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INFILTRATION RATE AS AFFECTED BY SOIL SURFACE CRUSTING CAUSED BY RAINFALL

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ABSTRACT

A non destructive method for evaluating infiltrability of wet and more or less crusted topsoils is proposed.

Water is supplied by drip sources placed close to the soil surface and area of saturated flux is measured when gravitational flows become prevailing.

The proposed method was applied to the study of top-soil crusting during the first stages of this process, observed on a loamy soil subjected to natural rainfall. When obtained under conditions of validity of the method (i.e. high initial moisture content and no ponding water), results proved to be consistent with morphological observations and observed behaviours during rainfall.

INTRODUCTION

The progressive decrease of infiltrability can be regarded both as a consequence and as a cause of the structural degradation of soil surface exposed to rainfall. In a previous paper (BOIFFIN, 1985), we developed the latter aspect: the passage from structural crusts (1^{st} stage of soil crusting in situ) to depositional crusts (2^{nd} stage) was shown to be related to critical amount of water excess at the soil surface. The former aspect has been extensively studied by soil scientists. Starting from a fragmentary initial state, rainfall induces formation of thin but compact superficial layers, the saturated conductivity of which is lower by several orders of magnitude than in the underlying layers (Mc INTYRE, 1958).

According to HILLEL (1964), infiltration flux q_i through a crusted topsoil can be expressed as follows, assuming (a) a steady-state flow, (i.e. existence of a transmission zone with constant moisture content below the crust), and (b) a saturated crust :

$$q_i = K_s^c \, (ho + hi + zi)/zi = Ku \quad \text{(Rel. 1)}.$$

where K_s^c and Ku are hydraulic conductivities of the crust (saturated) and of the transmission zone (theoretically non saturated if the initial moisture content is low), respectively; ho is the hydrostatic pressure due to ponding and hi the matric suction (function of the water content of the transmission zone) exerted at the bottom of the crust; zi being the distance from this bottom to the soil surface. As time elapses, the structural degradation is expected to induce a decrease in K_s^c by increasing bulk density of the crust, and/or an increase in zi by a thickening of the crust;both leading to a decrease in qi. The higher the initial moisture content of the soil profile, the stronger the influence of K_s^c (i.e. of the structural state) on qi. From these considerations, it becomes clear that infiltrability measurements are useful in order to describe and predict soil crusting as a time-dependent phenomenon. The problem that remains not fully solved yet is the lack of a non-disturbing method for evaluating topsoil infiltrability, allowing to characterize a momentary definite structural state of the soil surface.

MATERIALS AND METHODS

According to this purpose, operating procedures should meet the following requirements :

. neither to induce nor to quicken or disturb in any way the structural evolution to be studied; this allows measurements to be made at several times on the same site;

. to take into account only surface transfer characteristics without any interference of underlying deeper discontinuities;

. to integrate lateral heterogeneities of millimetric or centimetric extent due to structural discontinuities.

Such conditions imply low amounts of water supply, without dissipation of kinetic energy, and preclude removal of samples for laboratory measurements.

The adopted solution consists in delivering water at a constant discharge rate from a pinpoint source which is the aperture of a capillary tube, supplied with water from a constant level tank. This drip source is placed close to the soil surface. Around the drip source, the wetted area includes a roughly circular saturated patch, which is easily distinguishible thanks to a bright film. After a while (less than 40 minutes under the experimental conditions of our work), this patch no longer expands. The measurements concern the area, or the equivalent diameter D, of this saturated patch.

High initial moisture content is a very important condition of applicability of the method, ensuring that :

. once steady state is apparently obtained, lateral flow can be neglected, what would not be the case with an initially dry profile (BRANDT et al, 1974). So, the relation between the source discharge rate Q and the diameter of the saturated patch D can be written, disregarding the evaporation flux, as :

$$Q = \pi D^2 q_i/4$$

q_i being governed by relation (1);

. the influence of h_i variations does not prevail and mask that of the terms expressing the structural evolution in Rel. (1), that is K_s^c and z_i (which can influence q_i if h_i remains slightly different from zero);

. slaking of aggregates under the drip source is avoided.

If several drip sources are placed at the soil surface in a given experimental site, when saturated patches are stabilized and assuming a constant q_i for any patch, a relation between Q and corresponding observed values of D is expected to have the following form :

$$D = u.\ Q^{1/2} \text{ with } q_i = 4/\pi u^2.$$

Determination of u through statistical curve fitting allows an evaluation of the average infiltration flux q_i for the given site, provided that the residual variance of the adjustment is reasonably low. If not, a rougher evaluation of q_i can be obtained from considering individual patches without ponding.

The interval of discharge rates used in this work was 5 to 250 $cm^3.h^{-1}$, but the actually useful range for crusted top soils is 5-100 $cm^3.h^{-1}$, because of risks of ponding for high discharge rates.

Practical means of calibrating discharge rates, evaluating the equilibrium of saturated patches, and measuring surfaces or diameters (for a detailed report see BOIFFIN, 1984) lead to relative errors of about 5 % on discharge rates above 25 $cm^3.h^{-1}$ and 5 to 10 % on diameters larger than 4 cm.

RESULTS AND DISCUSSION

This method was applied to the 2 sites (P and M) which were described in a previous paper (BOIFFIN, 1985). In this paper, we shall merely present 2 sets of results considered as typical examples, i.e. expose empirical rather than theoretical arguments.

1) Relations between infiltration flux and surface structural evolution on a given site.

An experimental plot, with a homogeneous initial structural state, was established on an unstable loamy soil on site P (20 % clay), and exposed to natural rainfall. On this plot, 10 series of infiltrability measurements were spread over a period of time from mid autumn to late winter, corresponding to the 2 previously defined degradation stages. Each series included 15 to 20 couples (D, Q). Table 1 indicates conditions prevailing at the time of the measurements, and parameters of the obtained adjustments $D = uQ^{1/2}$.

TABLE 1 : Evolution of the statistical adjustment $D = uQ^{1/2}$ with time (D saturated patch diameter in cm, Q source discharge rate in cm³/h)

TIME OF MEASUREMENT	INITIAL WATER CONTENT (W %)	ASPECT OF THE SATURATED PATCHES (puddles+or 0)	PARAMETERS OF THE AJUSTMENT		AVERAGE INFILTRABILITY (1) mm/h
			u	Part of explained variance	
20.11	24.0	0	1.13	0.87	10.0 *
24.11	24.0	0	1.11	0.82	10.3 *
26.11	22.8	0	1.42	0.82	6.3 *
30.11	24.4	0	1.47	0.67	5.9 *
9.12	25.9	0	1.88	0.00	3.7 **
17.12	30.8	+	2.40	0.61	1.0 ***
22.01	22.1	0	1.55	0.60	5.0 *
2.02	26.5	+	1.66	0.00	-
11.02	22.8	++	1.70	0.00	-
17.03	21.8	++	1.38	0.55	-

(1) * deduced from u
** deduced from patches formed under sources with Q < 100 cm³/h.
*** deduced from patches without visible ponding and Q < 100 cm³/h.

From 20/11 to 30/11, a period of time corresponding to the formation of structural crusts (stage 1), it can be seen that the model $D = uQ^{1/2}$ is acceptable. Considering the fairly high initial moisture content and the absence of ponding, it is plausible that the influence of the structural state (through K_s^c and z_i) is not masked by that of h_0 and h_i. Aggregates and structural crusts having the same average bulk density (1,75), moisture contents higher than 20% mean initial saturation of crusts and aggregates, even before water supply. u values obtained from curve fitting increase, implying a decrease in q_i from 10 $mm.h^{-1}$, at the beginning of stage 1, to 6 $mm.h^{-1}$, after the structural crust is well developed, covering about 50 % of the soil surface. After 30/11 the model $D = uQ^{1/2}$ no longer fits with results, because infiltration fluxes are probably partially controlled by hydrostatic charges h_0, varying from one patch to another. This is unquestionable when visible puddles are formed under most sources, which is the case for all series of measurements from 15/12 (beginning of stage 2), except for the 22/01 series, which follows a disturbance of crusts by frost. However, it can be seen that the average flux estimated from non-ponded patches drops down to values below 1 $mm.h^{-1}$; this gives an order of magnitude for the supplementary decrease of q_i due to depositional crust occurrence.

The comparison of average infiltration fluxes and rainfall intensities causing visible puddles to occur (Tab. 2) shows no major contradiction between steady state infiltrability measurements and soil behaviour under rainfall : puddles were found if, and only if, rainfall intensity was higher than estimated infiltrability for a sufficient time.

TABLE 2 : Comparison between measured infiltrability and intensities of observed rainfall causing puddles to form or not

PERIOD OF OBSERVATION	GROUP OF PLOTS (*)	METHOD OF SATURATED PATCHES: AVERAGE INFILTRABILITY FROM NON PONDED PATCHES (mm/h)	OBSERVED BEHAVIOUR OF THE SOIL SURFACE : NATURAL RAINFALL INTENSITIES (mm/h)	
			Without formation of puddles	with puddles
17-24/11	a	10.0	12.0**	-
27-28/11	a	10.3	12.0***	-
29/11-8/12	a	6.3 then 5.9	3.5	24.0
15-16/12	a	3.7	1.5	6.0
	b	3.7	1.5	6.0
	c	6.4	6.0	-
22/12-5/01	a	1.0	-	1.0
	b	1.0	-	1.0
	c	4.4	4.0	-
	d	6.6	4.0	-
23-29/01	a	5.0	1.0	-
10-11/03	a	2.2	-	2.5
29-30/04	e	47.1	15.0	-
30/04-16/05	e	20.4	5.0	-
23/09-6/10	f	8.8	-	40.0
13/10	g	46.0	4.0	92.0
8-10/11	h	7.1	-	21.0

* a, b, c, d : Plots exposed on the P site (time of exposure 10/11) receiving 100, 70, 30, 20 % of the incident rainfall kinetic energy respectively.

e, f, g, h : Plots exposed on the M site - Times of exposure : 29/04; 10/09; 12/10; 27/10.

** during 12 minutes

*** during 9 minutes.

2) Morphological evolution and infiltration fluxes during stage 1

Morphological observations and infiltrability measurements were carried out in diachronic series (evolution with time on same plots) and synchronic series (differences between plots submitted to different experimental treatments, such as rates of raindrop interception) on 2 sites (i.e. clayey-loam soil P with 20 % clay vs loamy soil M with 10 % clay). Morphological criteria were selected as relevant to describing morphological evolution in relation to crusting processes (according to BOIFFIN, 1985), that is : Sp (degree of soil surface coverage by continuous patches formed by the structural crust), and Dlim (equivalent limit size of solid structural shapes distinguishing crumbs that are already, or not, incorporated in those continuous patches), this latter criterion being related both to crust area and to crust thickness.

Table 3 presents statistical correlations obtained between these 2 criteria, and infiltrability evaluations. For each site, diachronic and synchronic variations have been combined. Results obtained on both sites converge towards the following conclusions :

. the morphological evolution of the soil surface, as assessed here, accounts for most of infiltrability variations, whether diachronic or synchronic:

. closest relations are obtained with the Dlim index, determination coefficients r^2 being higher in this case. This is consistent with the fact that Dlim is related to crust thickness, which can influence infiltrability (through z_i in relation 1) since matric suction h_i at the bottom of the crust is different from zero.

TABLE 3 : Statistical relations between measured infiltrability I (mm/h) and morphological criteria

SITE	MORPHOLOGICAL CRITERIA Sp (%)	Dlim (cm)
PALAISEAU (20 % Clay)	I = 10.0 exp (-0.029 Sp) n = 11, r^2 = 0.78	I = 10.1 exp (-1.20 Dlim) n = 11, r^2 = 0.89
MONTLUEL (10 % Clay)	I = 44.9 exp (-0.019 Sp) n = 12, r^2 = 0.78	I = 42.0 exp (-0.64 Dlim) n = 12, r^2 = 0.90

On the other hand, relations presented in table 2 exhibit clearly higher infiltrability for the loamy soil than for the clayey-loam soil, with the same surface state; for Sp = 100 % (surface entirely covered by a structural crust), calculated infiltrability would be about 6.6 mm/h on the former, vs. 0.6 mm/h on the latter. These results are to be compared with densities measured on crusts fragments taken from these 2 sites : 1.58 and 1.75 respectively. Such a contrast, primarily due to the textural difference (FIES and STENGEL, 1981), seems quite liable to induce a variation of hydraulic conductivity of the same order of magnitude as that deduced from morphological indicators through previous relations.

CONCLUSION

When obtained in conditions of a high initial moisture content and no ponding water under the sources, results provided by the proposed method seem to be consistent both with observed behaviour of the soil under natural rainfall, and with morphological characterization of the more or less crusted topsoil. Associating these results with direct observation of water excess formation under rainfall of known intensities, provided us with a fairly detailed description of the crusting-related progressive decrease of infiltrability. On both studied sites, a decrease of about one order of magnitude was recorded from the fragmentary initial state to the depositional crust final state. Considering simplicity and low costs of operating procedures, the method could be helpful in many purposes concerned with soil behaviour in the field. Theoretical developments are now necessary in order to precise the meaning of q_i values obtained in relation to hydraulic conductivities of crusts, and to define rigourously its conditions of validity.

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