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DEVELOPMENT OF A CRUST FACTOR FOR A GREEN AMPT MODEL

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ABSTRACT

The formation of a soil crust has been shown to cause a major decrease in infiltration and needs to be accounted for in infiltration models. In response to this need, a procedure based on such properties and wetted front depth was developed for incorporating the steady state crust conductivity into the hydraulic conductivity term of the Green-Ampt infiltration model. This effective hydraulic conductivity is calculated as a harmonic mean of the crust and subcrust hydraulic conductivity. Tests on a range of soils verified that the procedure gives an acceptable first approximation of the crust effects. KEYWORDS. Hydraulic conductivity, Soils, Data base, Surface soil layer, Rainfall.

INTRODUCTION

The formation of soil crusts have been shown to be a major modifier of infiltration (Duley, 1939). Also, crust causes a significant decrease in the hydraulic conductivity of the surface soil layer (Tackett and Pearson, 1965). The decrease in hydraulic conductivity has been reported to range from a 20-fold to a 2,000-fold decrease (Sharma, 1980; McIntyre, 1958).

The soil crust is normally formed by raindrop compaction and by washing fine particles into the soil matrix causing a very dense layer (McIntyre, 1958). The thickness of the layer has been reported to vary from 1 to 5 mm (Tackett and Pearson, 1965; Sharma, 1980). Also, the formation and thickness of a soil crust is influenced by texture (Mannering, 1967; Onofick, 1983; Gantzer, 1980), aggregate stability (Allison, 1985), organic matter (Ahmad and Robbin, 1971), tillage and landuse practices (Linden, 1979; Sharma, 1980; Falayl and Bouma, 1975; Moore et al., 1980). Several authors have investigated how the crust conductivity varies with time (Edwards and Larson, 1969; Moore, 1981a, 1981b; McIntyre, 1958; Callebaut et al., 1985) and concluded that it is formed rather rapidly, probably within the first 30 minutes of rainfall. Edwards (1967) and Edwards and Larson (1969) showed that the effect of a crust on the saturated water content and the soil water retention curve is relatively small in comparison to the effect on the saturated hydraulic conductivity.

Brakensiek and Rawls (1983) developed a method based on Sharma's work (1980) for determining the final hydraulic conductivity of a crust from soil texture and the saturated hydraulic conductivity of the undisturbed soil. Also, they incorporated the crust conductivity into a two-layer model using a harmonic mean of the conductivities. Chu et al. (1986) discovered that the harmonic mean will not work when the wetting front depth is greater than about 70 cm.

Many infiltration models (Brakensiek and Rawls, 1983; Moore, 1981a; Chu et al., 1986) have been developed which account for a crust. However, most of them are numerical and work on a multilayer soil system which is very time consuming computationally. Because of the computational time, multilayer models are not being widely used in operational infiltration-based watershed models. Thus, it is the purpose of this article to develop a method to incorporate the effects of a crust into a one-layer Green-Ampt infiltration model using readily available soils data and utilizing computer time more efficiently.

Brakensiek and Rawls (1983) calculated the effective hydraulic conductivity of a two-layer soil, crust, and subcrust, by a harmonic mean:

$$K_e = L / [(L - Z_c) / K_{su} + Z_c / K_c] \quad (1)$$

where
K_e = effective conductivity of the two-layer system,
L = wetted depth,
Z_c = crust thickness,
K_{su} = subcrust hydraulic conductivity,
K_c = crust hydraulic conductivity.

They also presented an equation to predict the steady state crust conductivity based on a steady state relationship derived by Moore (1981a). The equation is

$$K_f = [Z_c / (\psi_i + Z_c)] (SC)(K_s) \quad (2)$$

where
K_f = steady state crust conductivity,
ψ_i = steady state capillary potential at the crust/subcrust interface,
SC = correction factor for partial saturation of the subcrust soil,
K_s = saturated subcrust conductivity,
Z_c = crust thickness.

Data from Sharma et al. (1980) provides values of ψ_i for standard U.S. Department of Agriculture soil texture (Table 1). The partial saturation of the subcrust (SC) was

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calculated by Brakensiek and Rawls (1983) and are also presented in Table 1.

Assuming that $K_f = K_c$ and K_{su} = (SC) (K_s), equation 1 becomes

$$K_e = L / [(L - Z_c)/(SC)(K_s) + Z_c/K_f] \quad (3)$$

and equation 2 becomes

$$K_f / Z_c = (SC)(K_s) / (\psi_i + Z_c). \quad (4)$$

Combining equations 3 and 4,

$$K_e = [SC / (1 + \psi_i / L)](K_s) \quad (5)$$

and the crust thickness (Z_c) has canceled out. Rearranging equation 5, a crust factor (CF) defined as K_e / K_s can be determined as

$$CF = K_e / K_s = SC / (1 + \psi_i / L) \quad (6)$$

with the wetted depth (L) as the only unknown . The crust factor (CF) approaches SC as the wetted depth increases. It is important to understand that equation 6 does not calculate a transient crust conductivity since it assumes that the steady state crust conductivity has been reached.

In order to use equation 6 in modeling, SC and ψ_i required a continuous function description; thus, the following relationships were derived from the data presented in Table 1:

$$SC = 0.736 + 0.0019 (\% sand) \quad (7)$$

n = 11,
r = 0.96,
standard error = 0.05,
and

$$\psi_i = 45.19 - 46.68 (SC) \quad (8)$$

n = 11,
r = 0.91,
standard error = 1.29.

Figure 1 illustrates how the crust factor varies with the wetted depth for three soil textures.

TABLE 1. Mean steady state matric potential drop, ψi, across surface seals and subcrust conductivity reduction factor by soil texture

Soil texture	Percent sand	Matric potential drop, ψ (cm)	Reduction factor for subcrust conductivity (sc)
Sand	90	2	0.91
Loamy sand	80	3	0.89
Sandy loam	65	6	0.86
Loam	45	7	0.82
Silt loam	25	10	0.81
Sandy clay loam	60	5	0.85
Clay loam	30	8	0.82
Silty clay loam	10	10	0.76
Sandy clay	50	6	0.80
Silty clay	10	11	0.73
Clay	25	9	0.75

Experiment Methods

The USDA-ARS Water Erosion Prediction Project (WEPP) conducted a series of cropland and rangeland experiments for determining hydrologic and erosion parameters for a soil loss model (Laflen et al., 1987).

Rainfall simulation experiments were conducted by 33 cropland soils and 20 rangeland soils in the United States. The soils were located in 24 states and encompassed a wide range of parent materials, climates, textures, and other soil properties. The soils were sampled and characteristics that

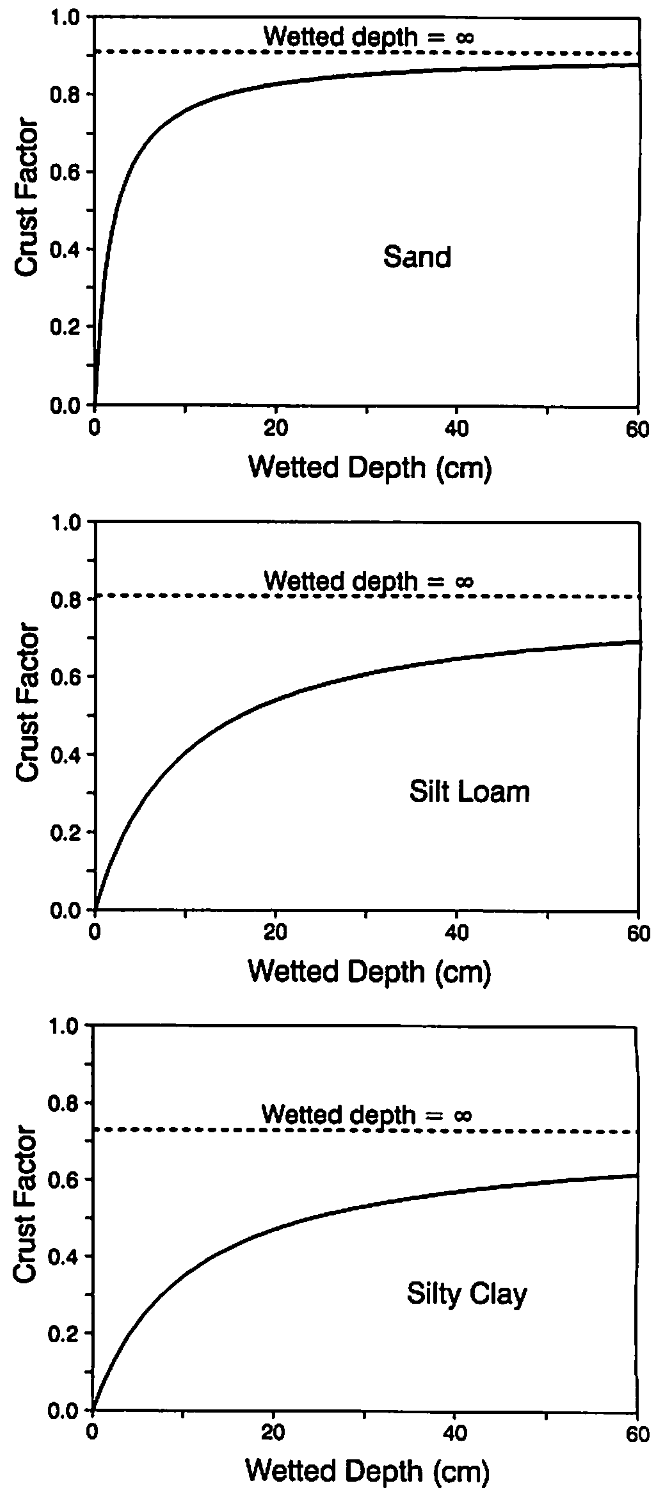

Figure 1–Change in crust factor with wetted depth.

might be used as predictors of soil erodibility and infiltration were measured.

The cropland plots were prepared by first removing all surface residue. Three to 12 months before the test, the plots were moldboard plowed to a depth of 20 cm. After plowing, the plots were lightly disced and maintained weed and grass free until the tests were conducted. Immediately before the test a ridging tool was used to form the ridges in the small interrill plots. For the covered plots the ridges were flattened. The plots were 50 cm wide and 75 cm long. On each site there was a total of six to eight uncovered plots and two to four flat plots covered with furnace filter or burlap. Rainfall was applied using a rotating boom rainfall simulator at a rate of about 6 cm/hr until runoff was nearly constant, usually about an hour.

The rangeland plots were prepared by clipping all vegetation at ground level and removing all clippings and surface cover (rocks, litter, etc.) with a minimum disturbance to the soil surface. The plots were 60 cm wide and 120 cm long. On each site there were two uncovered plots and two plots covered with window screen. Rainfall was applied in the same manner as the cropland studies.

Both rangeland and cropland tests were conducted at existing soil moisture level which was normally very dry. Additional rainfall and flow addition tests were performed, however, they are not described here since they were not used in this analysis. A full description of the WEPP experimental design is given by Laflen et al. (1987) and Simanton et al. (1987).

Analysis

For each site an average (two to eight plots) accumulated infiltration and final infiltration rate for the initial one hour run was determined from the rainfall/runoff data. Plots that had a final infiltration rate greater than 90% of the rainfall rate were eliminated from the analysis because it was assumed that the rainfall rate was not sufficient to reach a steady state infiltration rate. The porosity of the soil wag determined from measured soil bulk density and the available porosity was determined as the total porosity minus the measured initial soil moisture. From the measured data and the Green-Ampt wetting front capillary pressure predicted by the equation developed by Rawls and Brakensiek (1985), the effective hydraulic conductivity of the covered and uncovered plots was determined using the following form of the Green-Ampt infiltration model (Li et al., 1976):

$$K_e = f \Big/ \left(1 + \frac{n\psi}{F}\right) \qquad (9)$$

where

K_e = effective hydraulic conductivity,
f = final infiltration rate,
F = accumulated infiltration,
ψ_i = wetting front capillary pressure head,
n = available porosity (total porosity minus soil water).

Assuming that the effective hydraulic conductivity for the covered plot represents an uncrusted hydraulic conductivity while the uncovered plot represents the effective crusted hydraulic conductivity, the crust factor (CF) can be determined by dividing the uncovered effective hydraulic conductivity by the covered effective hydraulic conductivity. The crusted and uncrusted hydraulic conductivities and the soil properties are summarized in Table 2. The uncrusted effective hydraulic conductivities for the agricultural soils are probably on the low side since a crust was formed during the run.

Results

The wetting front depth (L) for the event was calculated by dividing the accumulated infiltration by the porosity minus initial soil moisture. The crust factor was calculated from equation 6. The SC and ψ_i in equation 6 were calculated from soil properties using equations 7 and 8. The crust factors predicted in the above manner were compared to the crust factor calculated from the measured cover and uncovered hydraulic conductivities.

The comparison was performed separately on the agricultural and range plots. Using linear regression techniques, the measured crust factor was related to the predicted crust factor forcing the intercept to be zero, resulting in the following:

Agricultural

$$\text{CF (measured)} = 0.82 * \text{CF (predicted)} \qquad (10)$$

R = 0.90,
N = 20,
standard error = 0.02.

Range

$$\text{CF (measured)} = 1.04 * \text{CF (predicted)} \qquad (11)$$

R = 0.91,
N = 18,
standard error = 0.04.

Comparison of crust factors is shown in figure 2. Since the formulation assumes the crust to be in place during the whole run, the over prediction of the crust factor (CF) for the agricultural plots could be caused by the forming of a crust during the events which will cause more infiltration and a larger wetted depth. The greater infiltration will cause the measured crusted effective hydraulic conductivity to be smaller, thus causing the measured crust factor to be smaller than if a crust had been present during the whole run. The plot comparisons indicate a reasonable comparison and validates our procedure. We feel the agricultural and range comparisons verify the simple method for predicting the effect of crust on hydraulic conductivity. Additional research is needed to describe the crust conductivity during crust development.

Summary

A crust factor was developed for incorporating the effect of a crust into the Green-Ampt effective hydraulic conductivity. We found that a relationship existed between the crust factor and the percent sand and the wetted depth. Thirty-six soils covering a wide range of conditions were used to validate the crust factor.

TABLE 2. Summary of soil and infiltration properties of sites

Soil	Texture	Sand	Clay	Organic carbon	Bulk density	Soil moisture	Hydraulic conductivity		Crust factor
							Uncovered	Covered	
		(%)	(%)	(%)	(g/cm^3)	(% vol)	(cm/ hr)		
AGRICULTURAL									
Academy	SL	63	9	0.3	1.61	1	0.69	3.36	0.21
Amarillo	LLS	84	8	0.2	1.55	10	1.73	2.25	0.77
Carilou	GL	47	12	1.8	1.21	8	0.94	2.94	0.32
Cecil	SCL	65	20	0.7	1.47	3	1.51	3.31	0.45
Collimer	SiL	7	15	1.0	1.28	14	0.39	0.86	0.45
Frederick	SiCL	5	52	1.3	1.20	15	0.32	1.29	0.24
Gaston	CL	36	39	1.1	1.18	14	0.39	1.92	0.20
Grenada	SiL	2	20	1.3	1.30	8	0.40	1.23	0.32
Heiden	SiC	8	52	1.4	1.00	22	0.68	2.89	0.24
Hiwassee	S L	64	15	0.8	1.39	3	1.37	3.79	0.36
Los Banos	C	16	44	1.2	1.00	4	0.33	1.18	0.28
Manor	L	44	26	1.0	1.26	10	1.09	3.28	0.33
Miami	SiL	4	23	0.8	1.29	6	0.09	1.12	0.08
Miamian	L	31	25	1.8	1.16	7	0.47	1.43	0.33
Nasene	SiL	14	12	1.3	1.34	6	0.49	0.78	0.63
Opequin	CL	38	31	1.4	1.30	14	0.84	2.45	0.34
Palouse	SiL	12	16	1.3	1.15	13	0.27	0.93	0.29
Portneuf	SiL	20	11	0.7	1.23	7	0.85	1.57	0.54
Sharpsburg	SiC	3	42	1.7	1.14	29	0.98	2.16	0.45
Zahl	L	46	24	1.5	1.25	14	0.67	3.11	0.21
RANGE									
Degator	SiCl	8	40	1.5	1.50	15	0.15	0.47	0.32
Forrest	SL	60	17	3.6	1.46	11	0.40	1.88	0.21
Gariper (87)	SL	54	16	1.7	1.48	10	0.78	1.74	0.45
Gariper (88)	SL	54	16	1.7	1.40	6	0.70	1.10	0.63
Grant (87)	SL	53	14	1.2	1.47	18	0.90	1.67	0.54
Grant (88)	SL	54	16	1.2	1.37	13	0.27	0.86	0.31
Hackroy	SiL	44	8	1.0	1.44	11	0.49	0.67	0.73
Querencia	SL	64	10	0.8	1.50	4	1.58	1.87	0.84
Quinlan	L	43	15	1.1	1.40	10	0.38	1.09	0.35
Pierre (87)	SiC	12	49	1.8	1.37	15	0.11	0.45	0.24
Pierre (88)	SiC	12	49	1.8	1.30	11	0.06	0.40	0.15
Pierre (87)	C	23	43	2.0	1.49	15	0.09	0.35	0.26
Pierre (88)	C	23	43	2.0	1.30	13	0.21	0.57	0.37
Power	SiL	25	8	0.9	1.29	12	0.93	1.29	0.72
Stronghold	S L	68	16	1.4	1.60	11	0.76	3.26	0.23
Sumit (87)	S L	76	4	0.8	1.59	17	2.56	3.13	0.82
Summit (88)	LS	76	4	0.8	1.71	2	1.40	2.39	0.59
Vida	L	47	17	2.7	1.51	9	1.15	1.98	0.58

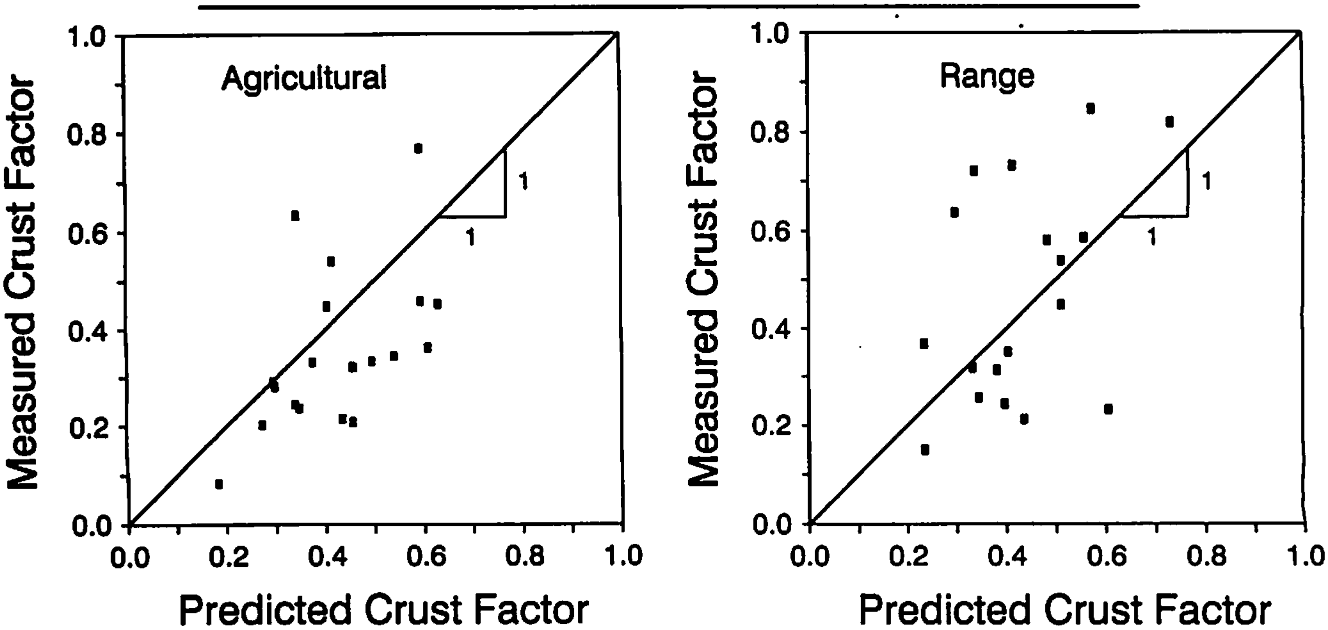

Figure 2–Comparison of crust factor predictions.

References

Ahmad, N. and A.J. Robbin. 1971. Crusting of river state soil in Trinidad and its effect on gaseous diffusion percolation and seedling emergence. *J. Soil Sci.* 22: 23-31.

Allison, L.E. 1985. A study of synthetic aggregate breakdown using logarithmic normal-distribution analysis. *Soil Sci. Soc. of Amer. Proc.* 20: 314-316.

Brakensiek, D.L. and W.J. Rawls. 1983. Agricultural management effects on soil water processes. Part II: Green and Ampt parameters for crusting soils. *Transactions of the ASAE* 26(6): 1753-1757.

Callebaut, F., D. Gabriels and M. DeBoodt. 1985. Assessment of soil surface sealing and crusting. In Proceedings of the Symposium held in Ghent, Belgium, ISSS.

Chu, S. T., C.A. Onstad and W. J. Rawls. 1986. Field evaluation of a layered Green-Ampt model for transient crust conditions. *Transactions of the ASAE* 29(5): 272-1277.

Duley, F.L. 1939. Surface factors affecting the rate of intake of water by soils. *Soil Sci. of Amer. Proc.* 9: 60-64.

Edwards, W.M. 1967. Infiltration of water into soils as influenced by surface conditions. Unpub. Ph.D. thesis, Iowa State University, Ames.

Edwards, W.M. and W.E. Larson. 1969. Infiltration of water into soils as influenced by surface seal development. *Transactions of the ASAE* 12(4): 463-465.

Falayl, O. and J. Bouma. 1975. Relationships between the hydraulic conductance of surface crusts and soil management in a typic Hapludaff. *Soil Sci. Soc. Amer. Proc.* 39: 957-963.

Gantzer, C.J. 1980. Physical and morphological investigations of surface seal formation on selected soils. Unpub. Ph.D. thesis, University of Minnesota, St. Paul.

Laflen, J.M., A.W. Thomas and R. Welch. 1987. Cropland experiments for the WEPP project. ASAE Paper No. 87-2544. St. Joseph, MI: ASAE.

Li, Ruk-Ming et al. 1976. Solutions to the journal of Green-Ampt infiltration equation. *J. Irrigation and Drainage Div., ASCE* 102(IR2): 239-248.

Linden, D.R. 1979. A model to predict soil water storage as affected by tillage practices. Unpub. Ph.D. thesis, University of Minnesota, St. Paul.

Mannering, J.V. 1967. The relationship of some physical and chemical properties of soils to surface sealing. Unpub. Ph.D. thesis, Purdue University, Lafayette, IN.

McIntyre, D.S. 1958. Permeability measurements of soil crusts formed by raindrop impact. *Soil Sci.* 85(4): 185-189.

Moore, I.D. 1981a. Infiltration equations modified for surface effects. *J. Irrigation and Drainage Div., ASCE* 107(IRI): 71-86.

Moore, I.D. 1981b. Effect of surface sealing on infiltration. *Transactions of the ASAE* (24): 1546-1552.

Moore, I.D., C.L. Larson and D.C. Slack. 1980. Predicting infiltration and micro-relief surface storage for cultivated soils. WRCC, University of Minnesota, Bulletin No. 102.

Onofick, O. E. 1983. Characterization of surface crusts formed by simulated rainfall on six California sites. Unpub. Ph.D. thesis, University of California, Davis.

Rawls, W.J. and D.L. Brakensiek. 1985. Prediction of soil water properties for hydrologic modeling. In *Proc. of Symp. sponsored by Comm. on Watershed Mgt.*, 293-299. Irrigation and Drainage Div., ASCE.

Sharma, P.P. 1980. Hydraulic gradients and vertical infiltration through rain-formed quast seals on a range of Minnesota soils. Unpub. M.S. thesis, University of Minnesota, St. Paul.

Simanton, J.R., L.T. West and M.A. Weltz. 1987. Rangeland experiments for the WEPP Project.

Tackett, J.L. and R.W. Pearson. 1965. Some characteristics of soil crusts formed by simulated rainfall. *Soil Sci.* 99(6): 407-413.