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EVALUATION OF CRUSTING APTITUDE ON SIEVED SOILS. A NEW APPARATUS

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1. Introduction

The problem of crusting and surface sealing of certain soils has always presented a problem for growers of annual crops from seed because seedlings, if they emerge at all, can do so only through cracks in the crust. Formation of a crust soon after a crop is sown may allow only few seeds to emerge so that the crop has to be replanted. Crops particularly sensitive are small seeded grasses [23] and vegetables as carrot [32], onion [33] and also bean [27] and sugarbeet [12]. Interest in the topic as a research objective arose following the studies by Richards [26] which used the modulus of rupture technique to define the critical crust strength of artificial crusts. Crusting is a complex process [3, 9] resulting above all from the action of some meteorological conditions on soils in which fine and rough silt prevail, with low clay and organic matter content[1] [13]; sandy soils can also be subjected to crusting [15].

Crusting develops over time and deepens by several millimetres under the action of falling drops of water during heavy rains or sprinkler irrigation on aggregates exposed at the soil surface. These events during wetting leading to a collapse of soil aggregate by slaking, primary particle dispersion, micro-sedimentation near the soil surface or in larger pores. If top soil shrink on drying the porosity of superficial layer is reduced and small hard flat clods are formed reducing seedlings emergence. When the soil expands again, with the addition of water, some water infiltration occurs and, the soils become muddy, and scarcely permeable to both water and air, until the subsequent exsiccation [5, 6, 17, 31].

The process has been analysed from various different perspectives and different mechanisms, more or less connected, have been proposed (disruptional layer, skin layer, washed in-out layers) all in some way linked to a weakness of soil structure stability [2, 9, 18, 22, 24].

It follows that the methods of soil structure stability evaluation, although the uncertainties, are outnumber than that turned at proneness assessment of soil to crusting and loss of permeability of the top layers. This latter aspect, besides, has been mostly studied by mechanical resistance of standardized crusts brought to the dry state in laboratory, while the evolution of the crusting development over time is widely underestimated despite many researches about the decreasing of infiltration rate during rainfall [4, 10, 20, 21].

By designing and constructing this apparatus it was intended to estimate the reduction of hydraulic conductivity over time of superficial soil layer as a consequence of crusting, using soil having structure like to that freshly tilled.

2. Description of experimental apparatus

The principles of the method consist of exposing a given layer of sieved and dried soil sample, to the action of a simulated rain for a short time and repeated for an adequately long duration. The evolution of the hydraulic conductivity of the sample submitted to this treatment is continuously followed.

An air dried sample of the soil to be tested is first disaggregated and sieved to a chosen diameter (e.g. under 2 mm). An open box (fig. 1s; about 100 x 75 x 65 mm^3) with large holes (5 mm in diameter at the bottom, covered by a nylon sheet), is filled with 20 mm of perlite also covered by a nylon sheet. The box is then completely filled to its rim with washed river sand (0.02 mm<d<2mm).

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[1] The FAO crusting index is:

$$CI = \frac{(1.5 \times \text{fine silt }\%) + (0.75 \times \text{coarse silt }\%)}{(\%\text{ clay}) + (10 \times \text{o.m. }\%)}$$

being fine silt (0.02-0.002 mm), coarse silt (0.05-0.02 mm), clay (<0.002 mm) free of organic matter and all in per cent of fine dry matter.

On the flat sand surfaces of the box a square plexiglas frame (fig. 1t; internal side 50 mm; height 20 mm) is placed and the sieved soil material is poured in up to the rim.

A second plexiglas frame similar to the first one (fig. 1v; internal side 50 mm, and 10 mm height) is placed on the first frame after smearing the surface between the frames to prevent water leakage from joint.

The sand box is then immersed in a large container full of deionised water, until the upper sand level. The soil sample is then wetted by ascensum, and is ready to be submitted to the treatment.

The mechanical part of the equipment is formed by of steel frame which supports a continuous current engine 180 W (fig. 1m). By means of a gear (fig. 1g) the engine rotates a metallic disc (D) with an internal diameter of 288 mm and a raised border of 30 mm. The frequency of the disc is 0.05 Hz (3 revolutions per minute). A hallow pivot permits the outflow of excess water.

The above-mentioned sand box complex is placed on the disc against its border. Suspended above the sand box (18 mm from the sample surface) a rain sprinkler (fig. 1sp) is placed parallel to the radius of the disc plane, so that it rises about 2 cm out of the disc border. The sprinkler is made up of a plexiglas cylinder 100 mm long with a 20 mm internal diameter. It is closed at one end and a series of 20 holes, 1 mm diameter, are bored along a directrix line on the lower side of the cylinder, 5 mm apart. The opposite end of the sprinkler cylinder is connected by a plastic tube and a water tap (fig. 1r) to the water source which is delivered at constant pressure by a Mariotte device. The intensity of the rain can be regulated by fixing a suitable source distance, obtaining a different head pressure at the sprinkler. In practice has been used a source distance of 116 cm.

3. Model and Calculations

To evaluate the volume of water captured by the sample when passing under the sprinkler, it was assumed that the effectively used square frame (A'B'C'D'; fig. 2b) having side *l* be substituted by the quadrilateral ABCD as in fig. 2a. This latter has the same area as the square A'B'C'D' and is delimited by the concentric arcs AB and CD and by the segments

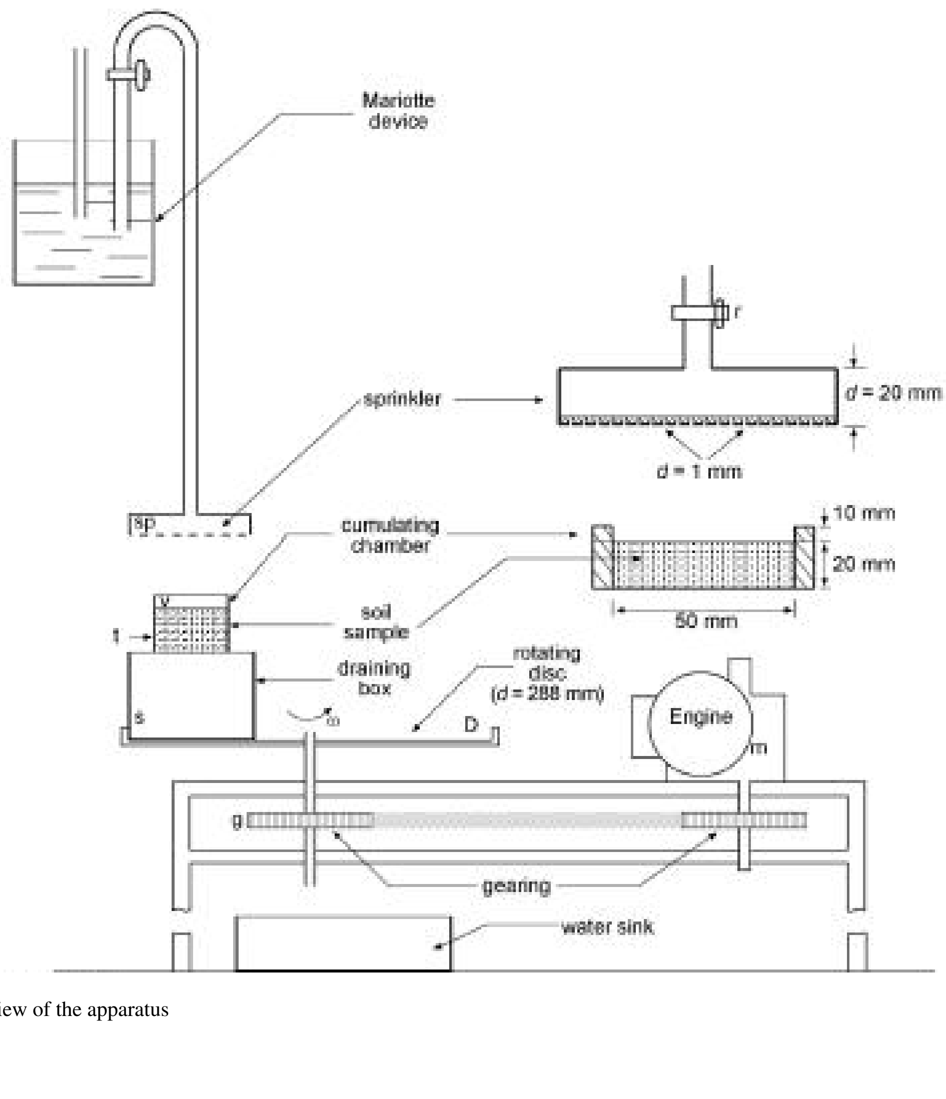

Fig. 1 - Overall view of the apparatus

AD and BC taken on the radii R, r in m of the rotating disc and having the length R-r. Since the two figures have an equal area, this can be calculated as

$$A_s = l^2 \qquad 1a)$$

$$A_q = \alpha_r (R^2 - r^2)/2 \qquad 1b)$$

thus

$$l^2 = \bar{l}\,(R-r) \qquad 1c)$$

where $\bar{l}$ in rad m is the mean arc length (EF in fig. 2a); it can be also described by

$$\bar{l} = \frac{\alpha_r}{2}(R+r) \qquad 1d)$$

where α_r in rad is the angle described during the passage of the sample under the sprinkler, which occurs in the time t_i. This time is evaluated as

$$t_i = \alpha_r(\tau/2\pi) = \alpha_r/\omega \qquad 1e)$$

in which ω in rad s^{-1} is the angular speed of the rotating disc and τ in s its period.

In this model l of the square in fig 2b is assumed equal to $\bar{l}$ in fig. 2a. The evaluation of the mean wetting time is given by dividing the mean arc length by $\omega\bar{r}$, thus

$$\bar{t} = \frac{\bar{l}}{\omega \bar{r}} = \frac{\bar{l}}{\omega \frac{(R+r)}{2}} = \frac{2\bar{l}}{\omega (R+r)} \qquad 2)$$

where $\bar{r}$ is the radius respective to $\bar{l}$.

In this expression one knows that $\bar{l}$ is 0.05 rad m; ω is equal to 0.314 rad s^{-1}; R must be taken from the distal end of the frame containing the sample, to the rotation centre, i.e. 0.120 m, while r is left free to vary for successive integration.

On the other hand the discharge per unit length of the sprinkler is calculated with

$$Q_L = V_d/t_d L_d \qquad 3a)$$

where V_d in m^3 is the volume discharged per unit time t_d in s per unit sprinkler length L_d in m. In the experiment the value of Q_L taken has been:

$$Q_L = \frac{517.58\times10^{-6}\ \mathrm{m}^3}{10\times10^{-2}\ \mathrm{m}\times 60\mathrm{s}} = 8.63\mathrm{x}10^{-5}\ \frac{\mathrm{m}^2}{\mathrm{s}}$$

The water volume (V_c) captured by the soil sample is given by Q_L multiplied by the mean wetting time ($\bar{t}$) under the sprinkler and by the length of radial side (R-r). When moving from r to R, however, because the length of the concentric arcs changes too and so does the time of exposure to the sprinkler action (for the same disc rotation speed v) the volume V_c changes accordingly. It is then necessary to integrate the water (V_c) captured by all elementary anulus dr from r to R, thus

$$V_c = \frac{2Q_L\bar{l}}{\omega}\int_r^R (R+r)^{-1}\,\mathrm{d}r \qquad (4a)$$

in which only Q_L, $\bar{l}$, ω, R are known. The solution of the (4a) in r is :

$$V_c = \frac{2Q_L\bar{l}}{\omega}\ln[r+R]_r^R = \frac{2Q_L\bar{l}}{\omega}\left[\ln 2R - \ln(R+r)\right] \qquad (4b)$$

which is a function of Q_L only if r is known.

Furthermore

$$R+r = 2R-(R-r) \qquad (4c)$$

as in the case of our instrument and with the values previously given, the V_c stored during 1 passage under the sprinkler is

$$V_c = \frac{2\times 8.63\times10^{-5}\times 0.05}{0.314}\times[\ln 0.24 - \ln(0.24-0.05)] = 6.4\times10^{-6}\ \mathrm{m}^3 \qquad (4d)$$

The thickness h_c of the stored water (including the very short drainage) is given by dividing the value of V_c by the area A_s of the square frame, equal to 25×10^{-4} m^2 thus

$$h_c = V_c/A_s = 2Q_L\bar{l}\left[\ln\frac{2R}{2R-(R-r)}\right]\Big/\omega A_s \qquad (4e)$$

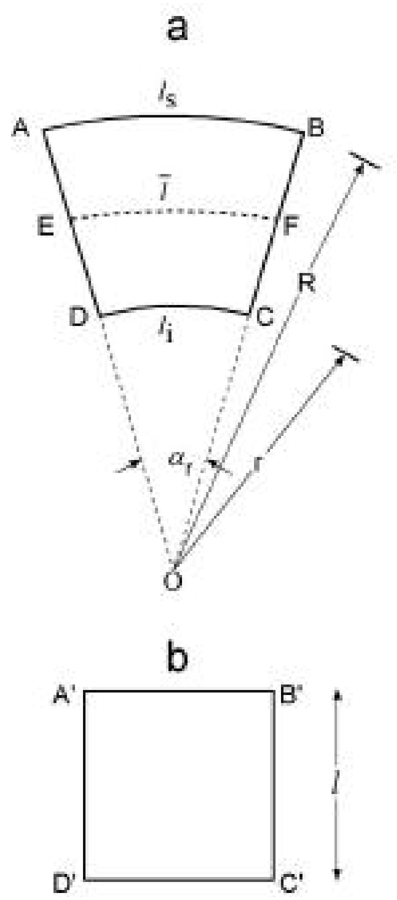

Fig. 2 - Outline of the equivalence of the square A'B'C'D' and the quadrilateral ABCD.

In the most frequently observed case, the stored water h_c has been equal to 0,002568 m, i.e. 2.57 mm (experimentally it ranged from 2.5 to 2.7 mm).

The water stored during one passage under the sprinkler must drain through the saturated sample as the hydraulic conductivity in the sand box is higher by many order of magnitude respect to the soil sample and therefore offer a negligible resistance to water flux. The system behaves then as a variable head permeameter [16] and the Darcy low can in this case be written as

$$\frac{dh_c}{dt} = -K_s \frac{\Delta\psi_t}{s} \tag{5a}$$

according to which the water dh_c entering the sample in time dt is given by the product of hydraulic saturated conductivity K_s divided by the sample thickness (s) and multiplied by the difference of the total head (Ψ_t) of the water considered; this total head is the water head on the soil sample (h_c) plus the thickness of the soil sample (s). Equation 5a can be written therefore as

$$dh_c = -K_s \frac{h_c + s}{s} dt \tag{5b}$$

and then:

$$-\int_0^t dt = \frac{s}{K_s} \int_{h_c+s}^{s} \frac{dh_c}{h_c + s}$$

so that after integration and evidencing K_s:

$$K_s = \frac{s}{t} \ln\left(\frac{h_c + 2s}{2s}\right) \tag{5c}$$

which shows that h_c reduces to zero in time t, and gives the value K_s for the sample (which remain constantly saturated). The time required for draining V_c is approximately (to less than 1 revolution time) the product of period τ, equal to $2\pi/\omega$, by the number of revolutions before a new wetting (n).

Therefore the saturated conductivity is calculated as

$$K_s = \frac{s\omega}{2\pi n} \ln\left(\frac{h_c + 2s}{2s}\right) \tag{6}$$

where K_s is valid for the mean of the sample thickness (s = 0.02 m) and is calculated gauging n by view.

In reality, the crust is not homogeneous. There is an effective variation in the hydraulic conductivity K in each soil sample thin layer when decreasing downward as the test proceeds after the first sprinkling [8, 11]. It is therefore more correct to consider the hydraulic conductance per unit horizontal area in s^{-1}, which is given [1] by K_s/s, sometimes indicated with symbol L_p [T^{-1}] or by its reciprocal [28, 30].

4. Notes on the method

The proposed method is time-consuming especially when the soil tends to form resistant crust with low conductance. A possible automation could suppress the disc rotation and consider the irrigation of a given surface. This would however require too many details in the choice of a standard rain intensity, drop diameter, surface distribution and so, in place of the sprinkler distribution from a linear source.

The assumption of the chosen quadrilateral instead of a square with equal areas could be demonstrated to play some role when integrating the captured rain from r to R. Compared to the complexity of the exact solution, the approximation used was felt acceptable.

Certain aspects of the results are particularly interesting. When the K_s values, observed on soils pre-saturated for 1 hour before the sprinkling, are plotted against time t (t is inclusive both of wetting time and drainage) both on a logarithmic scale, the values, with few exceptions, show a straight-line pattern (fig. 3). The limit for this conductance tends from 1 to 20×10^{-6} s^{-1}. The initial value and slope of these graphs are a clear measure of structure stability as a function of time. The role of the initial soil diameter may differ for different soils [7]. In some case the soil show a high degree of aggregation and do not collapse, immediately, to the beating action of simulated rain and an initial platform is evident (fig. 3a bottom left). For some soils the proneness to crusting has been evaluated as function of initial saturation of the sample. Soils ranked as resistant to crusting according to FAO index do not show K_s value very different if they were saturated by ascensum for 1 h or not before the sprinkling; on the contrary among the less resistant to crusting, those put without pre-saturation under the sprinkler action show in time a large decrease in K_s value respect to the saturated one. This is highlight by the larger direction coefficient of regression line (fig. 4b).

Another interesting graph (fig. 5) is obtained expressing log K_s as a function of the total water volume corresponding to that ordinate. The total water volume V_Σ in cm^3 captured by the soil sample is calculated with :

$$V_\Sigma = V_c \times N$$

where N is the number of wettings. The results multiplied by 10 express the water passed through in mm.

Of the many possible exponential formulas to fit these data [15, 20] the graph which seems preferable is the following hyperbola (fitted using a non linear regression program):

$$\log K_s = \frac{a + bV_\Sigma}{c + V_\Sigma}$$

where a - bc are curvature parameters of hyperbola; a/c is the initial value of log K_s (corresponding to V_c = 0) and b is the horizontal asymptote indicating the limit to which the curve of log K_s finally tends (the graph log K(log t) fails to give this information).

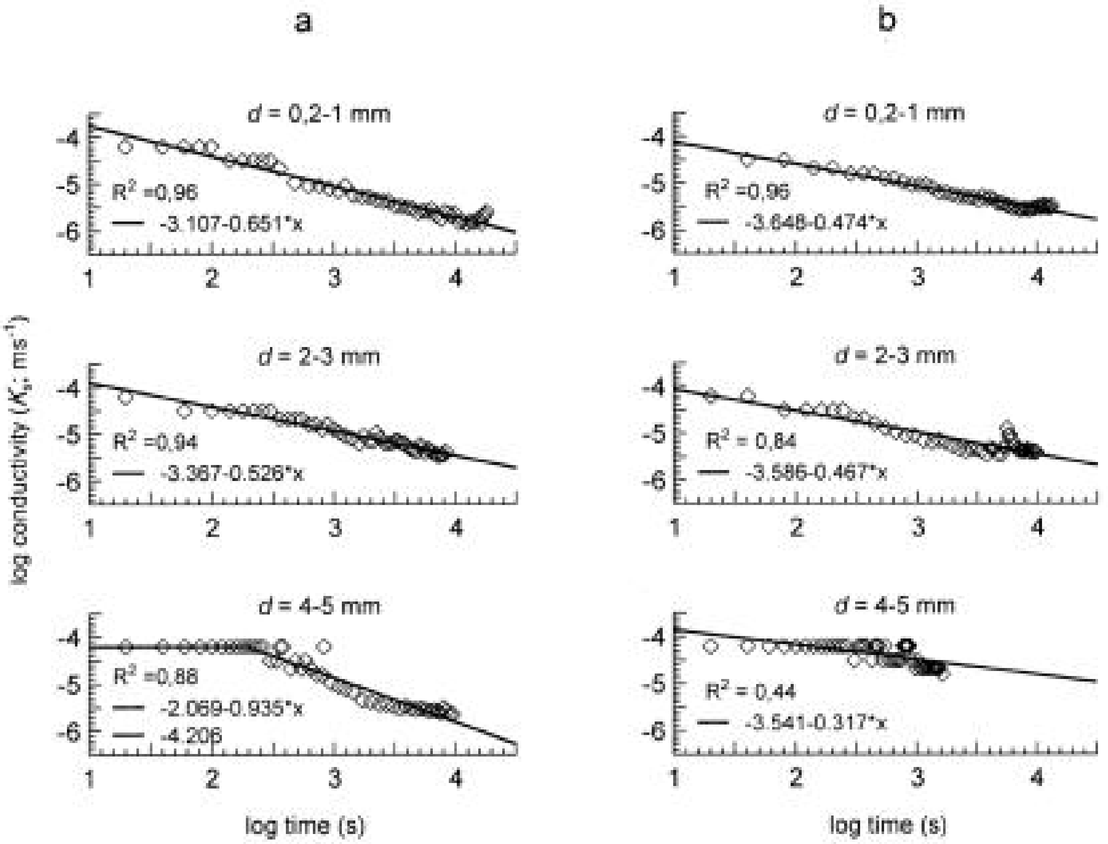

Fig. 3 - Log-log plot of hydraulic conductivity K_s, in ms^{-1} versus time in s for two soils. Left : field of Cadriano; right field of Carpi. The hydraulic conductivity varies with the diameter of the sieved crumbs. With larger crumbs there is an initial platform indicating water resistance.

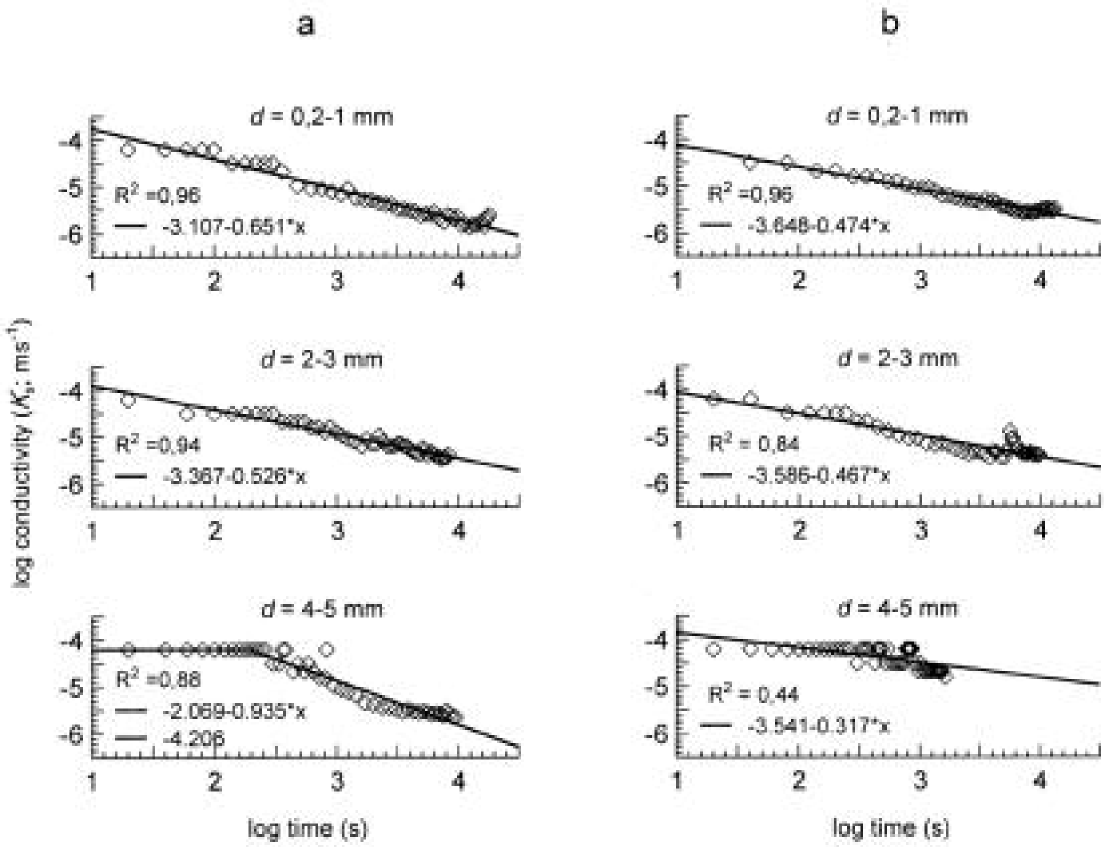

Fig. 4 - Effect of pre-saturation of the sample before starting the sprinkling. Left : field of Molinella; right: field of Ferrara. The effect of pre-saturation is more important in the less resistant soil of Ferrara.

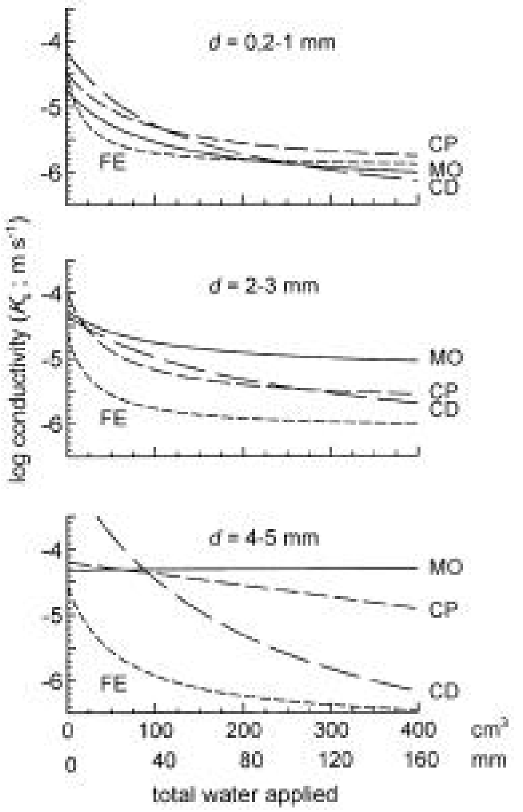

Fig. 5 - Comparison of different fields for the hydraulic conductivity (K_s) as function of the total water applied (CD = Cadriano; CP = Carpi; FE = Ferrara; MO = Molinella)

5. Conclusions

The rather simple equipment here described offers the possibility to follow the evolution of the change of hydraulic conductivity in a layer of sieved dry soil when subjected to a repeated series of sprinkle irrigation. The instrument permits the regulation of rain intensity and of the water pressure.

The results can be expressed in two ways: (a) the plot of log K as a function of log t is usually linear and the parameters of this line express the resistance of the crusts to the water flows. b) the expression of log K as a function of the total water passed fits satisfactorily fits a hyperbola, the parameters of which give a measure of curvature, and more interestingly, give an evaluation of the limit of log K in the log term.

The role of different soil resistances, of different crumb diameters, and different pre-wettings of the soil sample are shown as possible variants.

The apparatus could be used to study the effect of water drop characteristics (energy, momentum, etc.).

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SUMMARY

Soil surface crusting has severe agricultural and environmental effects. The action of beating rains can destroy soil surface structure and in some cases lead to surface sealing and crusting which, in turn, reduce soil conductivity, seed emergence and increase the runoff hazard. The susceptibility of different soils to crusting was studied by a new experimental apparatus and model. A micro rain – simulator mounted on a rotating disc sprinkles water on soil sample and after a certain time (or revolutions of the disc) the water ponded on soil surface completely percolates and water is again applied to the soil surface. The model was used to follow the variation of soil hydraulic conductivity as a function of time or total water applied during the crust formation. The effects of soil sieved crumbs and duration of pre-saturation were investigated during the crust formation. For some soils crusting decreases along the sprinkling events, with the diameter of aggregates presenting high values; sometimes significant structural deterioration in the aggregate of higher diameter occurs after a initial resistance to crusting as evidenced by a sharp reduced hydraulic conductivity. The role of the pre-saturation time seem more important for less resistant soils.

Keywords: crusting, hydraulic conductance, experimental apparatus.

List of symbols

A_q	*area of the square, m²*
A_s	*area of the quadrilateral, m²*
h_c	*water thickness stored by soil sample, m*
l	*side length of the square, m*
L_d	*unit sprinkler length, m*
$\bar{l}$	*mean arc length, rad m*
Q_L	*discharge per unit length of the sprinkler,* $m^2 s^{-1}$
R	*distance from rotation centre to the distal end of the disc frame, m*
r	*distance from rotation centre to the proximal side of the frame, m*
R-r	*length of the radial side, m*
$\bar{r}$	*radius of* $\bar{l}$*; equal to* $\frac{(R+r)}{2}$*, m*
t	*time required for draining* V_c*, s*
t_d	*unit time, equal to 60 s*
t_i	*time taken by the sample to pass under the sprinkler, s*
$\bar{t}$	*mean wetting time of the sample under the sprinkler, s*
V_c	*water volume captured by the soil sample,* m^3
V_d	*volume discharged per unit time* t_d*,* m^3
α_r	*angle described during the passage of the sample under the sprinkler, rad*
τ	*period of rotating disc, s*
ω	*disc rotation angular speed,* $rad\ s^{-1}$