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NOTES

A RAINFALL SIMULATOR WITH NONREPETITIOUS MOVEMENT OF DROP OUTLETS[1]

W. B. KLEIJN, J. D. OSTER, AND N. COOK[2]

Abstract

Problems encountered in simulating uniform rainfall inside the laboratory are discussed. A new rain simulator is described which eliminates nonuniformity by a nonrepeating movement of drop outlets. The model tested applies rain to a ring-shaped area of 0.21 m^2 with a coefficient of variation of about 7%. By using drop outlets of different sizes, one also can adjust the raindrop size distribution.

Additional Index Words: **rainfall applicator, rainulator.**

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RAIN SIMULATORS are used for laboratory studies of soil detachment, crust formation, and infiltration. They may be constructed with either single or multiple outlets (Mutchler and Hermsmeyer, 1965). The latter are discussed here.

Multiple outlet simulators often fail to provide uniform rain. The causes of nonuniformity can be divided into two categories: unequal flow rates through the individual drop outlets, and repetition of drop impact location. Unequal flow rates through individual outlets are a major problem when a single pump is used to drive water through all the outlets. Within the range normally found in rain simulators, the flow is laminar and Poisseuille's law applies; the flow rate is linearly related to the fourth power of the hydraulic radius. Therefore, a relatively small difference in the

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hydraulic radius of the outlet tubing can cause large differences in flow rate among outlets.

Another reason for nonuniform flow through the outlets is entrapped air. The forces acting on any entrapped air bubble are: the force due to the density difference between water and air, the surface forces on top and bottom of the air bubble, and the force which causes the flow through the outlets. Entrapment of air can be reduced by avoiding abrupt decreases of the inside diameter of the flow tube and by using de-aired water. If de-aired water is not used, a pressure > 100 kPa will prevent bubble formation due to degassing. Often air bubbles can be removed by applying high flow rate or by bending the tubing so that the dominating forces work toward the tube outlet. A filter in the water supply tubing is recommended to prevent clogging; likewise, the outlets should be cleaned to prevent salt accumulation. The design proposed by Romkens et al. (1975), in which each drop outlet is provided with water by a separate syringe, eliminates the problems mentioned above. This simulator provides a nonrepeating movement of the outlets via an intricate mechanism using four motors.

The simplest rain simulators have stationary drop outlets. However, stationary outlets will cause deep impact holes directly beneath the outlets. Munn and Huntington (1976) describe a field rain simulator of limited height (3.5 m) which uses air turbulence to randomize the impact of drops. Ekern and Mickenhirn (1947) report that from heights of 10.5 m, the drop impact is also randomized inside the laboratory. Another example of this is given by Walker et al. (1977). However, in most experiments (including those from greater height), moving outlets are used to obtain a more uniform rain (Epstein and Grant, 1966; Romkens et al., 1975). Usually the movement is repetitious, which often results in a fixed pattern of raindrop impact. Random raindrop impact can be simulated by a movement that satisfies the following conditions: (i) the average rate of raindrop impact on any area (of certain size) tends to be equal as the time interval of rain application approaches infinity, and (ii) over a short interval the raindrop impacts are reasonably spread over the entire impact area.

Thus, we designed a rain simulator that uses a nonrepetitious movement of the outlets to achieve uniform application of raindrops. In this rain simulator, each outlet covers the entire experimental area with a uniform rain. Different flow rates from the various drop outlets do not influence overall rainfall uniformity. The movement of each drop outlet is a combination of two motions—rotation and oscillation. Rotation is provided by mounting the outlets on a rotatink disk; oscillation is provided by sliding the outlets radially across the disk in a slot (see Fig. 1). The radial movement of all outlets is controlled by a cam that has the same center of rotation as the rotating disk. The outlets are mounted on cam followers mechanically held against the cam. A nonrepeating movement is obtained when the ratio of the rotational speeds of the disk and the cam cannot be written as a ratio of integers. Thus condition 1, as mentioned previously, is satisfied. Condition 2 may require some experimentation to find a suitable ratio. To obtain uniform rain over the experimental area, the equation that has to hold for the radial movement is,

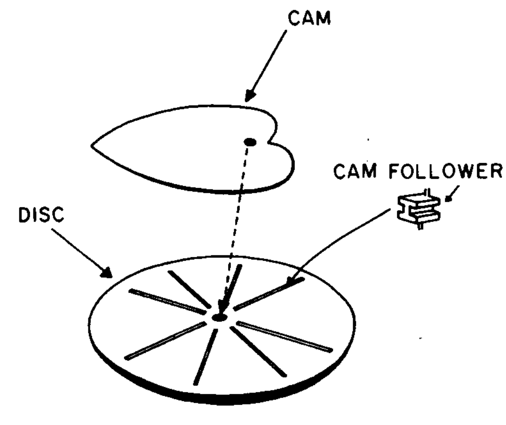

Fig. 1—Principle of the new rain simulator.

$$2\pi r \Delta r = k_1 \Delta t, \qquad [1]$$

where r is the radius, t is time, and k_1 is a constant. Equation [1] relates surface area (on the left-hand side) with the time interval Δt of rain application. Thus, we can write the following differential equation,

$$\mathrm{d}r/dt = k_2/r \qquad [2]$$

where k_2 is a constant. At $r = 0$, the velocity is infinite; since this is physically impossible, the experimental area is necessarily restricted to a ring. As the cam and disk rotate with constant angular velocities, we have

$$dr/\mathrm{d}\theta = k_3/r \qquad [3]$$

where θ is the angular coordinate and k_3 is a constant. Equation [3] can be integrated with the following boundary conditions,

$$\begin{aligned} &\text{at } \theta = 0,\ r = R_{\min} \\ &\text{at } \theta = \pi,\ r = R_{\max} \end{aligned} \qquad [4]$$

where $R_{\min}$ and $R_{\max}$ represent the minimum and maximum radius of the cam and $R_{\max}$ is 180° away from $R_{\min}$. The resulting solution is (for $0 < \theta < \pi$):

$$r = \left[\frac{(R^2_{\max} - R^2_{\min})}{\pi} + R^2_{\min}\right]^{1/2}. \qquad [5]$$

This equation describes the cam shape, with each half of the cam being symmetrized.

The rotation speeds of disk and cam have to be low to avoid significant horizontal displacement of the drops during the fall. Over a time of fall Δt the radial displacement d can be approximated by:

$$d = \{[r^2 + (r\frac{\mathrm{d}\phi}{\mathrm{d}t}\Delta t)^2]^{1/2} - r\} + (\mathrm{d}r/\mathrm{d}t)\,\Delta t \qquad [6]$$

where $\mathrm{d}\theta/\mathrm{d}t$ is the rotational speed of the disk. The first term in Eq. [6] is the radial component of the displacement due to the centripetal force and the second term is due to the radial movement of the cam followers. Note that r and $\mathrm{d}r/\mathrm{d}t$ are functions of the rotational speed of the cam relative to the disk. Since the drop size is a function of the outlet diameter and shape, the drop size distribution can be adjusted by using outlets with different diameters or shapes. Experimentation will have to be done to obtain a controlled drop size distribution because calculation

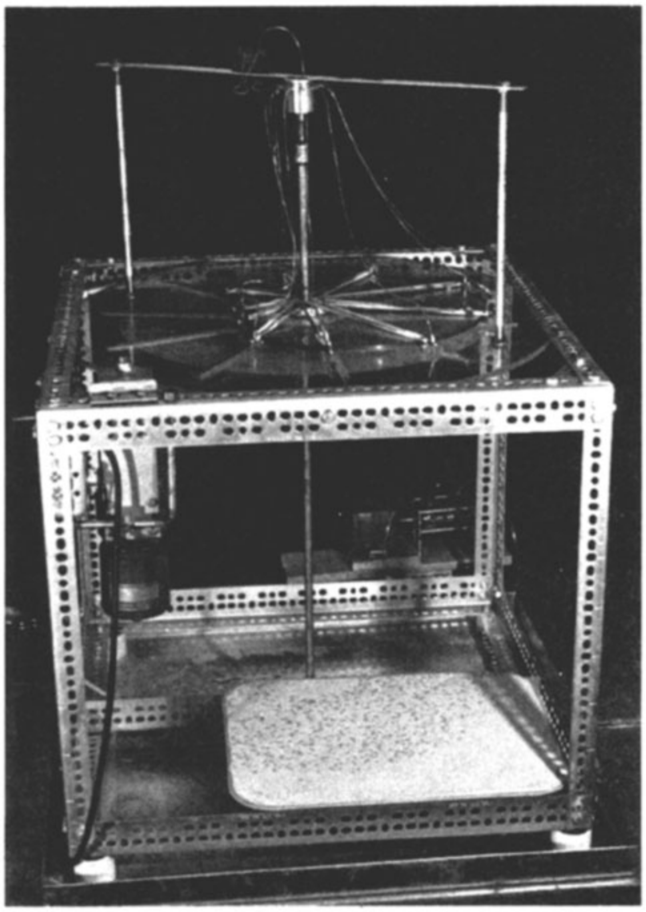

Fig. 2—The rain simulator. The tray with sand shows the drop impact location after several minutes.

of the tubing resistance is often difficult (Ekern and Mickenhirn, 1947). If a particular drop size distribution is desired, problems due to air bubbles, unpredicted tubing resistancies and clogging must be resolved. These problems, however, do not influence the uniformity of rainfall. Information about raindrop size distribution is available from Laws and Parsons (1943).

The number of drop outlets is determined primarily by the highest rainfall rate desired. To prevent a continuous flow from the outlets at high rainfall rates, more outlets have to be used.

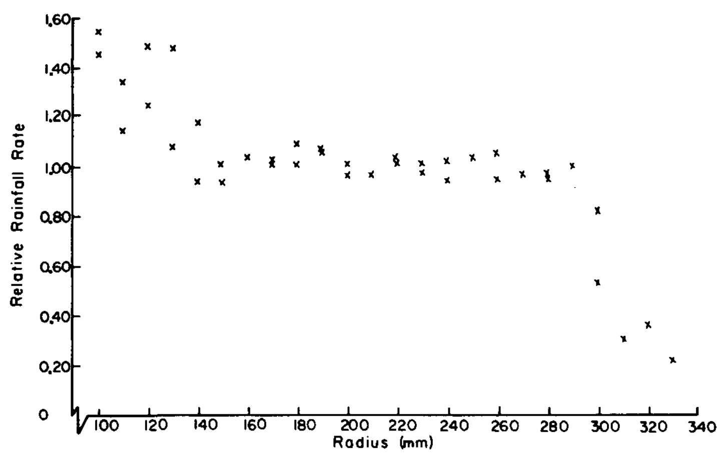

Fig. 3—Relative rainfall intensity as a function of the radius.

Table 1—The measured coefficient of variation of rainfall.

Rain intensity	Time of application		
	30 min	1 hour	2 hours
	%		
6 mm/hour	7.5	6.6	6.0
7.8 mm/hour	4.9	6.5	6.7

Construction Details of the Rain Simulator

The rain simulator described here was constructed to rain on samples no larger than 15 cm in diam. The steel frame of the simulator is 0.70 by 0.77 m. The rotating disk, 760 mm in diam, and cam are made of plastic (thickness 12.7 mm). The disk has slots for 10 outlets. The disk is held in place by three horizontal and three vertical ball bearings. The shape of the cam is based on Eq. [4], with a maximum radius of 305 mm and a minimum radius of 0 mm. At the center, the curvature of the cam was smoothed and it was also corrected for the spacing between cam and outlet. A teflon sheet is placed between the disk and the cam to minimize friction. The cam is centered in the disk by a ball bearing and is driven by a crossed V-belt, which can be adjusted by a tension pulley. Crossing the V-belt slows down the oscillating movement (both cam and disk rotate in the same direction). The disk is driven by an adjustable rubber wheel which presses against the edge of the disk. The rubber wheel and drive pulley are mounted directly on the drive shaft of the motor. The disk rotates at a speed of approximately 1.1 rpm; the cam, at approximately 7.5 rpm. Then the radial displacement of the drop falling from 600 mm (neglecting air resistance) as calculated from Eq. [6] is < 1 mm between 130 and 300 mm radius. Water is delivered by a single pump (Cole Parmer 7545)[8] to the distributor through the center of rotation of both disk and cam. From the distributor, which rotates with the disk, 10 flexible hoses lead to hypodermic needles (22G2) which serve as outlets. The hypodermic needles are mounted in plastic cam followers, which are held against the cam by rubber bands (Fig. 2). The number and size of the hypodermic needles limit the rainfall at 9 mm/hour. At higher flow rates, the outlets produce a continuous flow. For the machine described, the rate can be quadrupled by doubling the number of slots and needles per cam follower. Further increases could be achieved by refinements which could permit additional slots.

Figure 3 shows the relative intensity of the rainfall as a function of the radius after 2- to 3-hour rains at an intensity of 5 mm/hour from a height of 600 mm. The rainfall was measured in beakers with a diameter of 55 mm. Taking into account the width of the beakers, the figure shows that the rain simulator gives a uniform pattern between a radius of 130 and 300 mm. Table 1 shows the coefficient of variation obtained from similar measurements. Using a flow equivalent to 6 mm/hour, the standard deviation of the outflow from the individual drop outlets was found to be 26% over a 30-min interval. Since the coefficient of variation of rainfall does not show significant changes with time or intensity, the variation likely is mainly due to inaccurate measurements and lack of precision in the shape of the cam.

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[8] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the USDA.

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INFLUENCE OF A COMPACT ZONE ON SOLUTE TRANSPORT DURING INFILTRATION OF WATER[1]

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Abstract

In most soils, continuous plowing results in the formation of a compact zone below the plowing depth. Laboratory studies were conducted to examine the effect of such a zone on the displacement of chloride (Cl^-) during infiltration of water. A compact zone of 4- or 8-cm thickness of 1.62 g/cm³ or 1.80 g/cm³ bulk density was created at a depth of 8 cm in soil columns. A surface-applied slug of calcium chloride was leached with 4 or 6 cm of distilled water. The presence of a compact zone in the soil profile pushed the Cl^- peak deeper, dispersed the ions in a narrower region, and increased the peak Cl^- concentration. Increasing bulk density and thickness of a compact zone increased the depth of the peak Cl^- concentration.

Additional Index Words: **compact zone, chloride peak concention.**

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A layer of compact soil immediately below the depth of plowing called a plow sole, and traffic soles are commonly observed in cultivated soils (Baver et al., 1972). Almost every agricultural implement creates a sole of some kind under moist soil conditions (Trouse and Baver, 1965). Tillage implements tend to produce localized compaction by friction at the soil-metal interface (Nichols et al., 1958). Reaves and Cooper (1960) reported that maximum compaction produced by track-type tractors occurred at about the 8-cm depth. The density and thickness of a compact zone depends upon the type of implement and traffic, nature of the soil, crop management, water content of the affected layer, and duration for which the compressive force works.

A compact zone within the root zone could hinder plant growth by decreasing water permeability and aeration, and restricting penetration and proliferation of plant roots. Presence of such a zone may also affect plant growth through affecting nutrient movement in the soil profile. In this note we report the effect of compacted zone on the movement of chloride (Cl^-) in the soil during infiltration of water.

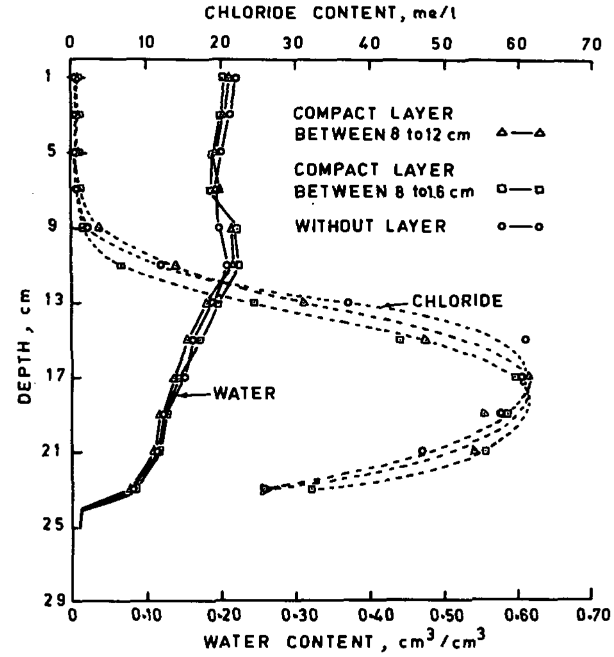

Fig. 1—Water and chloride distribution without and with compact zone (D_b = 1.62 g/cm³) 14 hours after a 4-cm water application.

Materials and Methods

Choa sandy loam soil (a Typic Ustochrept) containing 68.2% sand, 17.3% silt, 14.5% clay was packed to a bulk density of 1.40 g/cm³ in 50 cm long and 10 cm diam columns. Compact zones with bulk density of 1.62 g/cm³ and 1.80 g/cm³ and of 4 or 8 cm in thickness were created at a depth of 8 cm. Compaction at 8- to 12-cm and 8- to 16-cm soil depths was achieved by adding distilled water equal to 4 and 8% by weight, respectively, to the air dry soil (0.5% water by weight). The moistened soil was then packed with 20 strokes of a wooden rod. The water content and the depth of compaction were initially ensured by dry runs. The columns were allowed to dry to air dry conditions. This was ensured by weighing the soil columns to an accuracy of ± 0.5 g. The columns were installed in a constant temperature room (25 ± 1°C).

Twenty five milliliters of 20% calcium chloride ($CaCl_2$) solution were uniformly sprinkled over the column surface followed by application of 4 or 6 cm of distilled water by maintaining a constant head of 1 cm. Columns were covered with polyethylene sheet to check evaporation from the soil surface. The columns were sectioned in 2-cm depth increments after allowing fixed time for infiltration and redistribution. Chloride concentration in the soil samples was determined in a 1:2 soil-water extract.

Results and Discussion

The presence of a compact zone in the soil columns affected the distribution of water and Cl^- from a surface-applied $CaCl_2$ slug. The distribution and depth of the Cl^- peak 14 hours after applying 4 cm of water did not change regardless of the thickness of the compact zone of 1.62 g/cm³ bulk density (Fig. 1). The depth of wetting front after 14 hours was 24 cm. As the wetting front moved to the 32-cm depth after a lapse of 133 hours, sharp differences were ob-

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