A METHODOLOGY FOR DESIGNING FIELD RAINFALL SIMULATOR: REVIEW

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Abstract: The existing rainfall simulators were not able to reprove natural rainfall condition effectively. In view of this, a methodology for designing field rainfall simulator was reviewed with the objective of developing rainfall simulator that generates and reproduces rainfall condition. Monthly average rainfall intensity data is required to determine the median drop diameter of the rainfall simulator. Subsequently, the kinetic energy, flow rate and power requirement of the rainfall simulator should be calculated empirically. In addition, calibration of rainfall simulator in term of rainfall intensity, uniformity coefficient and kinetic energy is important for effective simulation with the natural rainfall. This review work found out that rainfall simulator could be used to develop models for predicting the fate and transport of pollutants in runoff. This review suggested that the effect of different pressurized nozzles on the intensity of rainfall simulator's performance be examined after designing rainfall simulator. Thus, optimization of pressurized nozzles on the rainfall simulator is required for effective Coefficient of uniformity and distribution of the system

Keywords: rainfall simulator, rain drop sizes, pressurized nozzles, rotating nozzle

INTRODUCTION

Erosion and sediment assessments are difficulty to carry out under natural rainfall due to uncertainty and its erratic nature (Sarkar, 2003; Grisner, 2012). In addition, rainfall intensity, duration, timing and distribution are beyond human control (Sarkar, 2003). The outcome of natural rainfall as regards runoff, erosion and sediment yield are unsuitable for comprehensive prediction (Sanguesa *et al.*, 2010). In view of these, there is need to design a field rainfall simulator that reproduces rainfall scenarios (Sarkar, 2003). Rainfall simulators are employed in numerous studies such as agricultural (infiltration, surface runoff, sediment and nutrient analysis) and environmental studies (Abudi *et al.*, 2012; Chouksey *et al.,* 2017). Rainfall simulator gives accurate reproduction of natural rainfall drop sizes and energies, ability to varying rainfall durations and intensities and its uniform uniformities over an area of $1m^2$ or larger (Abudi *et al*., 2012). There are two basic types of rainfall simulator used in field and these are spray/sprinkler nozzle and the drop-former type. The latter gives large drops ranged from 0.1 to 6 millimeters while the former produces rain dominated by a high intensity but pulsed at lower overall intensity which simulates rain intensities of 10 to 200 millimeters per hour (Abudi *et al*., 2012; Grisner, 2012). The drop-former type is employed where there is non-availability of water (Abudi *et al*., 2012) while sprinkler nozzle type is used major on the field.

Yusuf et al. (2016) examined the effect of vegetative cover and slope on soil loss using rainfall simulator. The study used rainfall simulator with drop velocity ($8.23m/s^2$) and coefficient of uniformity (84.4%) and results showed that vegetative cover with grasses reduced the runoff volume and soil loss. Qian (2014) examined the effects of different slope lengths and vegetation coverage ratios on the mechanisms of nutrient loss and runoff using rainfall simulator. The study revealed that the rainfall intensity was adjusted by adjusting the aperture of the nozzles of the sprinklers and water pressure. Their results showed that the majority of the nitrogen and phosphorus were in dissolved form. Comparing the kinetic energy of the rainfall event to simulated one and scaling up their results from a small simulator to watershed/basin are the issues in relating rainfall runoff losses with simulated runoff losses (Chouksey *et al.,* 2017). The study will produce the kinetic energy of natural storms by replicating the natural rainfall duration and intensity with the simulator. Long and Demars (2005) designed a prototype erosion control testing plot using rainfall simulator. The study identified that long-term and seasonal effects required to be studied to assess the usefulness of simulators. In the work of Kibet (2014), majority of the rainfall simulator designed are not standardized for predicting sediment in runoff. In addition, Sakar (2003) revealed that further assessment is needed to test the effect of height and operating pressure of the developed rainfall simulator on rainfall intensity for the runoff and soil erosion in the field. Sawatsky *et al.,* (1996) designed rainfall simulator to measure erosion of reclaimed surfaces and their study showed that there is need to use high impact spray nozzles are required to simulate different rainfall rate. In view of this, the study aims to develop a methodology for designing pressurized rainfall simulator that will simulate different rainfall rate.

LITERATURE REVIEW

Application of Rainfall Simulator

Rainfall simulator is a tool for infiltration, soil erosion, surface runoff and sediment transport studies as it allows rainfall-runoff generation under controlled and repeatable conditions (Horne, 2017). It is used to produce rainfall at a known depth and intensity in controlled manner (Chouksey, 2017). Rainfall simulators are used to apply uniform rainfall rates over land surfaces for assessing runoff under controlled conditions (Kibet, 2014). It could be used to assess losses of soil constituents in runoff. In addition, it is used to predict the likely occurrence of what happens under natural rainfall (Kibet, 2014). The study showed that trends between natural rainfall and rainfall simulation data follow the same pattern pointing to a consistency in processes (Kibet, 2014). The study found out that rainfall simulator could be used to develop models for predicting the fate and transport of pollutants in runoff.

Rainfall Simulator Characteristics

Pressurized Nozzle

Pressurized nozzles are suitable for different uses on the field (Blanquies *et al.,* 2003). The intensities of the pressurized nozzle can be varied more than that of drop forming type. The rainfall simulator with pressurized nozzle uses more water due to wider area than drop–forming type simulator (Yusuf, 2017). In addition, Navas *et al.,* (1990) developed rainfall simulator for runoff and soil erosion on the field. A 15 minutes duration of the natural rainfall was chose in line with the average duration of the storm event in the area. The rainfall intensities chose for this study were 48 mm/hr and 58mm/hr respectively. The fall velocities of the natural rainfall were the same with the simulated rainfall. The simulator rainfall has high number of large drops and smaller Kinetic energy. Cerda *et al.,* (1997) also designed small and portable rainfall simulator which was used for rugged terrain. This was used to assess water infiltration capacity. The study showed that both drop size and drop velocity of the simulated rainfall was the same natural rainfall. In addition, the kinetic energy of the simulator rainfall was lower than natural rainfall because the simulator was designed to assess water infiltration capacity (Cerda *et al.,* 1997).

Raindrop size distribution

Drop size is a key parameter in the detachment of soil because it determines the terminal velocity of the corresponding drop and therefore the rainfall kinetic energy. An effective rainfall simulator is required to reproduce raindrop sizes similar to that of a natural rainfall event. Kathiravelu *et al* (2014) found out that the raindrop-size distribution is complex. This unmanageable nature of raindrop distribution could be assessed by dividing the larger and smaller drops diameter into groups of equal volume

Rainfall terminal velocity

The velocity of the raindrop increase with drop size until it reaches terminal velocity (Kathiravelu *et al.,* 2014). The rainfall simulator nozzle should produce impact velocities equal to the terminal velocities corresponding to their drop sizes. Kathiravelu et al. (2014) carried out a critical review on rainfall simulator for urban purposes and the study identified that verification of raindrops is extremely unmanageable. The study revealed that the techniques used lack of detailed information. The drop-size distribution can be calculated using empirical laws linking fall velocity and raindrop diameter.

Rainfall kinetic energy

The kinetic energy of the rainfall simulator decrease as the duration of the rainfall increases because of the rise in the flow depth (Kathiravelu *et al.,* 2014). The kinetic energy of rainfall is used as an indicator for the potential ability of rainfall to detach soil and it is estimated from each raindrop event that strikes the ground surface (Chouksey, 2017; Abudi, 2012).

Rainfall Simulator Components

(i) Water source: This is the point where water is drawn from reservoir to the field.
(ii) Pumping Unit: It consists of water pump main and lateral line. Water pump conveys water from the reservoir through main and lateral line up to rainfall simulator nozzle. The water pumps capacity is calculated based on the design criteria.
(iii) Main lines: Main line pipe is either of HDPE or Aluminum pipes. The main pipeline convey water from the pumping unit to the several parts of the field. It is either permanent or portable. Main line pipes were buried underground so as to avoid disturbance during farm operation such as land clearing. In this review, one portable main line (6m in length and 50mm in diameter) is appropriate for the field rainfall simulator.
(iv) Lateral lines: Lateral line conveys water from the main line to pressurized nozzles. Lateral lines are made of aluminum pipes with couplings. The length of the Lateral pipes is available in 5m, 6m and 12m. The length could be joined together if the area is large. Crop geometry, water requirement and area needed to be wetted are the main factors determining number of laterals line. For this review, two 6m lateral lines are recommended for effective design.
(v) Nozzle/Sprinkler Head: This is the component that sprays water in the form of rain to the agricultural land. Optimum water pressure and wind velocity are the vital parameter that determines the nozzle suitability term of efficiency.
(vi) Riser: This pipe joins the pressurized nozzle to the lateral line. The diameter of the pipe varies from 12 mm to 75 mm with standard pipe threads. The riser height could be between 4and 5 m for tree sprinkling. High risers are required for taller crops such as sugarcane, banana, maize where height of the plant is high. For the purpose of this review, a riser height of 3m with 25mm diameter is appropriate.

METHODOLOGY FOR DESIGNING A FIELD RAINFALL SIMULATOR

Determination of raindrop size

The median drop diameter of the rainfall simulator is calculated according to Horne (2017)

$$D_m = 2.23I^{0.182} \quad (1)$$

Where,

$D_m = median\ drop\ diameter\ (mm)$
$I = monthly\ average\ rainfall\ intensity\ (\frac{mm}{hr})$

Determination of Kinetic energy and raindrop velocity

The kinetic energies of the rainfall simulator are estimated for rainfall simulator.

$$e = 11.897 + 8.73\log_{10} I \quad (2)$$

$$E = \sum_{i=0}^{n} e \times P \quad (3)$$

Where

$e = Kinetic\ energy\ (\frac{J}{mm}.m^2)$
$I = rainfall\ intensity\ \left(\frac{mm}{h}\right)$
$P = rainfall\ amount\ (mm)$
$n = number\ of\ rainfall\ periods$

$E = kinetic\ energy\ (\frac{J}{m^2})$

In addition, the raindrop velocity will be calculated using modified Newton's equation (Chouksey *et al*., 2017)

$$V = (17.20 - 0.84d) \times (d) \times 0.5 \quad (4)$$

Where

$V = raindrop\ velocity$

$d = diameter\ of\ the\ raindrop$

Determination of Flow rate

The flow rate was calculated in line with Devaranavadagi and Bosu (2014).

$$Q = iA \quad (5)$$

Where

$i = average\ monthly\ rainfall\ intensity\ over\ 30\ years\ (\frac{mm}{hr})$

$A = total\ area\ of\ the\ land\ (m^2)$

$Q = the\ discharge\ or\ Flow\ rate\ is\ in\ m^3/s$

Determination of the nozzle diameter

The nozzle diameter of the rainfall simulator is calculated as follows**:**

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

$$Q = VA \quad (7)$$

$$D = \sqrt{\frac{4A}{\pi}} \quad (8)$$

Where

$D = dianeter\ of\ the\ nozzle\ (mm)$

$v = velocity\ of\ flow\ \left(\frac{m}{s}\right)$

$A = area\ of\ the\ land\ (m^2)$

Determination of area covered by the rotating Nozzle

The area covered by the rotating nozzle is calculated in line with Michael (2008).

$$R = 1.35\sqrt{dh} \quad (9)$$

Where

$R = radius\ of\ wetted\ area\ covered\ (m)$

$d = diameter\ of\ the\ noozle\ (m)$

$h = pressure\ head\ at\ the\ noozle\ (m)$

Determination of Velocity of Flow of Water at Main and Lateral Line

The velocity of the water at the main and lateral line is calculated as follows:

$$V_1 = \frac{Q}{A_1} \quad (10)$$

$$V_2 = \frac{Q}{A_2} \quad (11)$$

$$V_3 = \frac{Q}{A_{13}} \quad (12)$$

Where

$A_1 = diameter\ of\ the\ main\ pipe$ (12mm)

$A_2 = diameter\ of\ the\ lateral\ line$ (5mm)

$A_3 = diameter\ of\ the\ nozzle$

$V_1 = velocity\ of\ the\ main\ line$

$V_2 = velocity\ of\ the\ lateral\ line$

$V_3 = velocity\ of\ the\ nozzle\ diameter$

Determination of the Water Losses in the System

The water losses at the main and lateral line is calculated as follow:

$$h_1 = K\frac{v_1^2}{2g} \quad (13)$$

$$h_2 = K\frac{v_2^2}{2g} \quad (14)$$

$$h_3 = K\frac{v_3^2}{2g} \quad (15)$$

Where

$h_1 = head\ loss\ at\ main\ line$

$h_1 = head\ loss\ at\ lateral\ line$

$h_1 = head\ loss\ at\ nozzle$

$V_1 = velocity\ of\ the\ main\ line$

$V_2 = velocity\ of\ the\ lateral\ line$

$V_3 = velocity\ of\ the\ nozzle$

K = the constant value (0.80)

$g = acceleration\ due\ to\ gravity\ (9.81\frac{m^2}{s})$

The total head loss was calculated as follow:

$H_T = h_1 + h_2 + h_3$

Determination of Mean Application Rate

The study used equation 14 to determine Mean Application Rate (MAR)

$$\mathrm{I} = \frac{q}{S_m \times S_l} \times 100 \qquad (16)$$

I= mean application rate is (mm/hr)

q = $Sprinkler\ discharge$ (mm^3/hr),

S_l = $Sprinkler\ spacing$ (m),

S_m = $lateral\ spacing$ (mm).

Determination of Power Requirement

The power requirement is calculated as described by Phocaides (2007)

$$P = \frac{Q \times H_t}{75 \times e_1 \times e_2} \qquad (17)$$

$P = Power\ requirement\ of\ the\ simulator\ \ (HP)$

$H_t = total\ head\ (m)$

$Q = total\ discharge\ (\frac{l}{s})$

$e_1 = pump\ efficency\ (0.5 - 0.8)$

$e_2 = driving\ \ efficency\ (fraction\ of\ 0.7 - 0.9\ for\ electric\ motor\ )$

$$H_t = H_a + H_i + H_p \qquad (18)$$

Where,

$H_a = Elevation\ head\ between\ first\ and\ last\ lateral\ (m)$

$H_p = Maximum\ friction\ loss\ in\ the\ main\ and\ lateral\ line\ (m)$

$H_i = Sprinkler\ noozle\ operation\ head\ \ (m)$

Rainfall Simulator Calibration

It is important to calibrate the rainfall simulator for rainfall intensity, uniformity coefficient and kinetic energy (Pall *et al*., 1993; Horne, 2017) for effective simulation with the natural rainfall. The calibration is estimated as described Sousa et al. (2017) as follows:

$$Rainfall\ intensity\ (mm\ h^{-1}) = \frac{volume\ water\ in\ the\ pipe\ (m^3)}{Area\ covered\ (m^2) \times simulated\ time\ (s)} \times 60 \qquad (19)$$

In addition, the variation of operating pressure for spray nozzle at 2.5, 3.5 and 4 bars at a minimum of 3 minutes give the best simulated natural conditions.

CONCLUSION

A methodology for designing a field rainfall simulator was reviewed. This methodology is important for the studies of infiltration, surface runoff, sediment, and nutrient loss analysis. In addition, this approach is important for assessing the long-term and seasonal effects of the rainfall simulator's usefulness. This method is good for examining the effect of different pressurized nozzles on the intensity of rainfall simulator's performance. This approach uses natural raindrop size, kinetic energy and raindrop velocity, flow rate, sprinkler nozzle diameter, sprinkler nozzle diameter for estimating power requirement of the system which has not been documented literatures. The study reviewed numerous methods for calibrating rainfall simulator based on the existing nature of the rainfall intensity, uniformity coefficient and kinetic energy. The operating pressure for this rainfall simulator ranged from 1.5 to 4.0 bars and these give the best simulated natural conditions. Thus, optimization of rainfall simulator produced from this approach will in turn produce the optimum CU and DU at different operating pressure.

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