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A PORTABLE RAINFALL SIMULATOR FOR SOIL CAPPING STUDIES

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ABSTRACT

Design considerations encompassing tropical rainfall conditions were used to design this portable rainfall simulator, tested and found effective for capping, infiltration and erosion studies. It provides controlled rainfall intensity, velocity and energy for laboratory studies. The rainfall simulator uses 0.8 mm external diameter hypodermic needles in a 20 C 20mm square array, with drops falling from the tips at essentially zero velocity. The average drop size was 2.89 mm. The unit is hoisted to a height of 6m to provide drop velocities of 7.9 m/s, which is 90% of the terminal velocity of natural rain, giving energy of 28.96 J/m^2/mm from a precipitation intensity of 90 mm/h. The uniformity of water application over the covered area of 0.16 m^2 ranged from 82-89%. Water to the perspex chamber was supplied from a tank by means of a peristaltic pump capable of providing precipitation intensities of up to 575 mm/h. The intrusion of air bubbles was overcome by using de-aired water, making the joints airtight and priming. Needles could be changed to alter drop sizes but the spatial distribution of raindrops remained fixed. The vertical height requirement to achieve acceptable raindrop velocities was also high.

Keywords: Portable rainfall simulator, design, construction and testing, controlled rainfall intensity, uniformity of water application, capping studies

1. INTRODUCTION

The paper describes the design, construction and testing of a rainfall simulator that was used in the laboratory work for capping studies. Natural rainfall is the main cause of sealing in soils (Hudson, 1981) but it is unpredictable, difficult to control and is frequently perverse, hence the need in research to create artificial rain to:

(i). Accelerate the work of interest such as, sealing a soil at different sodicities and salinities and to improve efficiency by controlling the all-important rainfall variable.

(ii). Control the repeatability of desired storms instead of trying to extrapolate or interpolate the results of measured storms to situations of interest.

Holder and Brown (1974) reported that varying the duration of rainfall at the same intensity resulted in larger differences in the impedance of the cap than varying the intensities for the same duration, hence the desirability of controlling rainfall intensities in studies on capping. The rainfall simulator must in principle be able to create caps repeatedly with similar characteristics as and when desired. Precision in simulation is also required for accurate results (Awadhwal and Thierstein, 1985).

The main purpose of a rainfall simulator as a research tool is therefore to apply water in a manner similar to natural rainstorms (Meyer, 1994). According to Moore *et al* (1983), data such as runoff and erosion during sealing can be accumulated under controlled and reproducible conditions using rainfall simulators.

An ideal simulator should be inexpensive to build and operate, simulate rainfall perfectly, be easy to move, and capable of being used whenever and wherever required. According to Meyer (1994) such an utopian simulator, however, is impossible to acquire or to make.

2. CHARACTERISTICS OF RAINFALL SIMULATORS

2.1 Desirable Features

Desirable features of simulators (Meyer, 1994; Hudson, 1981; Moore et al, 1983) are:

- Drop size distribution and fall velocity similar to that of natural rainfall,
- Intensities in the range of storms, for which results are of interest,
- Area sufficient to represent the treatments and conditions being evaluated,
- Drop characteristics and intensities of application fairly uniform over the study area,
- Angle of impact to be nearly vertical for most situations,
- Raindrop application to be nearly continuous over the study area, thus avoiding intermittent application of rain,
- Capability of applying the same simulated rain storm repeatedly,
- Satisfactory rainstorm characteristics when used during common field conditions, such as high temperatures and moderate winds. The simulated characteristics should operate effectively under controlled laboratory and field conditions,
- Portability, and

- Low cost.

2.2 Drop Production

According to Moore *et al* (1983), simulators use two main systems for producing drops. These are; nozzles from which water is forced at a significant velocity by pressure, and drop formers, where drops form and fall from a tip, starting at zero velocity.

The main disadvantages of drop formers are that tips produce only one drop size, or a very limited range of sizes and are used mostly for fundamental studies when a carefully controlled drop size is important (Meyer, 1994). Considerable height is required to achieve the terminal velocity of natural rain.

Nozzles, on the other hand, often use intermittent application, which according to Young (1979) has a significant effect on the amount of rainfall or energy a soil can absorb before runoff begins. The energy required to initiate runoff also increases with the length of time between intermittent applications of water due to delayed sealing of the soil surface. This effect happens because soil water pressure varies when subjected to intermittent rainfall. As the suction increases, the soil's shear strength increases and the resulting soil splash decreases. Therefore, time intervals between water applications of 10 seconds or more can cause delayed surface sealing (Towner and Childs, 1972).

2.3 Principle of Operation of Rainfall Simulator

The main purpose of the simulator was to apply precipitation on a continuous basis to a small area of 0.16 m^2 (1,600 cm^2) with a uniform raindrop distribution and at a known constant intensity and energy of impact. These were achieved by minimising climatic effects in the laboratory by shielding the simulator with plastic sheeting.

3. FUNCTIONAL CHARACTERISTICS OF THE TEST RAINFALL SIMULATOR

3.1 General Dimensions

The simulator (see Figure 1) was constructed with a 12 mm thick perspex, for application to an area not exceeding 400 X 400 mm. Water to the closed simulator chamber was supplied from a reservoir by means of a peristaltic pump. The overall external dimensions of the simulator are 500 X 500 X 105 mm, and its internal dimensions are 476 X 476 X 80 mm.

Distilled water was supplied to the rainfall simulator under a positive pressure head of 80 mm. Baffles at the top of the chamber dissipated the energy of water entering the chamber before the water was dispersed into the unit. Sealing the joints with a silicone sealant prevented leakage. The hypodermic needles of 0.8 mm external diameter fitted tightly in the base plate and were arranged in a square array at a spacing of 20 X 20 mm to mimic rainfall spacing. Two taps, 3 mm in diameter, were provided in the chamber to allow for the escape of entrapped air. The entire unit was hoisted to the allowable height of 6 m to provide raindrops with sufficient energy close to natural rainfall to seal the soil.

A vertical plastic windscreen, as shown in Figure 1, hanging loosely between the top of the simulator and the test soil, was used to prevent the drops from moving off the test area, and also to prevent oblique angles of impact. Verticality ensured that the maximum energy was used to seal the soil. The screen was also set far enough away to prevent electrostatic attraction between the falling drops and the walls. Randomisation of the drop pattern was achieved by allowing air entry at the side of the screen to provide some degree of turbulence within the tunnel during tests. The impact of the drops also generated some turbulence.

3.2 Drop Size

Natural rainfall consists of a wide distribution of drop sizes that range from near zero to about 7 mm in diameter with the median drop diameter being 1 to 3 mm (Laws and Parson, 1943). Also raindrop size distribution determined at KNUST by the flour pellet technique gave a drop size range of 0.55-3.97 mm for intensities of 2.32-78.3 mm/h (Quansah et al, 1997). With this knowledge, tests were conducted using two diameters of needles to obtain drop sizes within the median size range.

The drop sizes were formed by dripping water through needles of external diameters 0.4 and 0.8 mm. Drop sizes were determined as shown in Tables 1a & 1b by collecting and weighing 20 drops with 5 replications. Average drop size was 2.8940.017 mm with a standard deviation of 0.013 for the 0.8 mm diameter needle. According to Hudson (1981), high speed photographs of raindrops have shown that the shape of falling drops is not like the normal tear drop but rather spherical. The drop diameter was thus calculated by assuming a spherical shape for the drops and a water density of 1 g cm^{-3}.

$$d = 20\cdot\left(\frac{3m}{4\pi}\right)^{\frac{1}{3}} \qquad (1)$$

where, d is diameter of drop in mm, and

m is mass of water in grams

Twenty (20) drops from the hypodermic needle were weighed in a container and the diameter determined from Equation 1. The values obtained are tabulated in Tables 1a and 1b.

3.3 Number and Spacing of Needles

The total number of needles used was 400, spaced 20 mm by 20 mm in a square array, covering a total area of 0.16 m^2. The area of coverage was chosen to ensure that the simulated precipitation overlapped the receiving soil tray as shown in Figure 1. The spacing of needles, which is deemed to be good, was based on the model by Betzalel *et al* (1995) and Shainberg *et al* (1997).

Table 1a. Drop size determination for 0.8mm needle

No.	Mass of 20 Drops (g)	Mass of one Drop (g)	Diameter of a Drop (mm)
1	0.256	0.01280	2.90
2	0.257	0.01285	2.91
3	0.255	0.01275	2.90
4	0.247	0.01235	2.87
5	0.254	0.01270	2.90

Table 1b. Drop size determination for 0.4mm needle

No.	Mass of 20 Drops (g)	Mass of one Drop (g)	Diameter of a Drop (mm)
1	0.140	0.00700	2.37
2	0.140	0.00700	2.37
3	0.137	0.00685	2.36
4	0.132	0.00660	2.33
5	0.135	0.00675	2.34

3.4 Control of Precipitation Intensity

The volume of water pumped over five minute periods were measured at specific peristaltic pump speed settings. The measured volumes were divided by the cross-sectional area of coverage of the rainfall simulator, which is 0.16 m^2, and the value converted to intensity per hour. Each intensity is the average of five determinations. Intensities to be applied were then verified as shown in Table 2.

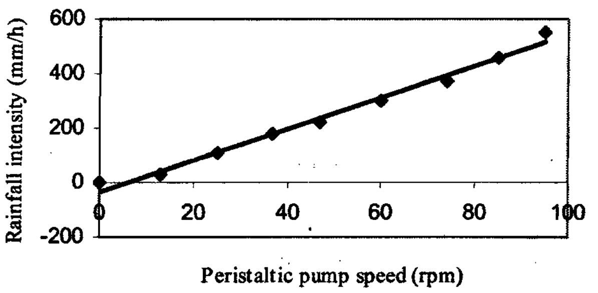
Table 2.: Speeds and rainfall intensities verified for capping tests

No.	Intensity (mm/ h)	Speed (rpm)
1	30	10
2	60	15
3	90	22
4	120	28

Control of intensity was achieved by means of a peristaltic pump (Watson Marlow Model, Falmouth) whose calibration is shown in Figure 2. Long life marprene tubing was used for the pump. The peristaltic pump was operated to maintain a constant rainfall intensity of 90 mm/h The use of a large closed container to supply water to the needles ensured that a small but identical positive pressure was applied to each needle.

To develop this relationship (see Figure 2), the pump was set at various speeds, with the volume of water pumped through the simulator being collected over time and measured. The intensity ranged from 0-575 mm/h. The simulator is therefore capable of applying the entire spectrum of rainfall intensities expected from natural rainfall under any climatic situation as shown in Figure 2. The speeds and intensities in Table 2 were then tested with five replications to confirm that the simulator functioned as intended.

Figure 2. Peristaltic Pump Speed versus Rainfall Intensity



3.5 Uniformity of application

Uniformity was determined by using the Christiansen (1942) uniformity coefficient as shown in Equation 2. A grid of 6 rain gauges of diameter 43 mm was used to determine the rainfall uniformity with intensities from 60 mm h^{-1} to 120 mm h^{-1}, and with 3 replications each. Each gauge was placed at the centre of six equal grids created on the test area. The Christiansen uniformity coefficient (C_u) measures the variation of rainfall $\bar{X}$ over the area, with a value of 100 indicating exact uniformity. Values of uniformity coefficients shown in Table 3 hardly vary and are well within acceptable limits (Christiansen, 1942; Young, 1979) and are higher than many other simulators, e.g. the C_u of a simulator with a rotating disk ranged from a minimum of 73% to a maximum of 94 % (Morin et al, 1967). The continuous-application simulator due to Shelton et al (1985) gave C_u values from as low as 38 % to 93 %. The Kentucky rainfall simulator by Moore *et al* (1983) also gave values from 82-84 % whilst the solenoid-operated simulator by Miller (1987) ranged from 85-93%.

$$C_u = 100\left(1 - \frac{\sum|X - \bar{X}|}{n\bar{X}}\right) \qquad (2)$$

where, X is the rain gauge reading at a point (mm)

is the mean value of rain (mm), and

n is the number of rain gauges

Table 3. Uniformity coefficients at selected speeds

No.	Speed of peristaltic pump (rpm)	Intensity of rainfall (mm/h)	Cu % (Standard Deviation)
1	15	60	82.3 (3.5)
2	22	90	88.6 (1.0)
3	28	120	84.1 (3.8)

3.6 Drop characteristics

The fall height for the simulator was fixed at 6 m vertically from the simulator to the surface of the test soil in the tray. This was done because prevailing laboratory space did not allow anything higher. An ideal height would have been 13 m but the 6 m height allowed the attainment of over 90 % of the terminal velocity of natural rainfall. Using data from Laws (1941), Gunn and Kinzer (1949) and Epema and Riezebos (1983), the terminal velocity for such a drop was found to be 7.92 m/s, 7.93 m/s and 7.87 m/s respectively from heights above 13 m. Using the design height to calculate velocity gave a value of 7.27 m/s.

3.7 Kinetic energy

Wischmeier and Smith (1958), used data obtained by Laws and Parson (1943) to develop a regression equation relating kinetic energy to intensity as follows:

$$KE = 11.9 + 8.73 \log I \qquad (3)$$

Hudson (1961), proposed a different relationship between kinetic energy and rainfall intensity for tropical conditions as follows:

$$KE = 29.8 - \frac{127.5}{I} \qquad (4)$$

In both Equations 3 & 4, KE is kinetic energy in J m^{-2} mm^{-1} and I is intensity in mm h^{-1}.

Based on first principles:

$$KE = \frac{1}{2} m v^2 \qquad (5)$$

or

$$KE = \frac{\Pi \rho_w d^3 v^3}{12} \qquad (6)$$

where, KE is unit kinetic energy (J/kg)

m is mass (kg)

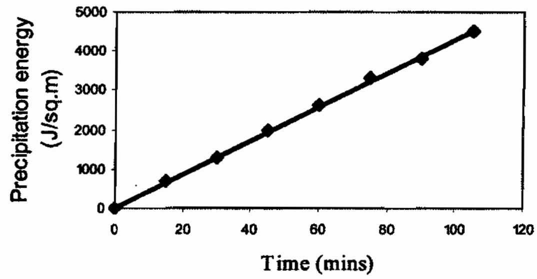
v is velocity (m s^{-1})

ρ_w is density of water which is 1000 kg m^{-3}

d is drop diameter (m)

The rainfall energy for the test intensity of 90 mm/h is predicted to be 28.96 J m^{-2} mm^{-1} and 28.38 J m^{-2} mm^{-1} using Equations 3 and 4 respectively. This compares favourably with 50% of rainfall intensities recorded at KNUST with energies of 20-28 J m^{-2} mm^{-1} (Quansah *et al*, 1997). The kinetic energy at the operating intensity does not change significantly irrespective of the method used. The unit energy based on equation 5 or 6 is 76.4810^{-3} J/kg. The kinetic energy for each time interval can be calculated by multiplying the energy by the corresponding rainfall amount for that time interval. Figure 3 shows the energy profile at the operating precipitation intensity. The energy profile shows a linear relationship over operating time and the total energy over the period was 4,561.3 Jm^{-2}.

Figure 3. Energy profile of rainfall simulator at 90mm/h operating precipitation intensity



3.8 Test Tray and Accessories

The rectangular test tray 365265140 mm was placed directly beneath the rainfall simulator, so that during rainfall simulation, the entire test area was overlapped by the precipitation as shown in Figure 1. The height of the wall by the side of the test soil controlled splashes from the test soil. The tray was established at a slope of 9 % to encourage runoff to occur, and also to provide a slope comparable to standard erosion research plots (Hudson, 1981). The whole set-up was placed within a much larger container to intercept all excess precipitation and splashes in order to keep the surroundings dry. The test tray was provided with a surface drain (Figure 4), which was used to collect runoff at 5-minute intervals. Another drain located at the base of the test tray, shown in Figure 4, was used to collect water draining from the test soil. Air-dry soil passing a 2 mm sieve was packed to a depth of 50 mm and a bulk density of 1.2 g cm^{-3}. At the base of the test tray a bed of coarse sand, 13 mm deep was provided for drainage purposes. This was covered by a capillary mat to prevent finer particles from being washed into the sand. The above arrangements are clearly illustrated in Figure 4.

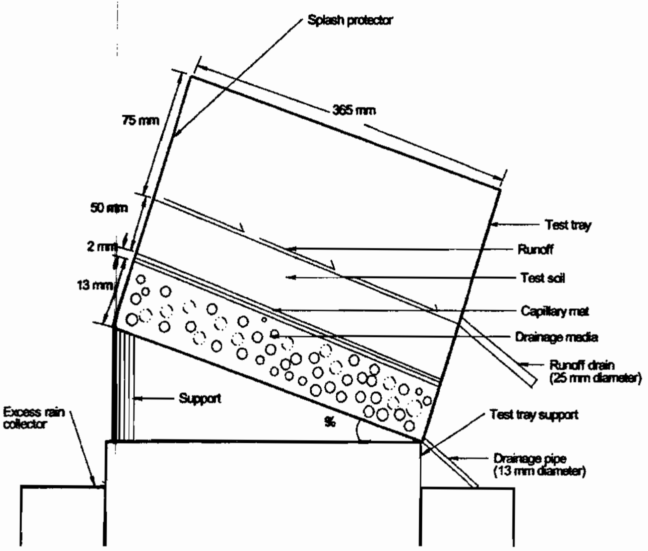


Figure 4. Test tray and accessories

4. CONCLUDING REMARKS

The designed simulator is simple, economical to construct and easy to operate by a single person in the laboratory. It is able to apply precipitation continuously at intensities of up to 575 mm/h, and reproducibility is very good. The drop size is also within acceptable sizes for natural rainfall. The drop size can be modified to mimic a wide range of raindrop sizes by changing the size of the needles.

The rainfall simulator can also be made to encompass a larger area by increasing its size. It has been applied successfully to create caps and measure the resulting infiltrability using a precipitation intensity of 90 mm/h. The simulator has a problem with the intrusion of air bubbles, which was overcome by using de-aired water and by making the joints of the chamber airtight and by priming the simulator to remove air bubbles before operation.

The needles can be changed to alter drop sizes but the spatial distribution of raindrops remained fixed. The other problem concerns the use of a constant water head, which is not the case with natural rainfall. The vertical height requirement to achieve acceptable raindrop velocities was also somewhat on the high side for laboratory work.

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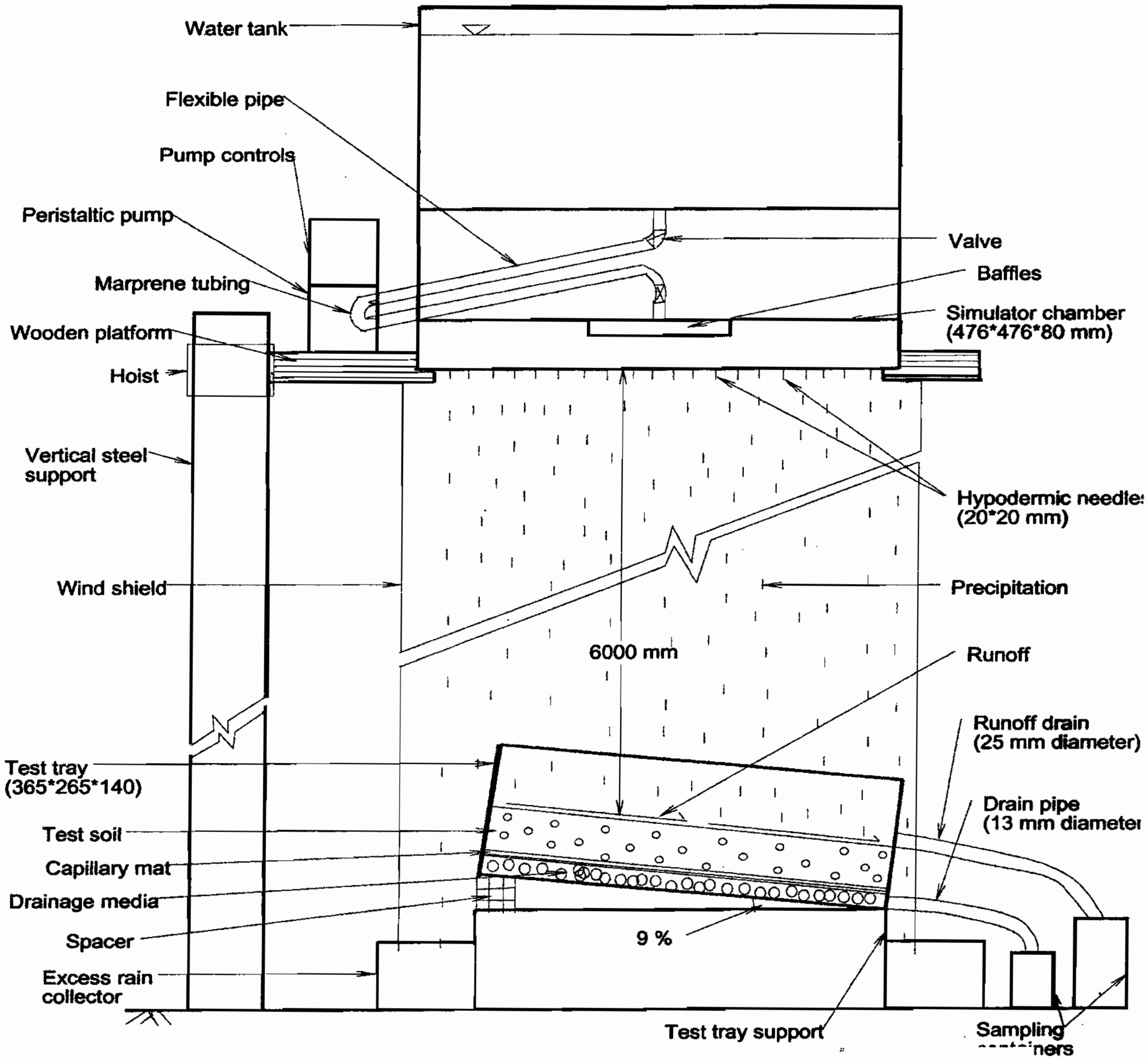

Figure 1. Schematic of rainfall simulator with test tray arrangements