depth in the soil.

THEORY

During infiltration and drainage, the main forces affecting movement of soil water are gravity and capillary. During infiltration, the force associated with capillary gradients acts in the same downward direction as gravity. When infiltration stops and drainage (also known as water content redistribution) starts, matric potential or water content gradients are in opposite directions in the upper and lower portions of the profile. Fig. 1 shows a typical soil moisture profile during redistribution. The gradient in water content at any depth between A and B is downward, whereas the direction of this gradient between B and C is upward. Because of their direction during drainage, gradients will not initiate a significant net downward movement of the water content profile. The thinning of the profile continues until the average water content reduces to a value for which the drainage flux is very slow. The objective is to reach a consensus on the magnitude of this flux and to determine the time and the water content at which it is reached.

Neglecting the influence of capillary gradients on the net movement of soil water, Darcy's law for unsaturated flow is:

$$q(t) = K(\theta) \tag{1}$$

where $q(t)$ (mm/day) = drainage flux as a function of time t (days); and $K(\theta)$ (mm/day) = unsaturated hydraulic conductivity at water content θ (mm³/mm³). In this technical note, the hydraulic conductivity is expressed as (Brooks and Corey 1964)

$$K = K_s\Theta^n \tag{2}$$

where K_s = saturated hydraulic conductivity; $\Theta = (\theta - \theta_r)/(\theta_s - \theta_r)$ = normalized water content; θ_r = residual water content; and θ_s = saturated water content. From Fig. 1, the rate of change of water content in the profile is given by the expression

$$\frac{d\Theta}{dt} = \frac{-q}{z_f(\theta_s - \theta_r)} \tag{3}$$

where z_f = depth to the wetting front during drainage. At all times, conservation of soil water mass in the profile requires that

$$z_f = \frac{I}{\Theta(\theta_s - \theta_r)} \tag{4}$$

where I = initial cumulative infiltration water depth (mm) at the beginning of water content redistribution. Substituting (2) and (4) into (3) and integrating the resulting ordinary differential equation with respect to time yields

$$\Theta = \left(\Theta_i^{-n} + \frac{K_s n t}{I}\right)^{-1/n} \tag{5}$$

where Θ_i = normalized water content at the beginning of soil moisture distribution. Eq. (5) describes the water content evolution during drainage given an initial depth of cumulative infiltration, I, and an average initial water content Θ_i. Morel-Seytoux et al. (1984) compared water content predictions from (5) with actual field data during drainage. Their results showed an excellent match between predicted and observed water content. The drainage flux is obtained by substituting (5) in (2) with the result

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[1] U.S. Dept. of Agric., Agric. Res. Service, 301 S. Howes, Box E, Fort Collins, CO 80522. E-mail: nachabe@gpsr.colostate.edu; formerly, Asian Inst. of Technol., School of Civ. Engrg., Water Engrg. and Mgmt. Program, Box 4 Klongluang, Pathumthani 12120, Thailand.

Note. Discussion open until January 1, 1999. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this technical note was submitted for review and possible publication on June 16, 1997. This technical note is part of the *Journal of Irrigation and Drainage Engineering*, Vol. 124, No. 4, July/August, 1998. ©ASCE, ISSN 0733-9437/98/0004-0230–0232/$8.00 + $.50 per page. Technical Note No. 16002.

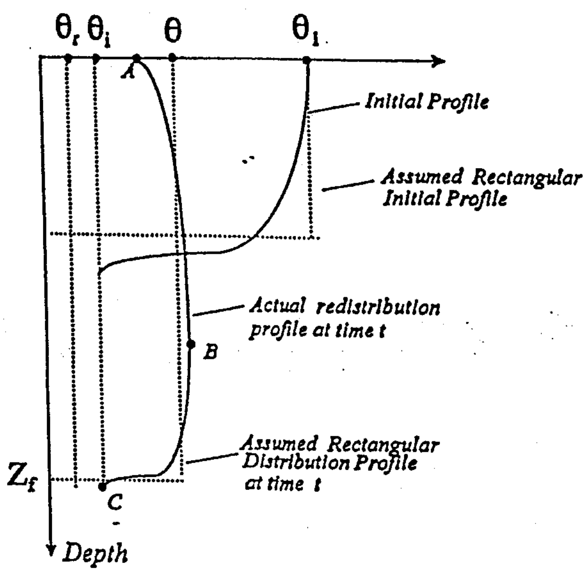

FIG. 1. Soil Moisture Profile during Infiltration and Drainage

$$q(t) = \frac{K_s}{\dfrac{nK_s t}{I} + \Theta_i^{-n}} \qquad (6)$$

Eq. (6) shows that the drainage flux decreases as time increases. The time to reach a particular drainage flux $q(t)$ is obtained by solving (6) for t as follows:

$$t = \left(\frac{K_s}{q} - \Theta_i^{-n}\right)\frac{I}{nK_s} \qquad (7)$$

Water Content at Field Capacity

When the soil reaches field capacity, the subscript fc will be used for all variables. The normalized water content at field capacity Θ_{fc} can be expressed in terms of drainage flux at field capacity, q_{fc}, by substituting (7) in (5) to obtain

$$\Theta_{fc} = \left(\frac{q_{fc}}{K_s}\right)^{1/n} \qquad (8)$$

The drainage time to reach field capacity is

$$t_{fc} = \left(\frac{K_s}{q_{fc}} - \Theta_i^{-n}\right)\frac{I}{nK_s} \qquad (9)$$

RESULTS AND ANALYSIS

For $I = 10$ mm and 100 mm, and $\Theta_i = 1$, Figs. 2(a and b) show the drainage flux evolution with time for typical sand, loam, and clay. Parameters K_s, n, θ_r, and θ_s for these soils are adopted from Rawls and Brakensiek (1989) and are shown in Table 1. $I = 10$ mm is a storm resulting in an infiltration depth of 10 mm, and $I = 100$ mm is a major rainfall or irrigation event. As illustrated in Fig. 2, the drainage flux decreases with time and is larger for sand that it is for loam and clay. Also, the larger the value of I is, the longer the time required to reach a small drainage flux.

Clearly, the two classical definitions of field capacity are identical, because after "few days," the drainage flux is "very slow" (Fig. 2). Indeed, after two days, this flux is less than 1 mm/day for all soils regardless of the initial infiltration depth. It is interesting to compare the water content from (8) with the water content at 1/3 bar matric potential. First, a consensus must be reached as to what is considered a very slow flux q_{fc} in (8).

Physically, field capacity signals that drainage is negligible and evapotranspiration has become a dominant process in depleting soil moisture. Therefore, one can theorize that q_{fc} depends on the time scale of the three important hydrologic processes affecting soil moisture, namely, infiltration, drainage, and evapotranspiration. Whereas infiltration occurs during storms or irrigation with a time scale ranging from a few minutes to several hours, drainage is a slower process than infiltration, and evapotranspiration is even slower than both

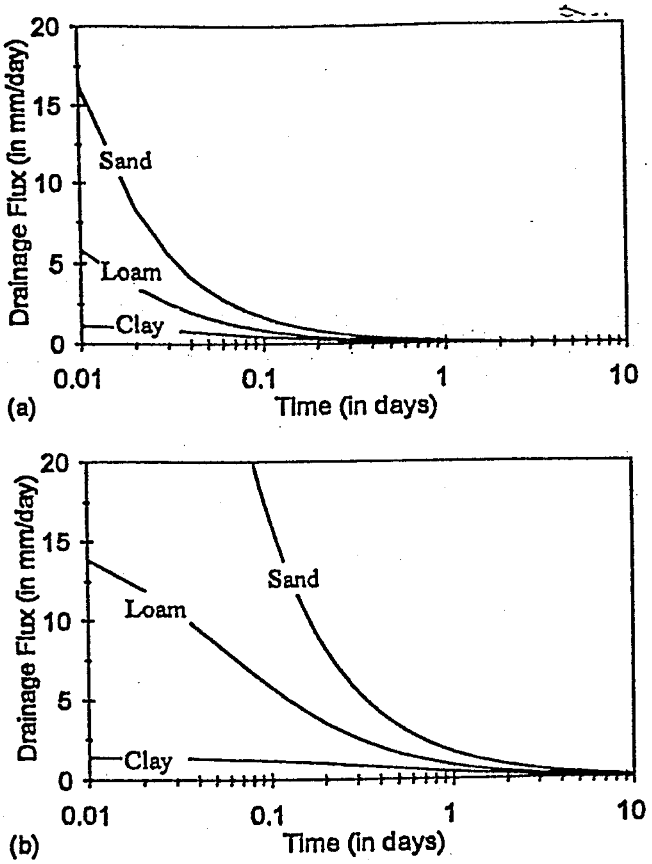

FIG. 2. Drainage Flux as Function of Time: (a) $I = 10$ mm; (b) $I = 100$ mm

TABLE 1. Soil Parameters for Soil Texture Classifications [after Rawls and Brakensiek (1988)]

Texture class (1)	θ_s (mm³/mm³) (2)	θ_r (mm³/mm³) (3)	K_s (mm/day) (4)	n (5)	$\theta_{1/3}$[a] (mm³/mm³) (6)	θ_{fc}[b] (mm³/mm³) (7)	t_{fc}[c] (days) (8)
Sand	0.437	0.02	504	5.88	0.091 (0.018–0.164)	0.107	3.34
Loamy sand	0.437	0.035	146.6	6.62	0.125 (0.06–0.19)	0.155	3.02
Sandy loam	0.453	0.041	62.2	8.29	0.207 (0.126–0.288)	0.215	2.41
Loam	0.463	0.027	16.3	10.94	0.270 (0.195–0.345)	0.284	1.82
Silt loam	0.501	0.015	31.7	11.55	0.330 (0.258–0.402)	0.293	1.73
Sandy clay loam	0.398	0.068	10.3	8.27	0.255 (0.186–0.324)	0.254	2.15
Clay loam	0.464	0.075	5.5	11.26	0.318 (0.250–0.386)	0.331	1.76
Silty clay loam	0.471	0.04	3.6	14.3	0.366 (0.304–0.428)	0.36	1.38
Sandy clay	0.43	0.109	2.9	11.97	0.339 (0.245–0.433)	0.338	1.64
Silty clay	0.479	0.056	2.2	16.33	0.387 (0.332–0.442)	0.392	1.20
Clay	0.475	0.09	1.4	15.12	0.396 (0.326–0.466)	0.398	1.28

[a] Water content at 1/3 bar matric potential; first line is mean value, second line is ± one standard deviation about the mean.

[b] Water content calculated with Eq. (8).

[c] Calculated with Eq. (9).

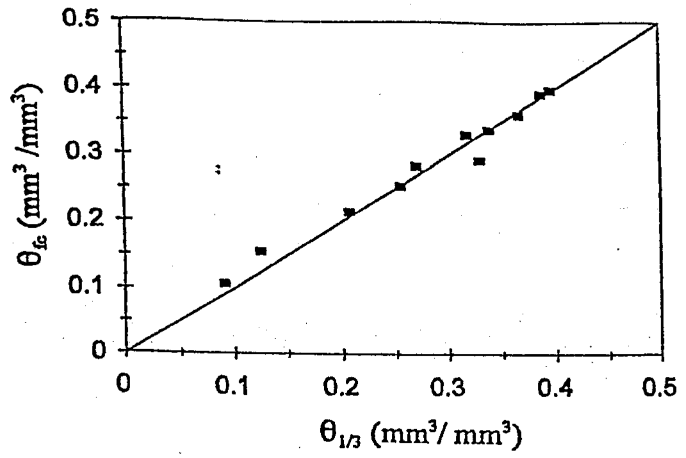

FIG. 3. Plot of θ_{fc} versus $\theta_{1/3}$, Showing Very Good Fit with $r^2 = 0.98$

infiltration and drainage. Assuming a reasonable average potential evapotranspiration rate of 5 mm/day (e.g., Linsley and Franzini 1972), it can be safely considered that field capacity is reached when the drainage flux is 0.05 mm/day, two orders of magnitude smaller than the potential average evapotranspiration. Clearly, when the drainage flux reaches 0.05 mm/day, drainage is fairly irrelevant to soil moisture distribution, and evapotranspiration becomes dominant in depleting soil moisture. Table 1 shows the water content at field capacity, θ_{fc}, for different soil textures when $q_{fc} = 0.05$ mm/day is used in (8). Also, Table 1 shows the water content at 1/3 bar matric potential, $\theta_{1/3}$, the traditional definition of field capacity (Colman 1947; Linsley and Franzini 1972). The water content at field capacity, θ_{fc}, is plotted versus $\theta_{1/3}$ in Fig. 3. Clearly, the match between θ_{fc} and $\theta_{1/3}$ is close for all soils. The r^2 coefficient was 0.98, indicating strong correlation. For all soils, θ_{fc} was within one standard deviation of $\theta_{1/3}$. This excellent match explains why $\theta_{1/3}$ is a reasonable estimate of field capacity. The last column in Table 1 shows the drainage time to field capacity when $I = 1$ mm and $\Theta_i = 1$ are used in (9). The drainage time is between one and five days for all soils. However, as implied in (9), the period of drainage to reach field capacity is not a characteristic of the soil; it is a function of both the initial infiltration depth and the water content of the soil. Therefore, it is not advisable to define field capacity in terms of a particular drainage time.

CONCLUSION

This technical note shows that field capacity can be explained well with the theory of drainage or water content redistribution. It is recommended to define field capacity in relation to a water flux instead of a particular drainage period. The formula $\Theta_{fc} = (q_{fc}/K_s)^{1/n}$ accurately predicts the water content at field capacity. If q_{fc} is considered 0.05 mm/day, the water content predicted with this formula will be close to the water content at 1/3 bar matric potential. Therefore, this formula can be used to estimate field capacity if actual measurements of water content at 1/3 bar are missing. Alternatively, this formula can be used to estimate the saturated hydraulic conductivity, K_s, if the water content at field capacity is known. In this case, the prediction equation is

$$K_s = 0.05\left(\frac{\theta_s - \theta_r}{\theta_{fc} - \theta_r}\right)^n \tag{10}$$

ACKNOWLEDGMENTS

Many thanks to students in "Irrigated Soils," which the writer taught at the Asian Institute of Technology in Bangkok, Thailand. Rainer Loof, coordinator of the Irrigation Engineering and Management program, is appreciated for giving the writer the opportunity to teach this course. This research was sponsored by a grant from the Asian Institute of Technology.

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