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Developing of the laboratory rainfall simulator for testing the technical soil surface protection measures and droplets impact

Développement du simulateur de pluie de laboratoire pour tester les mesures techniques de protection de la surface du sol et l'impact des gouttelettes

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ABSTRACT: Soil erosion and transportation of the detached soil particles towards the river networks is one of the key environmental problems connected to the intensive land use. The soil erosion is not only a problem initiated by intensive agricultural activity, but also of the engineering construction sites such as the slopes along the linear structures (roads, railroads, etc.). Soil erosion in this scale is very feasible to be monitored in the laboratory conditions. We have constructed the laboratory rainfall simulator in such a way, that we can design complicated experimental setups that we would hardly performed in the terrain. The simulator allows generating rainfall of various intensity and kinetic energy over inclined soil profile or soil sample. We are able to control the temperature of the soil profile (-15 to +40 °C) therefore we can simulate erosion processes ranging from permafrost to tropical soils.
Dimension of the soil sample with or without surface protection measures can be up to 4 m long and 1 m wide. Maximum plot inclination is 40 °. Maximal rain on the plot intensity is 200 mm/h. The simulator combines two basic types of nozzles (i) flat nozzles (VeeJet) with swiping; (ii) and full jet nozzles (WSQ) with interruptions. The automatic monitoring system records surface runoff, soil loss, percolating water, soil water and soil temperature regime.

RÉSUMÉ: L'érosion des sols et le transport des particules de sol détachées vers les réseaux fluviaux constituent l'un des principaux problèmes environnementaux liés à l'utilisation intensive des sols. L'érosion des sols n'est pas seulement un problème initié par une activité agricole intensive, mais également par les chantiers de construction tels que les pentes le long des structures linéaires (routes, voies ferrées, etc.). Il est très possible de surveiller l'érosion du sol à cette échelle dans les conditions du laboratoire. Nous avons construit le simulateur de précipitations de laboratoire de manière à ce que nous puissions concevoir des installations expérimentales compliquées que nous aurions difficilement réalisées sur le terrain. Le simulateur permet de générer des précipitations de différentes intensités et énergies cinétiques sur des sols ou des échantillons de sols inclinés. Nous sommes en mesure de contrôler la température du profil de sol (-15 à +40 ° C). Nous pouvons donc simuler des processus d'érosion allant du pergélisol aux sols tropicaux.
La dimension de l'échantillon de sol avec ou sans mesures de protection de surface peut atteindre 4 m de long et 1 m de large. L'inclinaison maximale de la parcelle est de 40°. L'intensité maximale de la pluie est de 200 mm/h. Le simulateur combine deux types de buses de base (i) les buses plates (VeeJet) et le balayage; (ii) et buses fulljet

(WSQ) avec interruptions. Le système de surveillance automatique enregistre les écoulements de surface, les pertes de sol, les eaux d'infiltration, les eaux de sol et la température du sol.

Keywords: soil erosion; rainfall kinetic energy; splash erosion; rills development; geotextiles

1 INTRODUCTION

Soil erosion by water is considered to be one of the major causes of soils degradation worldwide. The rate of erosion is driven by the rainfall intensity and duration (van Dijk et al. 2002).

Even though problematic of soil erosion is mostly related to intensive agriculture, also other human activities enhance the erosion. Construction of linear structures, such as roads, highways, railroads or water channels often results in sections that are cut in between steep banks. The slopes along the linear structures are usually extremely steep (slopes up to 1:1) and typically not vegetated and unprotected during the construction works. In such conditions the soil is prone to fast development of rills. Rill erosion is more severe than sheet erosion as it causes translocation of large amount of soil particles and also negatively affects hillslope stability. Consequences of the rill erosion on construction sites are therefore twofold: (i) pollution of the surrounding water drainage network and recipients by the sediment (often enriched with sorbed pollutants originating from the construction activities such as diesel and oils, paints, solvents, cleaners and other chemicals); (ii) damages of the structure affecting slopes stability.

Construction companies often carry out permanent or temporal (biodegradable) stabilisation of the slopes. This is done with use of natural or synthetic materials, typically various types of meshes, mats and fabrics.

The process of soil erosion initiation and the effectivity of the protection measures have been studied typically under natural rainfall conditions (Álvarez-Mozos et al. 2014). Disadvantage of the infield monitoring is the unpredictability of the rainfall. Therefore, rainfall simulators (RS) have been utilised for more systematic research.

Rainfall simulation experiments are widely used as a standard method to study various flow and transport processes induced by rainfall. They have been used on different land uses, slopes, scales, soils and climate conditions (Marques et al. 2007; Schindewolf & Schmidt 2012). But most of the experiments have been driven by a rather narrow objectives and often on agricultural land. The review of RS used across Europe provides (Iserloh et al. 2013) and historical review (Norton & Savabi 2010).

Laboratory conditions allow a perfect control of the system boundaries (rainfall intensity and duration, bottom boundary condition), initial soil and soil surface characteristics, monitoring of the ongoing processes (runoff, sediment transport, infiltration, rills development etc.). This helps to perform various scenarios and replications with different soil types, inclination or rainfall characteristics. The main disadvantage of the laboratory conditions is the disturbed (and translocated) soil sample. In the case of artificial soil profiles, such as tilled soil on fields or scraped and compacted embankments, we are able to mimic conditions very similar to the ones in the terrain.

I.e. (Kalibová et al. 2016) tested different technical measures to reduce the soil erosion on one selected slope inclination. Current research on RSs shows that the inclination of the soil sample is a very sensitive factor related to the sediment transport, therefore the erosion process should be investigated under more scenarios.

The aim of this manuscript is to present a technical description of a newly constructed laboratory rainfall simulator which was designed, except for the natural (agricultural) slopes, also for testing of the slopes typical for the linear construction sites. The RS allows inclination of the soil sample up to 40 % and generation a wide spectra of rainfall with different intensity, duration, hyetograph and kinetic energy. Soil in the container can be cooled down to -15°C and heated up to +40°C which helps us to observe the erosion and soil structure changes due to freezing and thawing mechanism (R. W. Van Klaveren & D. K. McCool 1998).

2 RAINFALL SIMULATOR DESCRIPTION

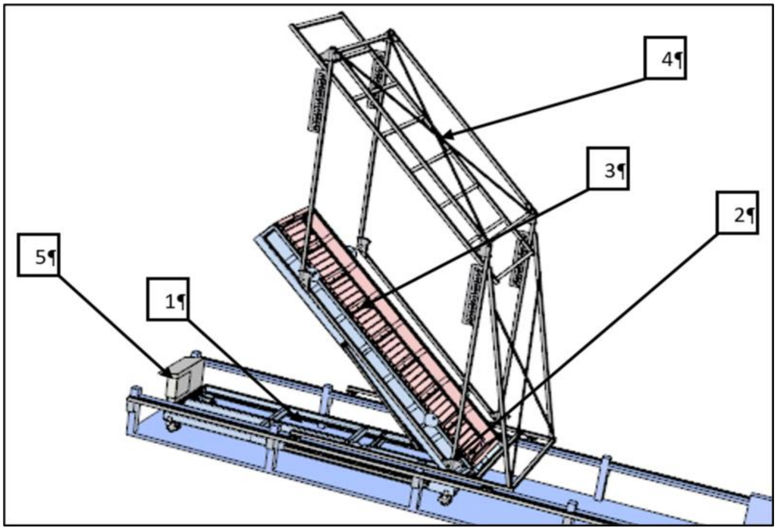

Figure 1: Sketch of the rainfall simulator, 1 – supporting frame, 2 – undercarriage with the piston for the container tilting, 3 – soil container with the heating radiator, 4 – vertically adjustable frame with the nozzles, 5 – control unit

The CTU in Prague laboratory rainfall simulator has been used for research activities related to plot scale rainfall-runoff processes, sediment transport, rills development and surface runoff regime on agricultural soils.

Former RS of the Norton Ladder Rainfall Simulator type, which was constructed in 1999, utilised swiping nozzles mechanism to generate required rainfall intensity. As it was intended for soil erosion studies on cultivated soils, the maximum inclination could be set to 10 %, which is similar to the maximum slopes of the tilled fields in the Czech landscape. The typical applied rainfall intensity ranged between 30 and 60 mm/h, the soil sample size was 4 x 0.9 m. Based on the experience with this RS we designed a new version of the RS which allows more versatility and can be easily modified according to the needs of the specific research questions. At the same time, we have sustained a certain continuity with the older RS so the new experiments results can be compared to the old ones.

Therefore, the length of the soil container remained at 4 m, the width was slightly increased to 1 m. The new construction permits slope setting between 0 and 40 %. We have a possibility to switch between various types of nozzles, set the distance between the nozzle and soil sample, easily change the soil containers, control soil temperature. The RS and the soil container are equipped with various monitoring sensors and automatic data logging.

2.1 Main RS components

For monitoring of the erosion processes and the protection effects of various technical measures on the road embankments we need to be able to quickly change the soil samples.

The undercarriage on the wheels allows horizontal movement of the container with the soil sample. Thus, the sample can be pushed outside the rainfall simulator and then lifted and transported with an overhead travelling crane.

The tilting of the soil sample is realised with a use of a piston; the maximum soil load is 3000 kg. The sprinkling frame is connected to the soil container, the nozzles incline automatically with the soil sample so the distance between the soil surface and the nozzles remains constant. This is important to achieve stable rainfall characteristics such as intensity and kinetic energy.

The rainfall simulator frame allows setting of the nozzles height between 2 and 2.8 m in 10 cm steps. There is a possibility to use two types of nozzles which are permanently installed: (i) swiping nozzles VeeJet 80100. The frequency of the swiping defines the rainfall intensity.; (ii) Pulse system nozzles WSQ 40 with a constant water pressure, where the rainfall intensity is controlled by solenoids closing and opening the nozzles inlets. The two systems can be easily switched in between each other.

The heating control system regulates the temperature of the soil sample in the range of -15 °C to +40 °C. This allows us to simulate winter conditions when the shallow soil profile is frozen and the freezing effect on degradation of the geotextiles.

2.2 Control unit

Control system is based on a modular unit by WAGO (PFC 750-8202). The unit controls all the components responsible for the rainfall simulation (such as the pumps, solenoids, monitoring sensors, nozzles swiping mechanism, heating system). The unit is connected wirelessly and via LAN to PC or tablet. The unit serves also as the data logging system with a sufficient internal memory for the sensors readings. The exact experimental setting can be stored and automatically repeated, so we can perform series of scenarios with the identical boundary conditions.

Drop size distribution (DSD) of the artificially generated rainfall is a function of the nozzle type (shape of the nozzle) and the water pressure (considering always the same water properties). The control unit is capable of fixing the water pressure to ensure required rainfall characteristics. The constant pressure is maintained through a recursive procedure via coupling of an electronic control step valve and the pressure sensors at the nozzles. Currently the system is optimized for two types of the nozzles (VeeJet 80100 and WSQ 40), we plan to implement also other types of nozzles to simulate rainfall of different DSDs.

Similarly, the soil temperature is controlled by the WAGO unit. User sets the required temperature in the WAGO user interface, the cooling/heating is automatically controlled based on the readings of the temperature sensors installed in the soil profile.

2.3 Sensors

Beside the mentioned sensors for monitoring of pressure in the water distribution system, discharge of water and soil temperature, we monitor processes related to water runoff, percolation and sediment transport.

Water content and electrical conductivity are monitored by soil water content reflectometers CS655 (Campbell Sci., UK), soil water potential is measured with T8 tensiometers (UMS, Germany) and dielectric water potential meters MPS-6 (Decagon Devices, USA). All the sensors are connected to the WAGO control unit via SDI-12 communication protocol. Water percolation through the soil profile is measured by tipping buckets, surface runoff is sampled and measured manually. The runoff samples are further analysed to obtain sediment concentration and sediment particle size distribution.

3 RESULTS

Simulated rainfall characteristics need to be as close to the natural rainfall as possible. There are three main rainfall properties that we have calibrated: (i) temporal rainfall intensity (set hyetograph); (ii) rainfall kinetic energy (as a function of DSD and drops velocity); (iii) rainfall spatial uniformity (as the properties of the natural rainfall are on the tested scale homogeneous).

Spatial uniformity of the rainfall intensity was tested with a use of collection rectangular buckets, each of a size 15 x 15 cm, distributed in a regular grid with a span of 25 cm (Fig. 3). In total rainfall from 36 % of the plot area (4 m^2) was collected. The spatial uniformity was statistically evaluated (average, median, standard deviation) and the Christiansen's index, which is a common measure for the RS spatial uniformity, was determined.

At first, 16 tests with various settings of the nozzles height and the water pressure were done. We identified an optimal water pressure for both types of the nozzles and confirmed that the soil sample inclination does not affect the rainfall properties (as the nozzles move vertically with the soil sample and the drops falling height remains constant). Results of the tests are in Figure 2.

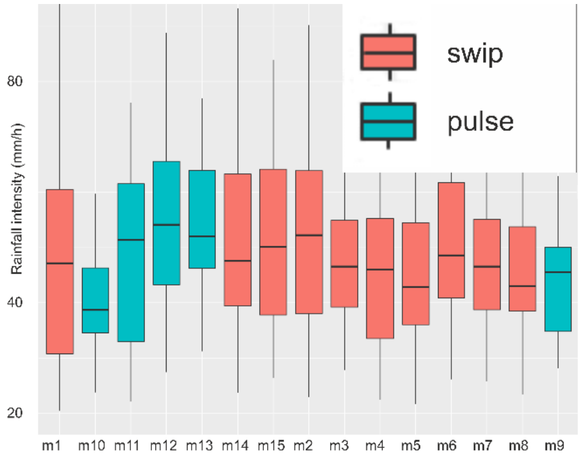

Figure 2 Spatial distribution of the sampling containers for the uniformity evaluation. The green boxes (SQ) represent the pulse nozzles, red boxes (VJ) represent swiping nozzles.

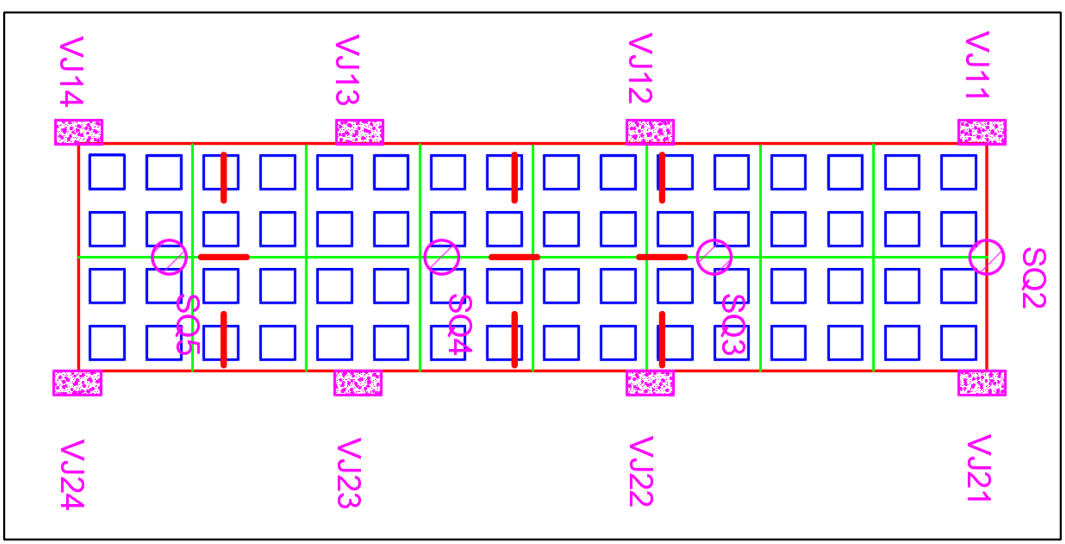

Figure 3: Spatial distribution of the sampling containers for the uniformity evaluation (blue squares) and positions of the LPM distrometer (red line). Position of the nozzles, SQ represents the pulse nozzles, Ping boxes (VJ) represents swiping nozzles and ping circle (SQ) preasure. The container (red rectangle) is 4 m long and 1 m wide.

Table 1: Rainfall characteristics for different drops falling heights and nozzle types

Test no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Elevation above surface (m)	2.0	2.0	2.35	2.35	2.7	2.7	2.7	2.7	2.7
Nozzle type	swipe	pulse	swipe	pulse	swipe	pulse	pulse	pulse	swipe
Average intensity measured by distrometer (mm/h)	36	229	39	232	22	215	113		
Average intensity measured by rain gauge (mm/h)	39	209	39	238	56	183	134	Slope 20°	
Kinetic energy (J/mm)	10	5.5	11	5.7	11	6.9	5.9		
Average intensity measured by the sampling buckets	83	163	47	216	46	186	119	125	48
CU index (%)	70	71	67	81	70	80	86	86	74

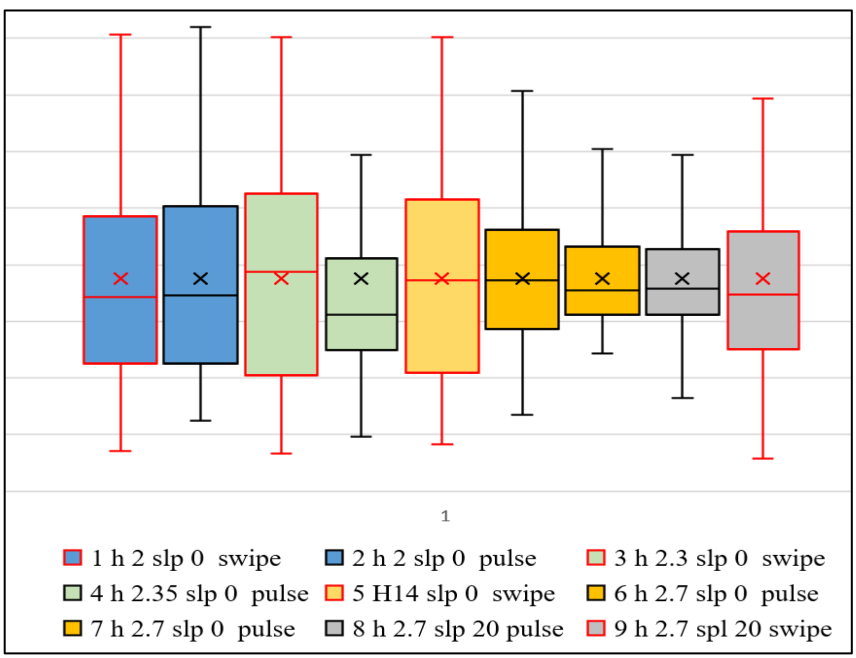

Figure 4. Comparison of the rainfall spatial uniformity for the tested scenarios recalculated to the unit precipitation intensity. The red bars represent experiments with the swiping nozzles, the black bars with the pulse nozzles.

We measured rainfall kinetic energy on nine positions bellow the nozzles for the scenarios 1 to 7 (Table 1). The kinetic energy was monitored by laser precipitation monitor LPM (Thies Clima, Germany). The distrometer records the rain drops passing a parallel planar laser ray of a wave length 780 nm. The cross-section area, including the correction factor for the specific distrometer (Frasson et al. 2011), is 44.1 cm^2. The distrometer classifies drops into 22 classes with the diameter between 0.24 mm and 8 mm, and 20 classes of the drops velocity between 0 and 10 m/s. This gives 440 combinations of drop sizes and drops velocities. The distrometer measures the rainfall with as low intensity as 0.001 mm/h, it also recognises a precipitation type (rain, hail, snow).

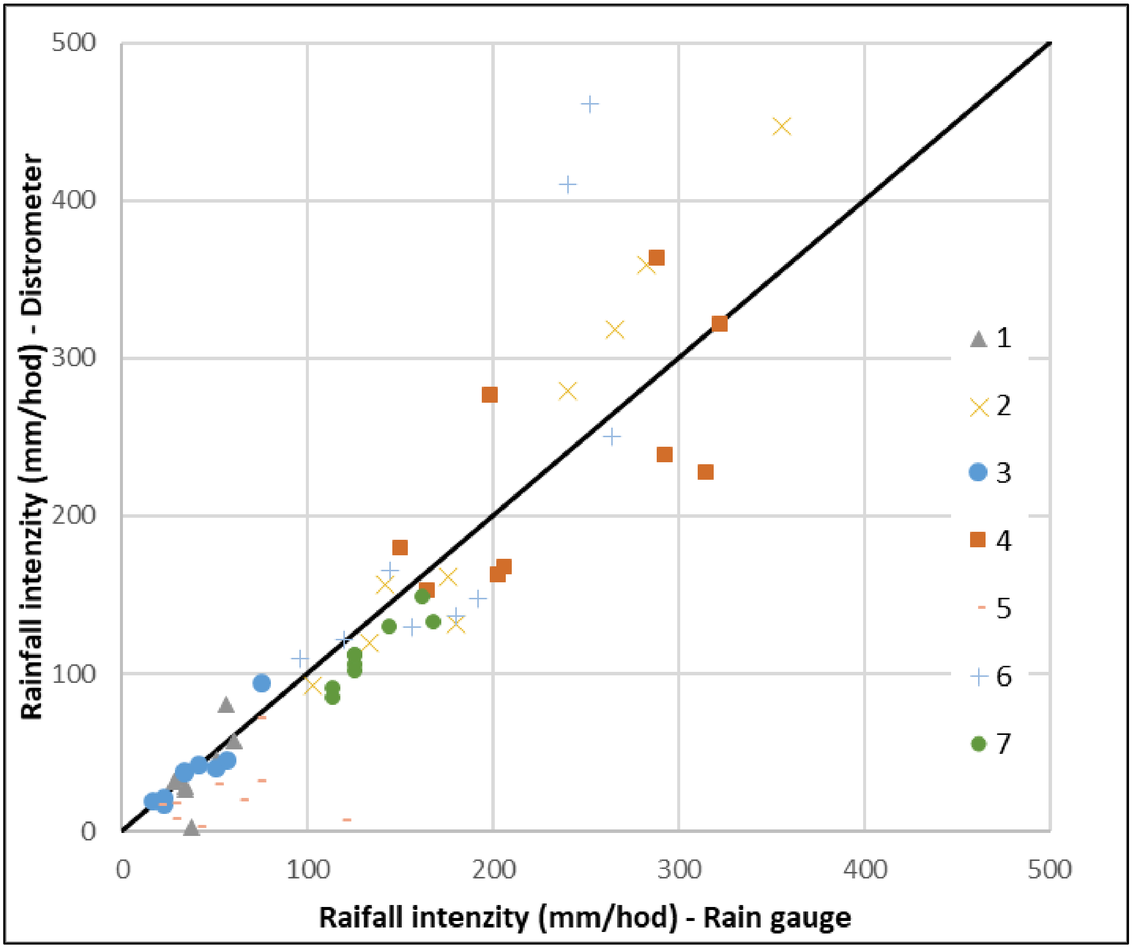

Figure 5 Comparison of the rainfall intensity measured by rain gauge and distrometer. The various symbols represent different scenarios. There is a strong deviation in the observed values for intensities above 200 mm/h.

4 CONCLUSIONS

The manuscript provides a technical description of the newly designed laboratory rainfall simulator located in the CTU in Prague. The unique design allows to use the RS for various types of experiments ranging from erosion of agriculture soils to stability of road embankments. The largest asset of the design is the possibility of easy and quick replacement of the soil samples and setting of the sample inclination, which may reach up to 40 %. Thanks to implementation of various nozzles and flexible positioning of the nozzles distance from the soil surface one can reach various rainfall characteristics.

Within the testing and calibration of the RS several experiments were performed that proved that:

- Kinetic energy of rainfall generated by the swiping nozzles is approximatelly double compared to the KE generated by the pulse nozzles system.
- Kinetic energy of the generated rainfall does not significantly change when the drops falling height is icreased from 2 m to 2.8 m.
- Nozzles with the pulse system generate rainfall with better spatial uniformity (higher CU index).
- The spatial uniformity increases with the increasing falling height, especially in the case of swiping nozzles system.

The tests have shown that the optimum setting is with the nozzles at its maximum height. The change in the nozzle system allows to assess the effect of two types of rainfall with same intensity, but different kinetic energy.

5 ACKNOWLEDGEMENT

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