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A comprehensive design of rainfall simulator for the assessment of soil erosion in the laboratory

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ABSTRACT

The present paper describes the design of a comprehensive rainfall simulator which is particularly meant for the assessment of soil erosion at plot scale by considering various soil grain types, soil slope angles, and surface exposures under different rainfall conditions. The entire setup is divided into four major parts: (a) water supply system with single spray nozzle, (b) supporting metal frame, (c) hydraulic jack attached container table for slope adjustment, and (d) temperature simulator. It covers an area of 3 m^2, out of which 0.5 m^2 is the target area or experimental plot and the simulated raindrops fall from a height of 2.3 m. Four types of full-jet spray nozzles are used to simulate rainfall intensities of 65, 93, 112, and 148 mm/h. The experimental plot can attain a maximum slope angle of 40° using a hydraulic jack unit. A temperature simulator is designed to replicate the natural conditions in the laboratory. Physical and numerical simulations are carried out to measure the characteristics of simulated rainfall and compare with those of natural rainfall conditions. The Christiansen coefficient (*Cu*) of the designed rainfall simulator varies from 81% to 88%. The rain droplet size ranges from roughly 1 mm to 5 mm and their corresponding terminal velocities range from 4.76 m/s to 10.64 m/s, striking velocities are found between 5.56 m/s and 9.63 m/s, and kinetic energies ranging from 0.0081 mJ to 3.0342 mJ. The total kinetic energy of the raindrops striking the soil surface in the entire plot area of 0.5 m^2 depends on the rainfall intensity and varies from about 6 J to 12 J. The designed setup is capable of simulating rainfall inside the laboratory with properties very close to those of natural rainfall. We adopt the Taguchi fractional factorial design of experiments to investigate the effects of different factors on soil erosion. Furthermore, statistical analysis of the experimental data is carried out by using signal-to-noise (*S/N*) ratio and the optimum condition for maximum soil erosion is predicted. The main objectives of this study are to design a comprehensive rainfall simulator setup, evaluate the properties of the simulated rainfall, provide a theoretical model and assess the several factors affecting soil erosion using reduced number of experiments in the laboratory.

1. Introduction

Rainfall simulators have been widely used for studying rainfall and hydrological processes of the soil such as runoff, erosion, and infiltration (Abudi et al., 2012; Agassi and Bradford, 1999; Aksoy et al., 2012; Andre and Anderson, 1961; Cerdà et al., 1997; Dunne et al., 1980; Parsakhoo et al., 2012). The most important objective of constructing a rainfall simulator is to replicate the process of natural rainfall which is a considerably complex phenomenon and has never been able to be replicated accurately (Aksoy et al., 2012; Bryan, 1981). In the last few decades, such rainfall simulators have become a significant tool for analyzing the soil erodibility with varying rainfall intensity on various soil types and different slope conditions (Grismer, 2012; Wang et al., 2010). Runoff is an important process related to soil erosion and it depends on natural rainfall and related factors such as variation in intensity, drop size, drop energy, spatial and temporal distribution (Pérez-Latorre et al., 2010), etc. In this context, it is pertinent to mention that rainfall simulators can provide a uniform rainfall distribution with a proper imitation of drop sizes and kinetic energies similar to that of natural rainfall (Lascano et al., 1997; Munster et al., 2006). The main advantage of such instruments is that they can produce a wide range of rainfall intensities as and when required in a controlled environment without having to wait for natural rainfall (Bowyer-Bower and Burt, 1989; Navas et al., 1990). However, in rainfall simulation studies, relevant knowledge of the corresponding natural rainfall properties like drop size, rainfall uniformity and kinetic energy are needed to be understood properly (Dunkerley, 2008; Van et al., 2002).

Rainfall simulators are classified into two broad categories: (a)

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drop-forming or non-pressurized nozzle rainfall simulators (DRSs) and pressurized nozzle rainfall simulators (PRSs) (Abudi et al., 2012; Aksoy et al., 2012; Grismer, 2012; Pall et al., 1983). In the DRSs, droplets are mostly generated through hypodermic needles, polyethylene tube and capillary tube (Chow and Harbaugh, 1965). In this setup, drop generator equipment is located at a certain height which creates the rain droplets under the effect of gravitational force. Simulated raindrops require a falling height of about 10–12 m in order to reach their terminal velocities (v_T) which are able to produce kinetic energies whose values are similar to those of natural raindrops (Aksoy et al., 2012; Bryan, 1981). In general, achieving the required height in the actual field is quite difficult and therefore, such types of rainfall simulators are not feasible for field study (Aksoy et al., 2012). In spite of this, many researchers have used DRSs to analyze the soil erodibility in the actual field. On the other hand, PRSs produce raindrops under applied pressure by using single or multi-nozzles. In comparison to DRSs, they can produce sufficient droplet velocities and corresponding kinetic energies at much lesser fall height (Aksoy et al., 2012; Foster et al., 2000). Although they produce ample droplet velocities and kinetic energies, the process exaggerates the energy flux since water flows due to the applied pressure (Abudi et al., 2012; Hignett et al., 1995; Meyer, 1965). To reduce this abundant flux, many developers have used the spray interruption concepts such as rotating boom, oscillation, and slotted rotating disk which kill the excess energy flux effects and lessen soil erodibility (Pall et al., 1983).

Soil erodibility depends on the striking velocity of the raindrops and the corresponding kinetic energy generated at the soil surface (Angulo-Martínez et al., 2012). Moreover, it also depends on various soil properties such as soil texture, structure, porosity, permeability, organic matter and moisture content (Andre and Anderson, 1961; Bryan, 1981). For small plots, soil erosion is usually expressed as the amount of soil loss per unit surface area per unit time (Lal, 1988). In literature, there is no standard plot size for the soil erodibility test. A variety of rainfall simulators have been developed which includes small portable infiltrometer with a circular rainfall area of 6 inch diameter as well as the Kentucky rainfall simulator which covered a relatively large area of dimensions 4.5 m by 22 m (Moore et al., 1983). There is no standard design of rainfall simulators and they vary according to various specifications such as rainfall intensity, spatial rainfall distribution, target area, drop size, droplet velocity and kinetic energy (Iserloh et al., 2013). However, the replication of natural rainfall is the prime goal of these rainfall simulators. Generated database is important for the runoff and soil erosion assessment which helps in building a good decision support system for erosion control planning. Therefore, a proper design of rainfall simulator is an important aspect and precise knowledge of rainfall properties is a fundamental requirement. The model simplicity, portability and economical are also desirable properties.

In this paper, we meet the following objectives, i.e. (i) designing a laboratory-based rainfall simulator for carrying out experiments on soil erosion, (ii) replicating natural rainfall in the laboratory and evaluating the simulated rainfall characteristics corresponding to natural rainfall such as drop size, rainfall uniformity, rainfall intensity, terminal velocity, striking velocity, and kinetic energy, (iii) constructing a theoretical model for estimating terminal velocity, striking velocity and kinetic energy of the rain droplets, and (iv) examining the performance of the developed rainfall simulator by carrying out experiments on soil erosion implementing the Taguchi design and estimating the optimum condition for maximum soil erosion. A vivid description of the designed rainfall simulator is provided along with comparisons with data of earlier studies to approve sanity checks. A theoretical model is constructed by carefully considering all aspects of the physical phenomenon that occurs in nature from the time a rain droplet starts falling and till the instant when it strikes the soil surface. The model comes in handy for accurately estimating various properties of the rain droplets in situations when it is not possible to carry out rainfall experiments either in the open field using natural rainfall or in the laboratory using simulated artificial rainfall. Finally, the performance of the whole experimental setup is examined by conducting a limited number of soil erosion experiments using the Taguchi method. A vivid statistical analysis is carried out to observe the effects of various factors on soil erosion and identify the optimum conditions required for maximum soil erosion.

The paper is organized as follows: Design of the rainfall simulator setup is given in Section 2, which describes different units of the setup e.g. (i) water supply system with centrally attached single spray nozzle, (ii) supporting metal frame, (iii) soil-slope container table attached with hydraulic jack for slope adjustment, and (iv) temperature simulator for experiments on temporally-varying soil erosion in the laboratory. Methods for evaluating simulated rainfall characteristics are well-defined in Section 3, which explains (i) rainfall uniformity, (ii) drop size distribution, (iii) rainfall intensity, and (iv) drop velocity and kinetic energy. According to the mass and size of the simulated droplets, this section describes the theoretical considerations to measure the terminal velocities, striking velocities, time taken to reach the experimental plot (soil surface) from the nozzle and generated kinetic energies. Section 4 includes the soil erosion experiments by implementing Taguchi's method. Conclusions close the paper in Section 5.

2. Design of rainfall simulator setup

In the present study, a pressurized-nozzle rainfall simulator has been designed for laboratory-based soil erosion study. The basic idea of the simulator model has been derived from the U.S. Department of Agriculture and Department of Natural Sciences, University of Maryland Eastern Shore, but a few necessary modifications have been done in the present rainfall simulator (Kibet et al., 2014). There are many important factors involved in the study of soil erosion such as rainfall intensity, soil slope, slope length, soil type, and surface microtopography. For considering all the aspects in our study, a complete setup of the rainfall simulator and associated equipments has been constructed for the temporal study of surface runoff and soil erosion. The entire setup is divided into four major parts (Fig. 1): (a) water supply system with single spray nozzle, (b) supporting metal frame, (c) hydraulic jack attached container table for slope adjustment, and (d) temperature simulator (see the schematic diagram in Fig. 1). Photographs of the real experimental setup are given in Fig. 2.

2.1. Water supply system and single spray nozzle

A pipe made of polyvinyl chloride (PVC) is used for the entire water supply system. In this setup, a tank of storage capacity 500 L is connected with 1 horsepower (HP) electric pump. Since the 1 HP pump generates excessive pressure at the nozzle, water flow has to be deviated in such a way so that the excess water which creates higher pressure at the nozzle can be drained and collected in the same storage tank for re-utilization. To control the flow rate and pressure, two control valves are used. Above the control valve, a flow meter is attached to the flow pipe at a convenient height for monitoring the flow rate. A pressure gauge is fixed close to the centrally attached single spray nozzle to read the flow pressure just above the nozzle. Spray nozzles of four different orifice sizes (given in Fig. 3 and Table 1) are used to simulate different rainfall intensities. The spray angle of the nozzles is 45°. The spray nozzles are constructed by "Spraytech Systems Pvt. Ltd., Thane (W), Mumbai 400604, Maharashtra, India (web: www.spraytechindia.com)".

2.2. Supporting metal frame

A supporting metal frame is constructed to attach the water supply system. The frame is made up of perforated metal bars. The perforations in the metal frame makes it convenient to change the dimensions of the rainfall simulator setup according to requirements. The rainfall