DESIGN AND CONSTRUCTION OF A SIMPLE RAINFALL SIMULATOR FROM LOCALLY AVAILABLE MATERIALS

***Yusuf, K. O; Olaoke, S.O; Iwayemi, A.K; Adewoye, W.A; Oyebode, O. O; and Omokore, S**

Department of Agricultural and Biosystems Engineering,
University of Ilorin, Ilorin, Nigeria

***= Corresponding author: yusuf.ok@unilorin.edu.ng or kamaru.yusuf@yahoo.com**

ABSTRACT

Rainfall simulator is an important instrument for producing artificial rainfall for the determination of soil loss from a catchment over a given period of time. The instrument is rarely available in most Nigeria Universities for practical demonstration for students and research in Soil and Water Conservation Engineering. This is due to high cost of the rainfall simulator and materials that are commonly used for the construction of rainfall simulator are not readily available or expensive in developing countries. In this study, a pressurized rainfall simulator was designed and constructed using the locally available materials mainly PVC pipe, shower rose and a pump for supplying water to the simulator for its operation. The main-pipe receives water from the pump and supplies it to the laterals. The laterals supply water to the distribution pipe which passes it to the shower rose. One hundred shower roses on ten laterals spray water to the ground surface through 2 mm openings. The simulator was 3 by 3 m and all the components are detachable for portability. The simulator rests on an adjustable frame which could be varied from 1 to 2 m height. The uniformity coefficient and drop velocity from the simulator during the performance test were 84.4 % and 8.156 m/s, respectively. The results of uniformity coefficient and drop velocity were within the range. The intensity of water dropping from the simulator depends on the inflow rate of water which could be regulated by the control tap fixed to the inlet main-pipe.

Keywords: erodibility, erosivity, rainfall simulator, uniformity coefficient

1. Introduction

Top soil is very important for agricultural purpose but it is usually washed away in the tropical countries like Nigeria by erosion due to heavy rainfall with high intensity which is common in tropics. The consequence of soil erosion is degradation of arable land thereby reducing the size of the productive land for agriculture. The potential ability of rainfall to cause soil erosion is termed erosivity while the vulnerability of soil to detachment by the impact of rainfall and transportation of the soil particles by the runoff is called erodibility (Schwab, *et al*., 1993). Man has no control over the natural rainfall properties such as rainfall intensity, drop size and duration of rainfall.

Rainfall simulator is a useful tool which is controllable for creating artificial rainfall that is synonymous to natural rainfall pattern in order to study the impact of rainfall on soil surface and how it causes erosion. Simulators are not readily available in Nigeria for research and not available in most Nigerian Universities for students to use for practical. There is need for a simple rainfall simulator which should be designed and constructed using the locally available materials for research and practical by students. Rainfall simulator for field experiment must be portable, withstand wear and tear, the components must be easily assembled and disassembled to eradicate theft, vandalism, ease of transportation, simple design and must produce rainfall similar to natural rainfall (Loch *et al.,* 2001).

1.1 Types of rainfall simulator

There are two main types of rainfall simulator which are; drop–forming simulator also known as non–pressurized simulators and pressurized nozzle simulators (Thomas *et al*., 1987). Drop–forming simulator is not usually portable and required high elevation between 10 and 12 m to attain the terminal velocity (Grierson *et al*., 1987). Bowyer – Bower and Burt (1989) also pointed out that pressurized nozzle rainfall simulator (spray type) uses more water (because of wide area receiving water) than drop–forming type simulator. The pressurized nozzle simulators are suitable for many areas and the intensity could be varied (Grierson and Oades, 1987). The intensity of water from the nozzle varies with orifice diameter, hydraulic pressure on the nozzle and the spacing of the nozzle. The operating pressures for the pressurized nozzle simulators usually produced by a pump are from 34 to 3400 kPa to produce the flow rates between 13.3 and 132 l/min. Bubenzer (1987) found that 41 kPa produced drop size and intensity similar to natural rainfall. The simplest form of sprays that may be suitable for many applications is a spray from watering can or the rose connected to a pressurized hose. Drop size distribution depends on many characteristics especially rainfall intensity. It varies with intensity ranging from 1 to 7 mm. The median drop size distribution for high intensity storm is 2.25 mm (Laws and Parsons, 1993). Rainfall from rainfall simulator should drop or fall at its terminal velocity, if they are to have the same level of energy as natural drops of the same size. Terminal velocity is defined as the velocity at which objects fall without further acceleration due to gravity. In other words, for a free falling sphere at terminal velocity, the gravitational force will equal the dynamic force on the falling sphere. Wischmeier and Smith (1978) found that rainfall intensity is highly correlated to kinetic energy of rainfall and kinetic energy is the most important factor influencing the ability of rainfall to cause erosion.

1.2 Equations related to kinetic energy of rainfall

The normal equation for kinetic energy of a moving object is given in equation (1) but Hudson (1963) derived expression for kinetic energy of rainfall for temperate and tropics which are respectively given in equations (2) and (3).

$$K.E = \frac{1}{2}MV^2 \qquad (1)$$

where *K.E* is kinetic energy of the moving object (J), *M* is the mass of the object (kg) and *V* is the velocity at which the object is moving (m/s).

$$K.E = 11.9 + 8.70 \log I \qquad (2)$$

$$K.E = 30 - \frac{125}{I} \qquad (3)$$

where *K.E* is the kinetic energy of the rainfall (J/m^2/mm) and *I* is the intensity of rainfall (mm/h).

Erosivity index (R) is the product of kinetic energy of rainfall (E) and maximum rainfall that occur in thirty minutes (I_{30}) as given in Equation (4)

$$R = EI_{30} \qquad (4)$$

1.3 Rainfall simulator system design

Ten (10) important criteria were normally considered for ideal rainfall simulators according to Moore et al. (1983) as cited by Wilson *et al*. (2014) were:

(i) drop size distribution similar to that of natural rainfall; (ii) drop velocity similar to that of natural rainfall; (iii) uniform intensity and random drop size distribution over the plot; (iv) continuous application over the plot; (v) nearly vertical impact angle; (vi) reproducible storm durations and intensities; (vii) ability to perform in conditions such as high temperatures and wind; (viii) sufficient areal coverage to meet needs of experiment; (ix) plot-to-plot and site-to-site portability; and (x) low cost.

1.4 Objectives of this study were to:

i. design and construct a simple rainfall simulator using the locally available materials.
ii. determine the uniformity coefficient of rainfall simulator.
iii. expose students to rainfall simulator for practical and research in soil and water conservation engineering.

2. Materials and methods

2.1 Design consideration of the rainfall simulator

The materials used for the design and construction of the rainfall simulator were the materials that are available in Ilorin. The inflow/outflow discharge for the rainfall simulator was based on the capacity (discharge) of the pump used for the rainfall simulator. This pump determined the drop velocity (m/s) of the water dropping from the simulator which is related to the rainfall intensity (mm/h). Parsakhoo *et al*. (2012) pointed out that velocity of raindrops with an average diameter of 3 mm was 7.80 m/s. The inflow rate of water into the simulator is controllable by a control tap fixed at the inlet main-pipe so that the rate of water dropping or drop velocity (spray water from the shower roses) could be varied to any desired rate or intensity. Maximum discharge of 5.5 hp pump used for pumping water into the simulator was 0.01 m^3/s according to the pump manufacturer. A smaller water pump could be used but the water flow rate from the simulator is a function of discharge rate of the pump. The mass flow rates, area, velocity of water to the main pipe, lateral and sub–lateral were determined from Equations (5a) or (5b), (6), (7) and (8), respectively (Bansal, 2003 and Douglas *et al*., 2008).

$$m = \rho \times Q \qquad (5a)$$

$$m = \rho \times V \times A \qquad (5b)$$

$$A = \frac{\pi D^2}{4} \qquad (6)$$

$$V_m = \frac{m}{\rho A_m} \qquad (7)$$

$$V_L = \frac{m}{\rho A_L} \quad (8)$$

$$V_S = \frac{m}{\rho A_S} \quad (9)$$

where m is the mass flow rate (kg/s), ρ is density of water (kg/m^3), Q is the discharge of water (m^3/s), A_m is the area of the main-pipe (m^2), D is the internal diameter of the pipe (m), V_m is the velocity of flow of water in the main–pipe (m/s), V_L is the velocity of flow of water in the lateral–pipe (m/s), V_S is the velocity of flow of water in the sub–lateral pipe (m/s), A_L is the area of the lateral (m^2) and A_S is the area of the sub–lateral (m^2).

2.2 Rainfall drop size and terminal velocity

There is a relationship between rainfall drop size and terminal velocity. This terminal velocity is related to rainfall drop velocity and drop velocity from the rainfall simulator is also correlated to the rainfall drop velocity. The relationship between various rainfall drop size and terminal velocity was shown in Table 1.

Table 1 Relationship between rainfall drop size and terminal velocity

Diameter (mm)	1.0	2.0	2.4	3.0	3.4	4.0	4.4	5.0
Terminal velocity (m/s)	4.03	6.49	7.27	8.06	8.44	8.83	8.98	9.09

Source: (Gunn and Kinzer, 1989).

2.3 Losses through the main, lateral and sub–lateral pipes in the simulator

The losses that occurred in the simulator were in the main pipe (due to inlet sharp entry), lateral (loss due to T – joint from the main–pipe) and sub–lateral (loss due to T – joint from the lateral to sub–lateral where the shower rose was fixed). The losses in the main–pipe, lateral and sub–lateral were determined using Equations (10), (11) and (12) (Bansal, 2003 and Douglas *et al*., 2008). Total head loss and drop velocity of water from the simulator were determined using Equations (13) and (14). The values of constant k_e and k_T were 0.5 and 1.8 as given by Douglas *et al.* (2008).

$$h_m = \frac{k_e V_m^{\ 2}}{2g} \quad (10)$$

$$h_L = \frac{k_T V_L^{\ 2}}{2g} \quad (11)$$

$$h_s = \frac{k_T V_s^{\ 2}}{2g} \quad (12)$$

$$H_t = h_m + h_L + h_S \quad (13)$$

$$V = \sqrt{\frac{2gH_t}{k_T}} \quad (14)$$

where h_m is the frictional head loss in the main-pipe (m), k_e is the entry loss constant, V_m is the velocity of flow of water in the main-pipe (m/s), V_L is the velocity of flow of water in the later (m/s), V_s is the velocity of flow of water in the sub-lateral (m/s), h_L is the head loss in the lateral (m), k_T is the T – joint loss constant, H_t is the head loss in the simulator network pipe due to T – joints (m), V is the mean velocity of water dropping from the rainfall simulator to the ground surface (m/s) and g is acceleration due to gravity (m/s^2).

2.4 Determination of velocity of flow of water in the pipes

The velocities of flow of water through the network pipes for the design of the simulator were determined using Equations (7), (8) and (9). Total head loss due to friction and mean velocity of water dropping from the rainfall simulator to the ground surface were determined using Equations (13) and (14). The velocities, area of each pipe and head loss in the network pipe were shown in Table 2.

Table 2 Velocity of water in the network pipes of the rainfall simulator

Parameter	Velocity (m/s)	Area (m^2)	Head loss (m)
Main-pipe	8.770	1.14 x 10^{-3}	1.960
Lateral	1.973	5.068 x 10^{-4}	3.571
Sub-lateral	0.790	1.126 x 10^{-4}	0.572
Total head loss	-	-	6.103
Mean velocity	8.156	-	-

2.5 Description of the rainfall simulator

The simulator was constructed mainly from PVC pipe and shower rose which are readily available in Ilorin, Nigeria. The main-line pipe which receives water from the pump has a diameter of 1.5 inches (3.81cm) and 3 m long. It has 10 holes of diameter 20 mm at interval of 0.3 m where the laterals were connected to the mainline pipe with help of T–joint pipe. The lateral has a diameter of 1 inch (2.54 cm) and 3 m long. Each lateral has 10 holes of diameter 1.27 cm at interval of 0.3 m where the sub–lateral (distribution pipe) was fixed to the lateral. The distribution pipe was 1.27 cm PVC pipe which was 5 cm long fitted to the lateral with help of T–joint and PVC glue. Each of the ten shower roses made of galvanized metal has 130 holes and each hole has a diameter of 2 mm where it was fixed to each sub–lateral using adaptor so that it can be removed at any time when it is required. The rainfall is 3 by 3 m which could be disassembled into smaller units for portability and could be easily reassembled together as a unit using union connector. The thread seal tape called Plumber's tape which is polytetrafluoroethylene (PTFE) was used to wrap the threads of the pipes before the lateral to prevent water leakage, sub-lateral and shower rose were screwed to the joint.

The simulator has an adjustable frame upon which is placed during operation as shown in Fig. 1. The frame was fabricated using two steel pipes which could be varied from 1 to 2 m. The bigger pipe which houses the smaller pipe was 100 cm long and the second pipe was 105 cm in length. The internal and external diameters of the bigger pipe were 48 and 50 mm respectively while the smaller has internal and external diameters of 45 and 47 mm respectively. The two pipes have 10 holes of diameter of 5 mm at interval of 10 cm where pinion was inserted for the adjustment of the frame height. The last hole on the bigger pipe was drilled at 2.5 cm from the top while the hole on the smaller pipe was drilled at 2.5 cm from bottom but the other nine holes were drilled at 10 cm interval. The bill of engineering measurement and evaluation, dimension of the rainfall simulator, isometric drawing, exploded view, rainfall simulator after fixing all the components and the rainfall simulator connected to the pump during its operation were shown in Appendices A, B, C, D, E and F.

2.6 Determination of coefficient of uniformity

Ten buckets (with area of 0.0616 m^2) were randomly put under the rainfall simulator (under the shower roses) and the pumping machine was set to discharge at full capacity for 60 seconds (s) as shown in Fig. 1 and Fig. 2. The volume from each bucket was measured using a 500 ml measuring cylinder and the following results were obtained as shown in the Table 3. The mean, standard deviation and uniformity coefficient was determined using Equations (15), (16) and (17), respectively as given by Christainsen (1942) as cited by Parsakhoo *et al*. (2012).

$$\bar{x} = \frac{\sum x}{n} \quad (15)$$

$$S.D = \sqrt{\frac{\Sigma(x-\bar{x})^2}{n}} \quad (16)$$

$$CU = \left(1 - \frac{\Sigma|x-\bar{x}|}{\Sigma x}\right) \times 100 \quad (17)$$

where $\bar{x}$ is the mean volume of water in the bucket (litre), x is the volume of water in each bucket (litre), Σx is the summation of x, n is the number of observation (buckets used), S.D is the standard deviation, CU is the coefficient of the uniformity and $|x - \bar{x}|$ is the absolute deviation.

Table 3 Volume of water in the ten buckets for determination of uniformity coefficient

S/No	Volume of water (litre)	$x - \bar{x}$	$(x - \bar{x})^2$
1	5.86	1.343	1.804
2	4.62	0.103	0.011
3	4.23	-0.287	0.082
4	5.10	0.583	0.352
5	3.80	-0.717	0.514
6	5.20	0.683	0.466
7	4.12	-0.397	0.158
8	3.30	-1.217	1.481
9	5.32	0.883	0.645
10	3.62	-0.897	0.805
Total	Σx = 45.17	$\Sigma\|x - \bar{x}\|$ = 7.030	$\Sigma(x - \bar{x})^2$ = 6.318
Mean	$\bar{x}$ = 4.517	-	-

$$CU = \left(1 - \frac{|7.030|}{45.17}\right) \times 100 = 84.4 \%$$

$$S.D = \sqrt{\frac{(6.318)}{10}} = 0.795$$

$$\bar{x} = \frac{45.17}{10} = 4.517 \text{ litre/min}$$

$$\bar{x}_h = 4.517 \times 60 = 271.02 \text{ litre/h}$$

The average intensity of rainfall over the entire area of the simulator was determined from Equation (18)

$$i = \frac{\bar{x}_h}{A_s} \quad (18)$$

where i is the intensity of rainfall (mm/h), $\bar{x}_h$ is the average volume of water falling on the ground surface under the entire area of rainfall simulator in hour (litre/h) and A_s is the area of the rainfall simulator which is 3 by 3 m (9 m^2).

$$i = \frac{271.02}{9} = 30.11 \text{ mm/h}$$

3 Results and discussion

The rainfall simulator was designed and constructed using locally available materials in Ilorin which can be used by students for practical and research in soil and water conservation engineering. The total cost of construction of the simulator and the water pump was ninety thousand, eight hundred and ten naira as shown in the Appendix A of Bill of Engineering Measurement and Evaluation (BEME). The coefficient of uniformity of the rainfall simulator was 84 % which indicated that the simulator has a good uniform distribution of water over the catchment (area) of the rainfall simulator. This coefficient of uniformity (CU) obtained during testing of the simulator was satisfactory because rainfall simulator by Parskhoo *et al*. (2012) had coefficient of uniformity between 81 and 82 % and recommended as satisfactory. The intensity of rainfall from the rainfall simulator was 30.11 mm/h based on the mean flow rate from the rainfall simulator over the area of the simulator (9 m^2). This intensity of rainfall from the simulator could be varied (increased or decreased) from the control tap fixed to the inlet main-pipe. The operation of the rainfall simulator was shown in Fig. 1 and 2 during the performance evaluation for the determination of coefficient of uniformity. The drop velocity of water for the rainfall simulator from the shower rose was calculated to be 8.156 m/s after losses due to entry, T – joints, and along the lateral. The calculated value of the drop velocity was in conformity with the work conducted by Gunn and Kinzer (1989) that rain drop diameter of 3.0 mm has a terminal velocity of 8.06 m/s. The isometric view, exploded view of the rainfall simulator were shown in Appendices C and D. The simulator after the components were fixed to their position on the frame was shown in Appendix E.

Fig. 1: Rainfall simulator in operation

Fig. 2: Buckets randomly put under the simulatorfor determination of uniformity coefficient

4 Conclusions

The rainfall simulator was designed and constructed from the locally available materials with shower rose used in the place of nozzle. The coefficient of uniformity of the rainfall simulator was 84 % which was within the recommended value.

Recommendation

A modification of the rainfall simulator could be done by any researcher by fabricating a smaller rainfall simulator with 5 to 10 shower roses (or any other spraying material or nozzle) and using materials that are readily available in the developing countries at a cheaper rate. Locally fabricated rainfall simulator should be calibrated and used for practical in Soil and Water Conservation Engineering by researchers and undergraduates students.

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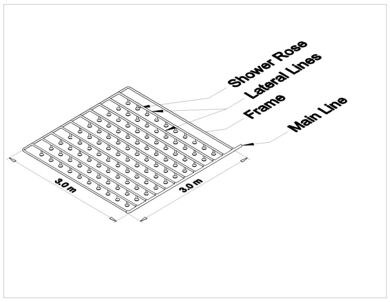
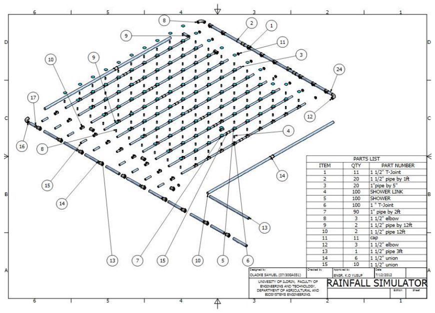
Appendix A Bill of Engineering Measurement and Evaluation of the rainfall simulator

S/No	Description of item	Quantity	Unit price (N)	Amount (N)
1	1.5 inches, 18ft long	1	600	600
2	1.5 inches tee joint	11	250	2,750
3	1.5 inches elbow joint	1	250	250
4	1.5×1.25 inches bush	12	150	1,800
5	0.5 inches adaptor	100	30	3,000
6	G.I shower rose	100	150	15,000
7	1 inches cap plug	12	50	600
8	0.75 inches cap plug	10	50	500
9	1 × 0.75 inches socket	10	70	700
10	1 inches PVC pipe	13	500	6,500
11	1 × 0.75 inches tee	100	50	5,000
12	0.75×0.5 inches bush	100	30	3,000
13	Medium Abro gum	5	500	2,500
14	0.5 inches PVC pipe	2	300	600
15	1 inches tee joint	10	70	700
16	1.25 × 1 inches bush	10	100	1,000
17	Thread tape	2	40	80
18	1.5 inches Union connector	3	450	1,250
19	1 inch Union connector	1	120	120
20	1 inch tiger union	12	120	1,440
21	Labour/hour	16	750	12,000
22	Transportation			2,000
23	5.5hp water pump	1	16,500	16,500
24	paint/thinner	1	1,420	1,420
25	steel pipes			10,000
26	Flat hose	10	150	1,500
	sub – total			**90,810**
	contingency (10% of sub - total)			9,081
	Grand total cost			**99,891**

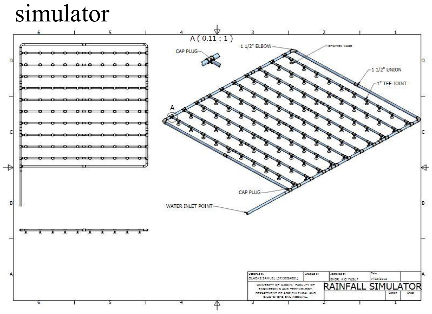
Appendix B Dimension of the rainfall simulator



Appendix C exploded view of the rainfall simulator



Appendix D Isometric drawing of the rainfall simulator



Appendix E Rainfall simulator after fixing all the components

Appendix F Rainfall simulator connected with pump for water supply to the simulator