Catena 140 (2016) 77–89

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Design and performance of a nozzle-type rainfall simulator for landslide triggering experiments

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ARTICLE INFO

Article history:
Received 8 June 2015
Received in revised form 16 December 2015
Accepted 18 January 2016
Available online 28 January 2016

Keywords:
Rainfall simulator
Infiltration
Drop size distribution
Soil erosion

ABSTRACT

Rainfall simulators represent a widespread tool for studying hydrologic processes involving interactions of rainwater with soils, such as soil erosion, overland flow generation, and infiltration. Nevertheless, researchers must often develop devices suiting their particular needs, due to a lack of a standard design. In this case, a rainfall simulator was needed for the production of heavy rainfall, to be applied for the study of infiltration dynamics and landslide triggering on an artificial hillslope with a planar size of 2 m by 6 m. Therefore, the goal of this study was to design and test a rainfall simulator characterized by the following main properties: i) range of rainfall intensity varying from 50 to 150 mm/h, ii) spatial uniformity of the produced rain of at least 80%, and iii) limited impact energy on the soil in order to avoid surface erosion, which can alter the infiltration processes responsible for the landslide triggering. To achieve these objectives, three nozzles were first individually tested, in order to identify the main variables affecting their functioning and performance. Further investigations were then carried out to find the best configuration of nozzles for the final version of the full-scale rainfall simulator and test its performance. Depending on the desired rainfall range, four different configurations of nozzles, distinguished by the number of active nozzles and their location, were chosen to cover the required intensity interval. The simulator performance was assessed via the Christiansen uniformity coefficient (CU), which resulted in values larger than 80%. The drop size distribution was assessed by means of the oil method and used for the calibration of a numerical model aimed at estimating the impact energy of the drops falling onto the soil. This allowed for the assessment of the rainfall potential erosion and its spatial distribution, highlighting that the surface erosion generated by the proposed rainfall simulator is limited, corresponding to the kinetic energy exerted by natural rainfall rates of no more than 10 mm/h.

1. Introduction

In the last decades, rainfall simulators have represented a widespread tool for studying hydrologic interactions of rainwater with soils, the main fields of investigation including soil erosion, overland flow generation, and infiltration (e.g., Tossell et al., 1987; Esteves et al., 2000; Hamed et al., 2002; Kato et al., 2009; Abudi et al., 2012; Caracciolo et al., 2012; Aksoy et al., 2012; Fister et al., 2012; Schindewolf and Schmidt, 2012; Schindler Wildhaber et al., 2012; Iserloh et al., 2013). Furthermore, their use is increasing for the improvement of process knowledge about landslide occurrences as well as debris-flow events in equipped laboratory devices, aimed at reproducing the phenomena under carefully controlled conditions, either in small-scale or full-scale physical models (Reid et al., 1997; Iverson et al., 1997; Iverson, 1997; Rahardjo et al., 2002; Ochiai et al., 2004; Moriwaki et al., 2004; Reid et al., 2011).

According to Esteves et al. (2000) and Battany and Grismer (2000), rainfall simulators can be classified in two types: (i) drip (or drop) formers, usually built with hypodermic needles, and (ii) nozzle-type. The choice is usually based on geometrical constraints, portability, and costs. Drip formers are typically used for areas no larger than 1 m^2, operate at low pressure, and generally produce a narrow range of drop sizes. Nozzles can be used also for areas larger than 1 m^2 (e.g., Meyer and McCune, 1958; Swanson, 1965; Niebling et al., 1981; Parsons et al., 1990; Riley and Hancock, 1997), operate at high pressure, and provide a wider range of drop sizes. For these reasons, they often impart excess kinetic energy to the drops compared with natural rainfall, resulting in a high risk of erosion.

As a result, considerable attention has been paid to estimate the kinetic energy of the induced rainfall at the impact of the drops with the soil surface, especially for simulators designed to control erosion dynamics, runoff generation, and changes of infiltration rate due to soil crusting (Kincaid et al., 1996; Esteves et al., 2000; Fox, 2004; Pérez-Latorre et al., 2010; Abudi et al., 2012; Caracciolo et al., 2012). As kinetic energy depends on both the size of the sprayed drops and the terminal velocity at the impact, these two terms need to be carefully investigated to assess the erosion potential of the produced rainfall. Several different procedures have been proposed in the past to this aim (see, e.g., Kincaid et al., 1996, for a review). One of the most widespread

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http://dx.doi.org/10.1016/j.catena.2016.01.018
0341-8162/

methods consists in collecting the raindrops in a layer of flour contained in a shallow can, while other techniques include the stain or the photographic methods. Most of these approaches require an extensive calibration and provide limited information on the drop size distribution (DSD). More recently, other devices have been developed to analyze the DSD by using technologies such as the laser disdrometer and high-speed video cameras (e.g., Tokay et al., 2013). Despite the good accuracy of these cutting-edge instruments, analyses of potential soil erosion generated by rainfall simulators and its spatial distribution over the plot area have been mostly limited to surface areas of no more than 1 m^2 (Iserloh et al., 2013).

Several authors have listed important criteria for "ideal" rainfall simulators (e.g., Highett et al., 1995; Cerdà, 1999; Iserloh et al., 2012). Some of these criteria are aimed at the similarity of the produced drops to natural rainfall (e.g., size, velocity, nearly vertical impact angle), some others are related to performance (spatial uniformity, capability of reproducing storms of different duration and intensities), while further desirable characteristics include portability and low cost. However, different applications require different properties and this has led to a lack of design standards and the development of a multitude of simulators, each suiting individual needs (Wilson et al., 2014). In particular, only few studies are available in the literature that report rainfall simulators specifically developed for landslide triggering, usually with limited information about the rainfall simulator characteristics and development. In their experiments, Moriwaki et al. (2004) used a large-scale (44 m by 72 m) rainfall simulator capable of reproducing rainfall rates ranging from 15 to 200 mm/h with characteristics very similar to natural rain, thanks to the high elevation (16 m) of the nozzles above the soil surface. On a smaller scale, Ochiai et al. (2004) were able to apply artificial rain at the rate of 78 mm/h to their slope by way of a rainfall simulator consisting of a framework of steel pipes with 24 sprinkling nozzles arranged 2 m above the soil surface.

In the present study, a rainfall simulator was needed for an artificial hillslope with a horizontal plot area of 6 m × 2 m = 12 m^2, used to simulate infiltration processes and shallow landslide triggering due to heavy rainfall. The required properties of such a simulator consist in producing: i) a wide range of rainfall intensity, varying from 50 to 150 mm/h; ii) an acceptable spatial uniformity of the rain on the plot area; and iii) a limited or no soil erosion due to the drop impact, in order to focus exclusively on the role of infiltration on the triggering of shallow landslides. The goal of this research was to design and test a new rainfall simulator and to verify that the chosen configuration satisfied the above properties.

The paper is organized as follows. Material and methods are reported in Section 2, which describes: i) some preliminary analyses, conducted on individual nozzles to assess their spray properties as a function of pressure, elevation above the surface and inclination; ii) the analyses carried out with the full-scale rainfall simulator over the artificial hillslope; iii) the methodology used to obtain the drop size distribution generated by a single nozzle; and iv) a numerical model implemented to compute the falling trajectory and impact velocity of the drops, in order to assess the rain maximum potential erosion, in terms of kinetic energy, and its spatial distribution. Section 3 describes the results, discussed within the context of existing literature in Section 4, while summary and conclusions close the paper in Section 5.

2. Material and methods

The design of the rainfall simulator was developed based on particular needs related to the specific purposes and geometry of the experimental facility. Rainfall must be applied onto an artificial hillslope, contained in a reinforced concrete box with a length of 6 m, a width of 2 m, and a maximum height of 3.5 m (i.e., a maximum slope of approximately 32°, Fig. 1). The purpose of this structure is to reproduce shallow landslide triggering under monitored hydrological dynamics induced by heavy rainfall. As we want to consider only the instability due to infiltration forces, the nozzles were chosen to reduce the size of the drops, in order to minimize impact kinetic energy and prevent soil erosion. Therefore, we elected to adopt wide angle square jet nozzles from Spraying System, models HH 14 WSQ, HH 20 WSQ, and HH 30 WSQ, corresponding to flow rate capacities (at 0.689 bar) of 5.3, 7.6, and 11.4 l/min, respectively.

2.1. Single nozzle performance

The performance of the single nozzles was analyzed with a laboratory device that allows for the monitoring and control of the operating water pressure and spray discharge. The discharge and the corresponding pressure values were measured with an electromagnetic flow meter and a pressure transducer, respectively, located at suitable distances from two control valves, which could induce disturbances on the flow and compromise the measurements. All data were recorded and collected at a frequency of 100 Hz with a data logger from Campbell Scientific (DAQ model).

The first tests on the nozzles consisted in spraying water on a surface of area 2 m × 2 m = 4 m^2, on which 41 rain gauges, with a height of

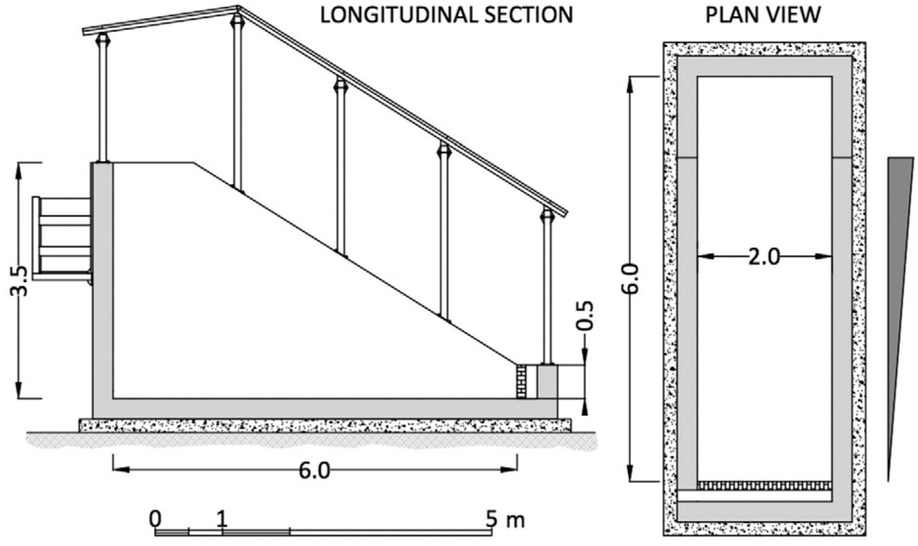

Fig. 1. Longitudinal section and plan view of the artificial hillslope.