A Rotating Boom Rainfall Simulator: Design, Constructional Features and Appraisal

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Abstract– **A rotating boom rainfall simulator, which is of low-cost, easy to transport and assemble, was designed and constructed based on an existing rainfall simulator. The existing rainfall simulator was tested and its deficiencies were corrected. The modified rotating boom rainfall simulator is a pressurized/nozzle type operated by a one-horsepower (1hp) surface pumping machine. The simulator spans over an area of 5.07 square metres (m^2) and the simulated raindrops fall from a height of 2.3 metres (m). The greatest advantages of this simulator are that it is portable due to its lightweight, can be easily assembled and disassembled, and easy to construct and it can operate at continuous flow without requiring any complex mechanism to control the intensity of rainfall. The calibration was based on uniformity of distribution, rainfall intensity, raindrops size and kinetic energy. It was operated at four different pressures: 70 kPa (10 psi), 124 kPa (18 psi), 138 kPa (20 psi), 159 kPa (23 psi). The uniformity coefficients (Cu) determined using Christiansen coefficient ranged from 74 % to 89 % for varying rainfall intensities between 108.54 mm/h and 189.62 mm/h.**

Keywords: rainfall, rainfall intensity , simulator, uniformity coefficient

I. INTRODUCTION

A rainfall simulator is used to mimic or replicate natural rainfall characteristics, either on the field or in the laboratory to determine surface runoff, infiltration, erosion and sediment yield. The significant goal of constructing a rainfall simulator is to precisely recreate the process of real/natural rainfall which is often a complicated process and found not to have been imitated accurately [1, 2]. Such rainfall simulators have become a valuable research tool in studying soil erodibility and erosivity at varied rainfall intensities on several soil types, and slope situations in the past and present years [3, 4].

They are crucial tools for studying the complex behaviour of runoff, soil loss and infiltration [5, 6] as well as research involving sediment, nutrient, and pollutants transport and for evaluating the effects of tillage management on densification and infiltration in agricultural soils [2]. The use of rainfall simulators reduce the irregular and unexpected variations of natural rainfall, allowing for precise and repeatable measurement of several parameters (such as slope, soil type, soil moisture, and vegetation cover) for the quick collection of such parameters while maintaining uniform rainfall conditions [7, 5].

Rainfall simulators for field experiments must be lightweight, durable, made from components that can withstand corrosion, must be easy to install and disassemble to prevent external attacks such as theft, destruction; mobility, have a simple design and must reproduce rainfall comparable to natural rainfall [8]. As a result, simulation has emerged as a significant research tool for developing and evaluating soil conservation projects [9].

Several researchers have designed, constructed, and calibrated rainfall simulators for rainfall studies. Reference [10] designed, constructed and tested a simple, low-cost portable pressurized nozzle type rotating boom simulator made from zinc-alloy material, distributed water uniformly over a plot of one square meter at a pressure of 25 kPa. [11] used a method to control the temperature of a rotating disk rainfall simulator by using two small air-condition compressing units, each of them connected to a spiral of metal pipe coated with polyethylene inside the water supply reservoir of the simulator. [12] used an imaging technique to determine the size of raindrops and the results stated that the high speed imaging technique is suitable as an applied method to estimate raindrop size distribution and fall velocity. This technique showed a great ability to accurately detect raindrops and offer enough knowledge about the raindrop parameters. [13] conducted a rainfall simulation study by designing and constructing a large-scale rainfall simulator based on ASTM D6459-15 for rainfall characteristics such as intensities, uniformities, drop size distribution and erosive energy produced by the simulator. [14] measured the characteristics of simulated rainfall and compared them to those of natural rainfall using physical and computational models. They estimated the values of terminal velocity, striking velocity and kinetic energy of the rain droplets with high accuracy. [15] also used a nozzle type rainfall simulator in the development and analysis of erosional drainage networks and soil surface roughness.

The objective of this study was to design and construct a rotating boom rainfall simulator to replicate natural rainfall on the field and to evaluate the simulated rainfall characteristics (rainfall intensity, uniformity, drop size and kinetic energy) – commencing from an existing rainfall simulator.

A. Types of Rainfall Simulator

To mimic rainfall in order to investigate various hydrologic processes, simulators are of two major categories:

(i) pressurized or nozzle type rainfall simulator
(ii) non-pressurized or drop forming rainfall simulator

Pressurized rainfall simulators use single or multiple nozzles to create raindrops under pressure [2].

Drop forming or non-pressurized rainfall simulator requires no pressure to form raindrops. Drops are formed at the base of a material known as drop former until the weight of the drop overcomes the surface tension force of the drop former the drop then falls with an initial velocity of zero [9]. To accurately simulate natural rainfall, several design criteria must be considered which include [[16 as cited by 9; 10; 17; 7; 12; 14; 13]] :

1. Distribution of drop size corresponding to natural rainfall
2. Even distribution of rainfall and random drop size distribution
3. Sufficient/adequate area of coverage
4. Total energy corresponding to natural rainfall.
5. Ease of transportation
6. Reproduction of rainfall with accuracy.
7. Rainfall intensity that meets study/research program's requirements
8. Terminal velocity of raindrops is approximated by drop impact velocity
9. Satisfactory characteristics under varying climates.
10. Relatively steady of rainfall intensity throughout the research area

II. MATERIALS AND METHODS

The study was carried out at the Department of Agricultural and Biosystems Engineering, Faculty of Engineering and Technology, University of Ilorin, Ilorin, Kwara State, Nigeria. Ilorin (Longitude $4^0\ 35'E,$ Latitude $8^0\ 30'N$) is in the Southern Guinea Savannah ecological zone of Nigeria with annual rainfall of about 1,300 mm. The wet season begins towards the end of March and ends in October while the dry season starts in November and ends in March [18].

B. Modes of operation of the simulator

The simulator consists of an auger/helical blade fixed to the center of the boom head at the top which forms the mechanism and effect the rotation of the entire boom head with the help of a bearing permanently fixed at the bottom of the boom head. Water from the riser pipe will strike the auger blade surface at a high pressure enough to overcome the entire weight of the boom head and then water starts to flow into the 4 arms before discharging out through the perforated nozzles.

C. Description of the existing rainfall simulator

The existing rainfall simulator [10], which served as a model for the modified simulator was a pressurized type, with a rotating boom head, having an auger blade and four 20mm diameter openings around the boom head to accommodate 20mm diameter PVC pipes with perforations. It has other components parts such as: 40 mm diameter gate valve, elbow and t-joint socket, 35 mm diameter socket, 40 mm diameter PVC pipe.

Upon testing the existing rainfall simulator, it was observed that some of its components like the boom head cover and riser pipe were leaking water which thereby resulted in non-uniformity of simulated rainfall distribution; distorted auger blade; and worn out bearing.

D. Description of the modified rainfall simulator

The modified boom simulator is a pressurized type, designed based on the existing simulator. It was constructed using PVC pipes and lightweight metal. It comprises a 115-mm-diameter boom head with an auger/helical blade at the top and four 23-mm-diameter internal diameter openings through which the boom arms are attached for easy water discharge in the nozzles. A bearing is also located at the bottom of the boom head. The water supply unit's intake pipe, the lateral pipe, and the riser are all made of PVC pipes of diameter 25.4 mm (1 inch) The simulator also consists of a steel tripod pipe which is adjustable so that the boom height can be raised to a height of 1 to 3 m. The components of the simulator are easily assembled this makes the simulator to be easily transported to any distance. The diameter formed by the length of the boom arms determines the area of coverage of the simulator which is approximately 5.07 m^2. The modified rainfall simulator is shown in Figure 1 and the costs of materials shown in Table 1.

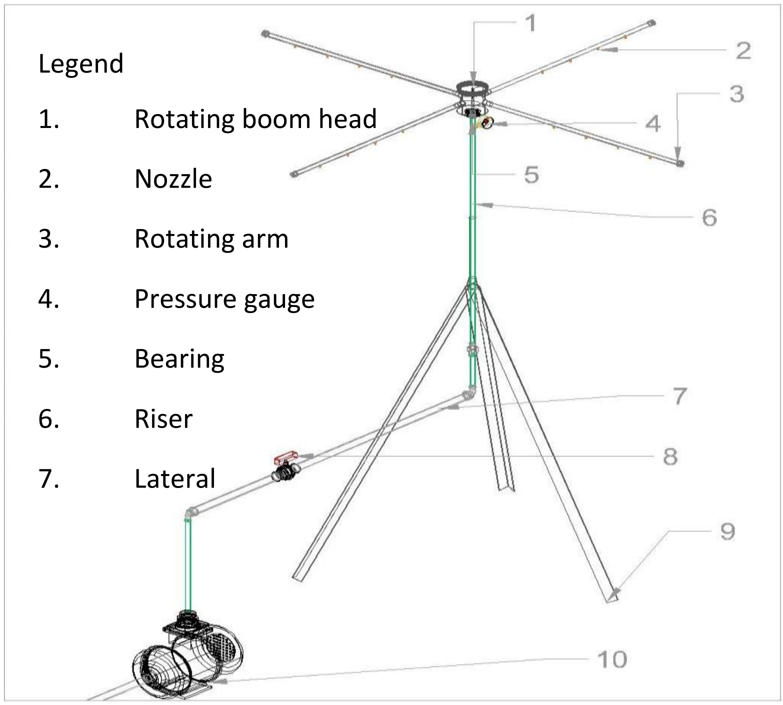

Figure 1. The developed rainfall simulator

Table 1 Bill of Engineering Measurement and Evaluation, BEME (2019 prices)

S/N	Description of item	Quantity	Unit price NAIRA	Amount NAIRA
1	1 inch pipe	3	600	1800
2	Pressure Gauge	1	4500	4500
3	1 inch gate valve	2	400	800
4	1 inch elbow	4	50	200
5	Steel pipe		2500	2500
6	Thread tape	1	100	100
7	Adapter	3	50	150
8	5 L buckets	6	250	1500
9	1 inch union connector	1	150	150
10	Abro gum	1	600	600
11	Motor oil	-	200	200
12	Vegetable oil	-	200	200
13	Laboratory	-	300	300
14	Transportation	-	1200	1200
	Total cost			14200

E. Methods for evaluating simulated rainfall characteristics

Simulated rainfall should mimic the features of natural rainfall, such as average rainfall intensity, drop size, rainfall uniformity, terminal velocity, kinetic energy, and rainfall duration.

Rainfall uniformity

Six (6) buckets were positioned under the test plot at 110 mm horizontal distance from the middle of the boom head to achieve the quantity and spatial distribution of simulated rainfall for a period of 5 minutes. Rainfall collected was then measured using a graduated measuring cylinder (in mL) to determine the volume of water collected. The uniformity of rainfall application was estimated using Christiansen coefficient (Cu) in equation (1);

Coefficient of uniformity, Cu $= [1 - \frac{\Sigma(D_i - D_{avg})}{nD_{avg}}]$x100 (1)

Cu = Coefficient of uniformity

D_i = depth of water in rain gauge, (mm)

D_{avg} = Average depth of water in rain gauge, (mm)

n = number of observation (buckets used)

Rainfall intensity

To measure the intensity, six (6) buckets were placed in a grid layout under the test plot at 110 mm horizontal distance from the centre of the boom head. The distance was maintained for each bucket throughout the test. For 5 minutes, the calibration was conducted. The rainfall volume in each bucket was measured using a graduated measuring cylinder (mL) at the end of the test, and the depth of water in each rain gauge bucket was obtained by dividing the volume of water in each bucket by the bucket's surface area. The average intensity of rainfall at different pressures was determined using equation (2) :

$i = 60[\sum_{n=1}^{n} \frac{D_n}{Nt}]$ (2)

where,

i = Rainfall intensity, (mm/hr)

D_n = Depth of rainfall, (mm)

N = Number of observations (buckets used)

t = Test duration (minute)

Drop size distribution

Distribution drop size is an important parameter in calibrating a rainfall simulator which gives information on the variation of droplet diameters in a given experiments. Oil-microscope is the method of drop size determination adopted or used in this study. It involves mixture of two immiscible oil. The oil-microscope method is an improvement over the oil method of [19] to determine small water drop sizes and their distribution. The following is a list of the steps involved in the procedure: as indicated in Figure 2, rectangular microscope slides were filled with a 2:1 combination of motor/engine oil and vegetable oil put beneath the nozzles for 2 seconds. The period was kept short to avoid raindrops colliding or overlapping. The amount of water drops collected in the microscope slides was determined by the dish's exposure time under a specific nozzle at a constant water pressure. To minimize overlapping droplets and make it easier to recognize individual drops, the drop population was kept low. The collected water drops or bubbles were then viewed under a microscope as shown in Figure 3 and the digital images obtained from the microscope were processed or analysed in an image analysis software known as Image J. The Image J software package enables to measure individual drop size, diameters and number of drops. The processing of drops using Image J software is as shown in Figure 4. The diameter of simulated drops analyzed by image processing technique was calculated in the range 0.05mm – <6mm which can be compared with that of natural rainfall that contains a wide distribution of drop sizes varying from near 0 mm (low-intensity rain) to about 7 mm in diameter (high-intensity rain). The median diameters (D_{50}) were equal to be from 2.03 mm to 2.22 mm for the intensities. The median diameters were determined from an empirical relation developed by [20] which is given in (3).

$$D_{50}=0.97I^{0.158} \quad (3)$$

Figure 2. Mixture of oil on a microscope slide

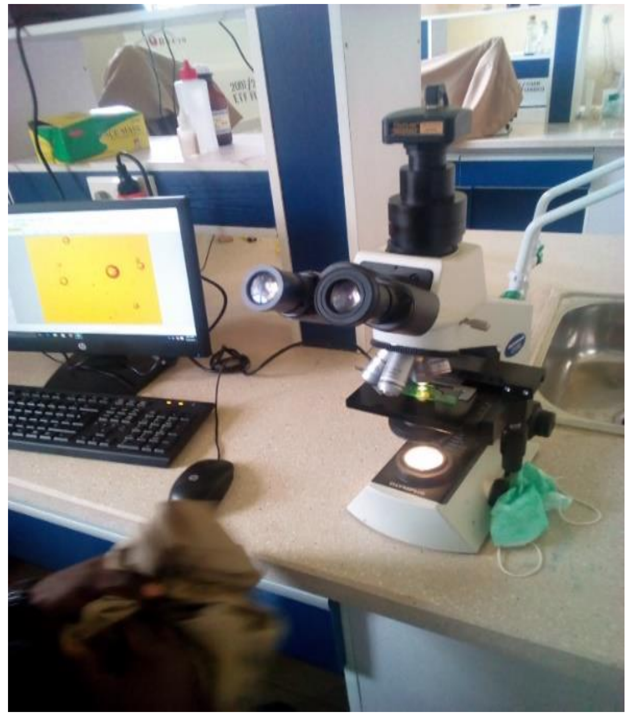

Figure 3. Viewing the raindrops under microscope

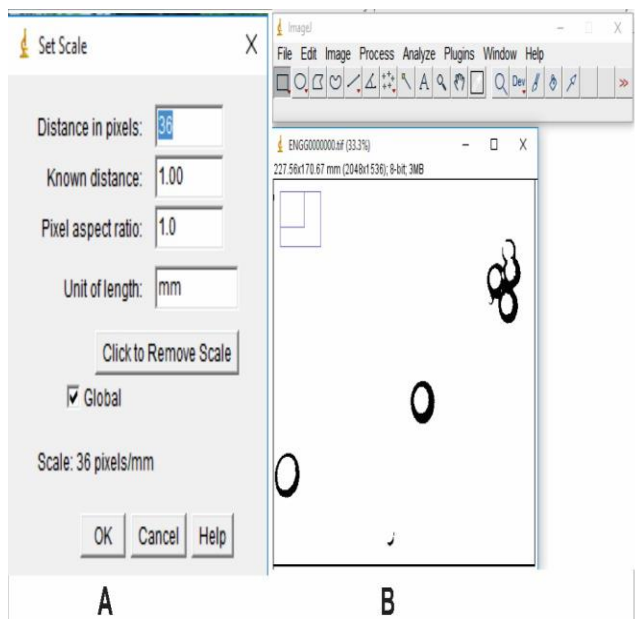

Figure 4. Processing of drops using Image J software

III. RESULTS AND DISCUSSION

The results from the operational testing of the simulator are shown in Tables 2 to 4.

Table 2 Uniformity of distribution

Pressure (kPa)	Coefficient of uniformity (%)	Intensity (mm/hr)
70	74	108.54
124	88	141.06
138	85	153.72
159	89	189.62

Table 3 Revolution

Pressure (kPa)	Revolution per minute (rpm)
70	35
124	48
138	56
159	67

Table 4 Mean drop diameter and terminal velocity

Rainfall intensity (mm/h)	Median drop diameter (mm)	Terminal velocity (m/s)
108.54	2.03	6.89
141.06	2.12	6.99
153.72	2.15	7.00
189.62	2.22	7.16

Discussion of results

Intensity, uniformity coefficient, and drop size were all measured and calibrated on the simulator. The simulator was run at various pressures ranging from 70 kPa (10 psi) to 159 kPa (23 psi), with rainfall intensities varying from 108.54 mm/h to 189.62 mm/h, resulting in a uniform rainfall distribution. Thus, at high pressure, high intensity of rain was produced and vice versa. It can be seen that the values of the rainfall intensities are quite large due to the operating pressures, the number of rain gauges (buckets) placed under simulator, opening and closing time of the valves. An average coefficient of uniformity (Cu) of 74%, 88%, 85% and 89% were computed for the rainfall intensities of 108.54mm/h, 141.06mm/h, 153.72mm/h, 189.62mm/h respectively. However, the coefficients of uniformity obtained during this study was satisfactory because the portable simulator developed by [2] has Cu between 82% and 89%. This means that the constructed rainfall simulator in this study has a good uniform water distribution over the catchment area of the simulator. The diameter of simulated drops analyzed by image processing technique was calculated in the range 0.05mm – <6mm which can be compared with that of natural rainfall that contains a wide distribution of drop sizes varying from near 0 mm (low-intensity rain) to about 7 mm in diameter (high-intensity rain). The median diameters (D50) were equal to be from 2.03 mm to 2.22 mm for the intensities. The kinetic energy of the simulated rainfall ranges from 29.64J/m2/mm to 31.76J/m2/mm

V CONCLUSIONS

An existing rainfall simulator was modified and calibrated. The modified simulator was evaluated in order to improve reproducibility as well as drop characteristics of generated rainfall. The simulator is capable of producing various rainfall intensities over 5.07 m^2 catchment area either on the field or in the laboratory. The greatest advantages of this simulator are that it is portable due to its lightweight, can be easily assembled and disassembled and easy to construct and it can operate at continuous flow without requiring any complex mechanism to control the intensity of rainfall. For different rainfall intensities ranging from 108.54 mm/h to 189.62 mm/h, uniformity coefficients (Cu) of 74 to 89 percent were obtained. The results showed that simulated rainfall has accurate uniformity of water distribution over the catchment area. Kinetic energy of the simulated rainfall ranges from 29.64J/m^2/mm to 31.76J/m^2/mm.

REFERENCES

[1] R. B. Bryan and S. H. Luk. Laboratory experiments on the variation of soil erosion under simulated rainfall. Geoderma, 26(4), 245 – 265, (1981).

[2] H. Aksoy, N. E. Unal, S. Cokgor, A. Gedikli, J. Yoon, K. Koca and E. Eris. A rainfall simulator

[3] For laboratory-scale assessment of rainfall-runoff-sediment transport processes over a two dimensional flume. *Catena*, *98*, 63-72, (2012).

[4] L. Wang, N. Dalabay, P. Lu, F. Wu. Effects of tillage practices and slope on runoff and erosion of soil from the loess plateau, China, subjected to simulated rainfall. Soil Tillage Res. 166, 147-156, (2010).

[5] [4] M. Grismer. Standards vary in studies using rainfall simulators to evaluate erosion. Calif. Agric. 66, 102-107, (2012).

[6] [5] T. Iserloh, J. B. Ries, J. Arnáez, C. Boix-Fayos, V. Butzen, A. Cerdà and C. Geißler. European small portable rainfall simulators: A comparison of rainfall characteristics. Catena, 110, 100-112, (2013).

[7] [6] M. Grismer. Determination of watershed infiltration and erosion parameters from field Rainfall Simulation analyses. Hydrology, *3*(3), 23, (2016).

[8] T. Iserloh, W. Fister, M. Seeger, H. Willger and J. Ries. A small portable rainfall simulator for reproducible experiments on soil erosion. Soil and Tillage Research, *124*, 131-137, (2012).

[9] R. Loch, B. Robotham, L. Zeller, N. Masterman, D. Orange, B. Bridge, and J. Bourke. A multi-purpose rainfall simulator for field infiltration and erosion studies. *Soil Research*, *39*(3), 599-610, (2001).

[10] R. Pall, W. Dickinson, D. Beals and R. McGirr. Development and calibration of a rainfall simulator. Canadian Agricultural Engineering, *25*(2), 181-187, (1983).

[11] A.O. Ogunlela and M. B. Fasasi. Design, construction and operational testing of a rotating boom rainfall simulator. Journal of Engineering & Engineering Technology , 4(2) : 138 – 143, (2005).

[12] E. Sachs and P. Sarah. Technical report of a rainfall temperature control system for rainfall simulators. Catena, 165, 516 – 519, (2018).

[13] A. Kavian, M. Mohammadi, A. Cerda, M. Fallah and Z. Abdollahi. Simulated raindrop's characteristic measurements. A new approach of image processing tested under laboratory rainfall simulation. Catena, 167, 190 – 197, (2018).

[14] M.D. Ricks, M. A. Horne, B. Faulkner, W. C. Zech, X. Fang, W. N. Donald and M. A. Perez. Design of a pressurized rainfall simulator for evaluating performance of erosion control practices. Water, 11(11), 2386, (2019).

[15] S. N. Mhaske, K. Pathak and A. Basak. A comprehensive design of rainfall simulator for the assessment of soil erosion in the laboratory. Catena, 172, 408-420, (2019).

[16] A. O. Ogunlela. Tillage – induced soil surface roughness under simulated rainfall. Nig. Journal of Mathematics and Applications. 10, 150 – 161, (1997).

[17] G. Bubenzer. Inventory of rainfall simulators. Paper presented at the Proceedings of the rainfall simulator workshop, (1979).

[18] J. B. Ries, M. Seeger, T. Iserloh, S. Wistorf and W. Fister. Calibration of simulated rainfall characteristics for the study of soil erosion on agricultural land. Soil & Tillage Research, 106 : 109 – 116, (2009).

[19] A. O. Ogunlela. Stochastic analysis of rainfall events in Ilorin, Nigeria. Journal of Agricultural Research and Development 1(1):39-50, (2001).

[20] J. D. Eigel and I. D. Moore. A simplified technique for measuring raindrop size and distribution. Transactions of the ASAE, 26(4), 1079 – 1084, (1983).

[21] P. T. Willis. Functional fits to some observed drop size distributions and parameterization of rain. Journal of Atmospheric Sciences, 41(9), 1648-1661, (1984).

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