Characterization of a Micro-portable rainfall simulator for a civil engineering studies

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ABSTRACT

Researchers are focusing increasingly on in-situ studies of several civil engineering problems where we find direct water interaction in the system. The need to identify the water interaction subprocesses has led to the development of small-scale rainfall simulations. We present a new upgrade rainfall simulator concept, a micro portable rainfall simulator, where we have an easily assembled/disassembled system, with different nozzle elevation between 1.3 and 2 m, for better portability and better adaptability to all platforms type. In aim to use our simulator in different projects, this device has passed through a validation step where we characterize and compare artificial rainfall to some credible simulators and natural rainfall. Essentially, it has been characterized by the use of water collectors and Laser Precipitation Monitor by Thies (LPM). At 2 m of elevation nozzle, this upgraded configuration shows satisfactory results compared to others credible simulators. It has a homogeneity with a high Christiansen-Uniformity Coefficient (CU) in one m². Regarding drop size/velocity distribution, the simulator has a close relationship to natural rainfall with a high percentage of drops which have approached drop size/velocity of natural rainfall.

Keywords: Micro-portable rainfall simulator; Drop size; Drop velocity; spatial rainfall distribution.

INTRODUCTION

The Rainfall simulator is an experimental device that produces an artificial rainfall on a test plot. It has become an important tool to evaluate soil and hydrological process [5], and sediment quality studies [7]. Traditionally, it aims to quantify runoff, infiltration and erosion process. Globally, rainfall simulators allow rapid experimentation and various hydrological scenarios, giving several measures while simultaneously controlling rainfall conditions without waiting for natural rainfall [12]. It also allows to eliminate the erratic and unpredictable variability of natural rain that can falsify some analysis. However, we cannot extrapolate the rainfall simulator results to others hydrologic conditions [4]. Based on this principle, several types of rainfall simulators has been realized with spraying elevation up to few meters and test plot area up to 100 m² (e.g., [26]-[27]-[38]). The technological advancements resulted in an improved rainfall simulator. All simulators are becoming smaller and profitable [3]-[8]-[15]-[32]. At local and laboratory scale, this amelioration oriented research to have more details about hydrologic process, with capacity to more identify and quantify infiltration variability and surface/subsurface runoff [10]-[31]-[32], and its effects on a soil, with capacity to quantify detachment and transport of soils [29]-[16]. Actually, scientific researchers are more and more oriented to an in situ analyze for several phenomena [24]-[31]. Thus, the portable rainfall simulator became an important and required tool in several fields where there are hydrological effects of rain (Engman, 1986; Foster et al., 2000; Herngren et al., 2005). The natural rainfall reproduction by the portable rainfall simulator is an important and difficult step. Indeed, the 1:1 in situ reproduction of natural conditions are not possible due to physical knowledge limitations of raindrop characteristics (raindrop size, rain velocity, rain kinetic energy, etc.) [22]. In addition, reproduction task is still complex and not easy to perform with presence of temporal and spatial variability [5]-[11]-[33]. Hence, to ensure reproduction of artificial rain, parameters like intensity, duration, drop size distribution, drop fall velocity and rainfall kinetic energy are kept constant during experiments. Furthermore, we must characterize the artificial rainfall simulation and compare them to the natural rainfall. In this paper, we present a characterization of a micro portable rainfall simulator based on one nozzle spraying system and with 2 m nozzle elevation with a test plot of one m². This characterization focuses on: (1) spatial homogeneity of the artificial rain, (2) drop size distribution according to fall velocity compared to other simulators and natural rain.

MATERIALS AND METHODS

The proposed Micro-portable rainfall simulator

The micro portable rainfall simulator is designed for an easy portability, to be lightweight and more practical with a use of inexpensive materials and easily available requiring minimal expenses of construction. Primarily, it is based on a flexible Plexiglas bottom frame constituting the test plot 1 × 1 m, demountable stainless steel structure for a solid but lightweight device and a spray-nozzle system. The bottom frame is composed of the Plexiglas barriers (1000 × 100 × 10 mm) where we find a turning point system ensuring an easy pliability and portability (fig.1). This frame is permanently assembled. It supports the metallic structure of our system (aluminum pipes). This structure was designed to produce centralization and stability of our spray nozzle system with several elevations (1.3 ; 1.5 ; 1.7 and 2 m) relative to the test plot. During the rain simulation, our device is protected with a plastic tarp to negate a wind condition. The production of artificial rain presents the core of our device. The spraying system is composed of a nozzle and an alimentation system. In this project, artificial rainfall is produced through the use of LECHLER nozzle (460.726 CC with full cone) centered on the frame top (between 1.3 et 2 m).

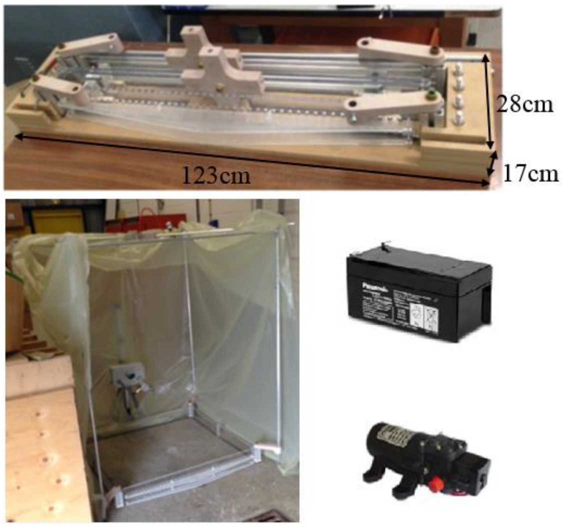

Fig. 1 The micro-portable rainfall simulator

This choice was motivated by the technical characteristics of this series where we find several full cone nozzles and their applications on one m² plots can be provided with a reduced height like 1.3-2 m compared to other marks [4]-[22]-[28]. The nozzle is connected to a PVC water distribution pipe (8 mm diameter) ensuring system supply. This supply is maintained by a portable pump system (electric mini-pump connected to a 12V battery) linked with pressure regulator and water container (fig.1).

Validation of rainfall simulator

Actually, the rainfall simulator cannot reproduce the natural rain. This limit is caused by the physical condition (natural cloud elevation, natural drop velocity, etc.). However, the rainfall simulator can produce an artificial rainfall, which approaches the natural rainfall with a fixed test condition. As the natural rainfall is known with important spatial and temporal variability [11]-[33], during experimentation we considered that rainfall intensity and distribution are homogeneous and constants. This normalization provides a way to collect necessary and comparable data. The artificial rainfall characterization is done by determining the spatial rainfall distribution and uniformity, drop-size distribution and fall velocity of these drops and kinetic energy [21].

Uniformity and spatial rainfall distribution

In an aim to produce quantitative information about rainfall simulator homogeneity, 16 cylindrical collectors, with a diameter of 9 cm have been dispersed equally within the test plot (fig.2). Each collector was exposed three successive times to the spray nozzle during 5 min and with several pressure levels between 0.25 and 1.5 bars (the average of the three measured values are applied in this work). We measured the water quantity collected within each location in the test plot. Within these values, we evaluated the rainfall simulator uniformity with other simulators across the means Christiansen-Coefficient CU (%) (1) [9] and Standard Deviation SD (2). The CU (%) coefficient presents credible uniformity indicators used in several scientific works [1]-[2]-[14]-[34]-[36] and the SD value present a credible statistic indicator to dispersion rate in the plot test.

$$CU = 1 - \frac{\sum_{i=1}^{n} |x_i - \bar{x}|}{\bar{x} * n} \qquad (\mathbf{1})$$

$$SD = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{(n-1)}} \qquad (\mathbf{2})$$

Where x_i is the rainfall quantity for each collector i (ml)

$\bar{x}$ is the mean of rainfall quantity for each collector

n is the total number of collectors.

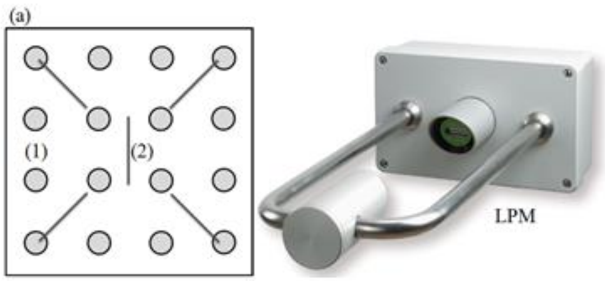

Fig. 2 Collectors (1) and LPM measurement position (2) in the test plot (a)

Drop size distribution and fall velocity

In an aim to evaluate the artificial rainfall, the determination of drop size distribution and fall velocity of these drops are required to validate our rainfall simulator. In our project, the LPM disdrometer (Laser Precipitation Monitor by Thies) was used to estimate drop size and fall velocity of the artificial rain (Fig.2). This disdrometer showed high precision and accuracy of measurement in rainfall characterization studies [20]-[23]-[30]-[37] and it's used by EDF and METEO FRANCE.

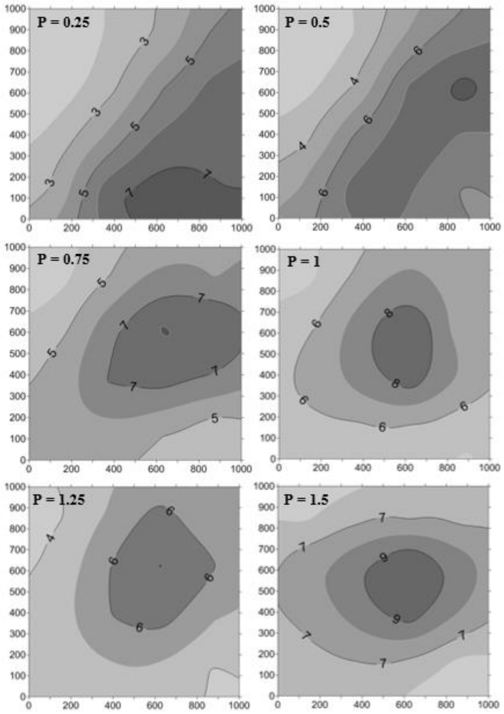

Fig. 3 Spatial variability of artificial rainfall

Note: the contour lines show the spatial concentration of artificial rainfall (mm)

This disdrometer allows the detection of particle precipitation between 0.16 and 8 mm and the determination of precipitation types (drizzle, rainfall, snow, hail and mixed precipitation). Moreover, it can estimate rainfall intensity with capacity up to 250 mm/h, but on the other hand, it only gives the drop size and fall velocity in class values. To attain best coverage of the test plot, the disdrometer LPM was positioned at different locations, allowing 5 minutes of measurement for each location (fig.2).

RESULTS AND DISCUSSION

In this work, we simulated rain with the Micro-portable rainfall simulator. This simulation based on a single nozzle (Lechler 460 726 CC) centered over the test plot. This simulation was performed with 2 m of spray height and by more pressure level (between 0.25 and 1.5 bar). Through spatial processing of collected measures with the kriging software "SURFER", we can evaluate the distribution and the spatial homogeneity of the artificial rainfall in the 1 m² test-plot (fig.3). This figure indicates a spatialization of a 2 m produced rainfall for each pressure level. It indicates a spatial rainfall variability at the test plot. Overall, we have a spatial uniformity with higher and lower degree of satisfactory for a pressure upper to 0.25 bar.

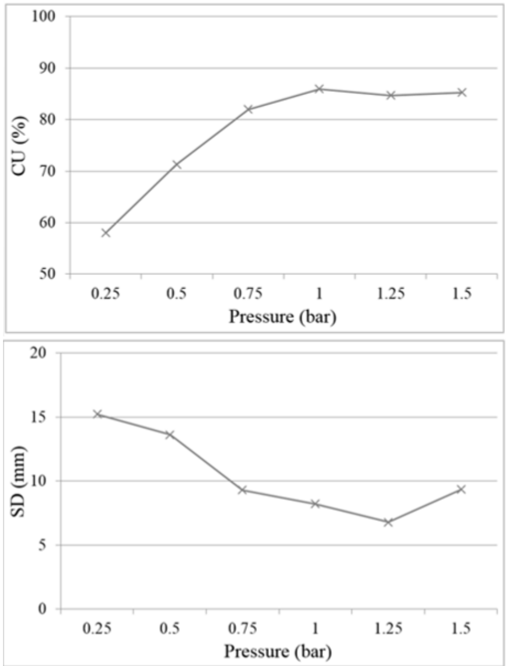

Fig. 4 Numeric indicators of uniformity

The application of 0.25 pressure level have result a high spatial variability at the test plot. The isohyets digress with pressure augmentation indicating a high spatial homogeneity of artificial rainfall. The augmentation of pressure results a more central and more distributed rain at the plot test. The one and 1.25 pressure level produce the higher homogeneity of rainfall with a lower of spatial variability. Beyond, the isohyets gets narrower and the spatial variability of rainfall increases indicating more spatial heterogeneity. This spatial variability was translated by numerical indicators CU and SD (fig .4).

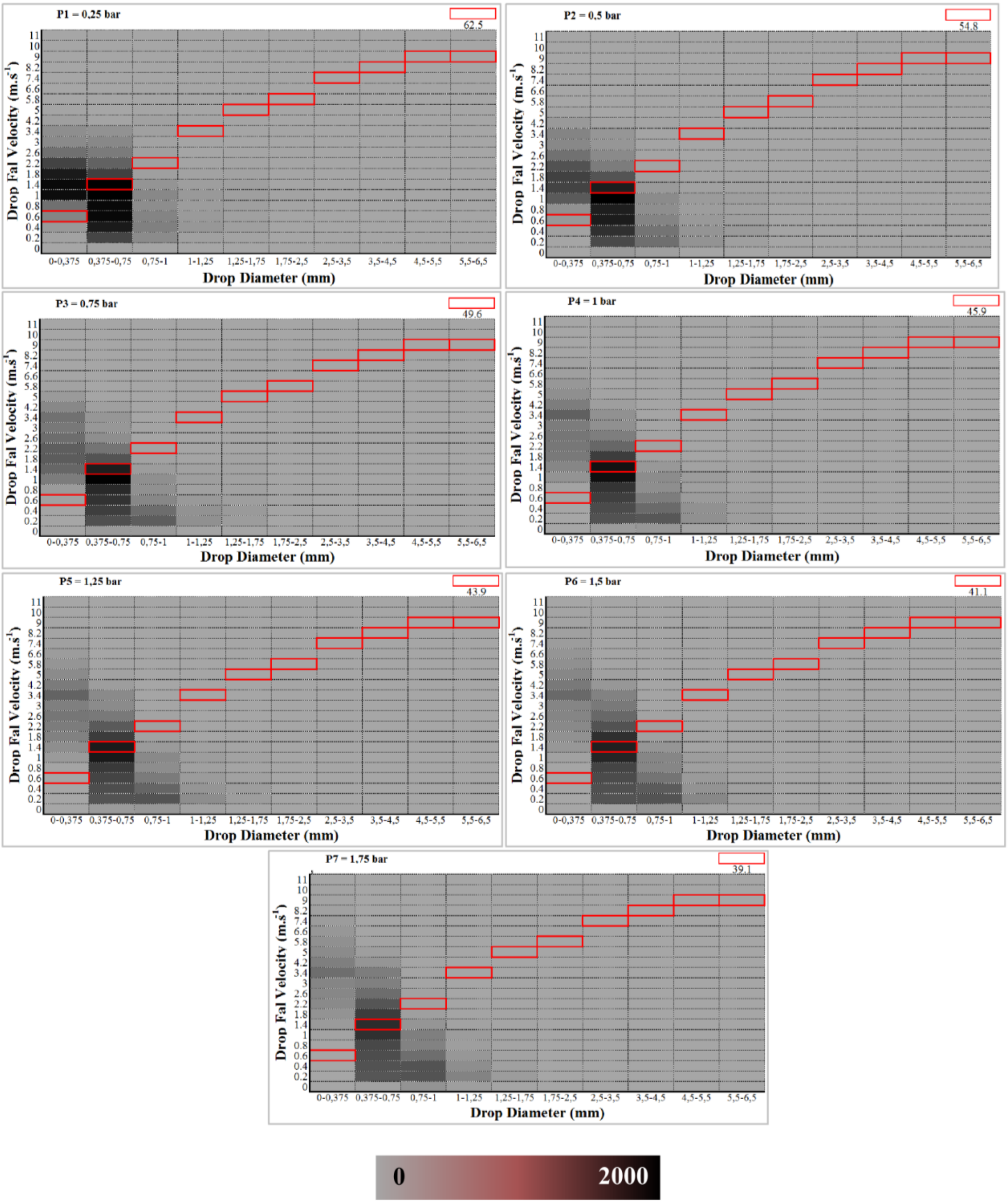

Fig. 5 Drop size distribution and fall velocity compared to natural rainfall

Note : the red squares present the characteristics of natural rainfall.

The different rainfall simulations presented a numerical evaluation of rainfall uniformity distribution. The results indicate that the micro portable rainfall simulator produces highly uniform artificial rainfall with CU between 72 and 87% for all levels of pressure upper to 0.25 bar (fig.4). In this condition, our rainfall simulator has a high and acceptable uniformity compared to the others rainfall simulator. In fact, the rainfall simulator of Iserloh et al., 2013, with the same test plot area (1 m²) but with the high spraying elevation (3.43 m), have the same uniformity (CU = 88%). Furthermore, [3] have reached less uniformity with a rectangular form (1 × 0.70 m) and 2.3 m of spraying elevation. The 2 m elevation level produces a high uniformity with minimal dispersion in the test plot (1 m²) indicated by a mean standard deviation between 6.8 and 15.2 (fig.4). This can be explained by the large spray diameter produced by the LECHLER nozzle at 2 m level elevation.

In this project, the mean drop size and fall velocity, of each pressure of the 2 m elevation, are measured by the LPM and the results are presented in the fig.4. The LPM results indicate that a large range of drop sizes from 0.125 mm up to 3.5 mm can be observed at every pressure level. The range of small drops is widely present compared to other ranges of drop size. The ranges of drop size between 0.125 and 0.75 is 70 to 84% of all drops for all pressure levels. The velocities of these ranges nearly coincide with that of natural ones, as indicated by [6]-[25], for vertical rainfall in calm conditions (fig.5). Large drops range is slow compared to natural fall with maximum velocity up to 5.8 m.s^{-1}. This result is similar to the results of all rainfall simulators tested with [21]. This rainfall simulator indicates that a global part of drops was smaller than 1 mm and had a maximum drop fall velocity nearly 5.8 m.s^{-1}. In this work, we have evaluated, for all the pressure levels, the percentage of drops approaching the natural relationship between a drop size and its fall velocity (fig. 5). This indicates that the amount of drops similar to natural ones decreases from 63 % to 39 % by increasing the nozzle pressure. This decrease can be explained by the spray form of the nozzle. In fact, the spray diameter increases with increasing pressure, making the drops scatter with different velocity range. This case can be verified with the variability of drops number of different classes (fig.5). When pressure increases, the high drop number classes (darker classes) will contain fewer and lower drops for the benefit of other classes (clearer classes) indicating a significant dispersion of drops type. Concerning the medium volume drop diameter (d50), its exact determination was not possible with the LPM because this device only records drop size classes and not the real size. Nevertheless, the calculation of d50 class values is the best option to characterize and evaluate geometry drops of the rainfall simulator compared to other simulators. The median volume drop diameter (d50) is between 0.5 and 0.75 mm for all pressure levels except for 0.25 bar which is between 0.375 and 0.5 mm (fig.6). This small diameter is similar to d50 values measured by many other rainfall simulators with nozzle elevation up to 4 m and with different rainfall intensity (e.g. [18]-[20]).

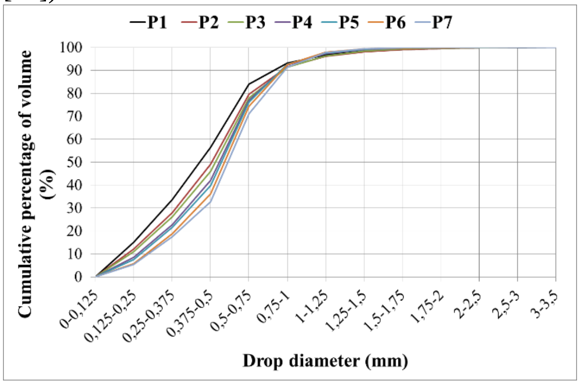

Fig. 6 Drop size cumulative of all pressure levels

CONCLUSION

The micro portable rainfall simulator was calibrated to meet basic requirements for in-situ studies of different fields. This new upgrade rainfall simulator concept improved the production of an acceptable artificial rain with satisfactory drop characteristics compared to other credible simulators and natural rainfall. At 2 m of elevation nozzle, it present a high homogeneity with the minimum of dispersion in 1 m². Regarding drop size/velocity distribution, it has a large relationship to natural rainfall. However, due to low fall height, the large drops range is slow compared to natural fall with maximum velocity up to 5.8 m.s-1. Furthermore, our simulator has a good mobility feature thanks to a compact and lightweight design, besides a low water and energy consumption. Compared to larger simulators, micro portable rainfall simulator has the advantage of being able to perform experiments on different specific surfaces with high repetition rates, adding to that an ease of handling and control of test conditions. So, we can adapt our simulator and realize different simulations in order to ameliorate and identify more knowledge in hydrological, environmental and civil engineering problems.

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