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THE DESIGN AND CONSTRUCTION OF A RAINFALL SIMULATOR

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ABSTRACT

A reliable, accurate and portable rainfall simulator was needed for vegetative and erosion control research at California Polytechnic State University, San Luis Obispo (Cal Poly) for California Department of Transportation (Caltrans) and California State University Sacramento. This simulator was designed to be easily set up and maintained as well as able to create a variety of rainfall regimes. The nozzle performance tests and lateral spacing tests were performed at Cal Poly's Erosion Research Facility. This simulator was designed and constructed based upon the principles of the Norton Ladder Type Rainfall Simulator. This simulator is the standard for research involving simulated rainfall. Construction took place at Cal Poly's farm shop. The rainfall simulator is a pressurized nozzle type simulator with a cam-operated oscillating boom. It emits uniform rainfall on a plot 1 m (3 ft) wide by 3.56 m (12 ft) long. The nozzles at 47.6 kPa (7 psi), Spraying Systems Company's Floodjet 3/8K SS45, emitted an average drop size of 1.7 mm (0.07 in) and a range of drop sizes of less than 1 mm to 7 mm (0.04 in to 0.3 in), correlating well to storms less than $50 \text{ mm} \cdot \text{hr}^{-1}$ ($2 \text{ in} \cdot \text{hr}^{-1}$) as is common on California's Central Coast. The structure of the simulator was built from aluminum, supporting the four-nozzle boom. The nozzles are spaced 99 cm (39 inches) apart. A box with an opening of 15 cm by 11 cm (6 by 4.5 inches) was beneath each nozzle to create the proper spray angle, critical for lateral spray uniformity. An additional opening in the box is attached to a system which returns the unused water to the storage tank. Flow meters control the inflow of water from the storage tank, ensuring each nozzle has the same discharge rate, no matter the orientation of the simulator. A computer-driven motor and cam system controls the storm intensity. The number of oscillations per minute of the nozzle across the box opening determines the intensity. Design storms resemble a bell curve, typical of California storms. The support system is collapsible, easy to set up and maintain. The resulting simulator is economical (less than \$7,000 to construct), made with commercially available parts, easy to set-up and maintain and highly accurate.

Keywords: rainfall simulation; nozzle; rainfall characteristics

Marketing Paragraph

The recent interest in testing erosion control products and increased regulations involving storm water quality has created a need for accurate testing equipment. The ability to accurately simulate rainfall has grown in necessity as testing of such materials increases. This paper deals with the complexities of rainfall and the performance goals involved in designing and building a rainfall simulator.

INTRODUCTION

Simulating Rainfall

The primary purpose of a rainfall simulator is to simulate natural rainfall accurately and precisely. Rainfall is complex, with interactions among properties (drop size, drop velocity, etc.) and large climatic variation based on topography and marine influences.

Properly simulating rainfall requires several criteria: 1. Drop size distribution near to natural rainfall (Bubenzer, 1979a). 2. Drop impact velocity near natural rainfall of terminal velocity (Laws, 1941) (Gunn and Kinzer, 1949). 3. Uniform rainfall intensity and random drop size distribution (Laws and Parsons, 1943). 4. Uniform rainfall application over the entire test plot. 5. Vertical angle of impact. 6. Reproducible storm patterns of significant duration and intensity (Moore et al., 1983) (Meyer and Harmon, 1979).

Drop size distribution, impact velocity and reproducible storm patterns must be met to simulate the kinetic energy of rainfall. Kinetic energy ($KE = mV^2/2$) is a single measure of the rainfall used to correlate natural storms and simulator settings.

Drop size distribution depends on many storm characteristics, especially rainfall intensity. Drop size distribution varies with intensity (from less than 1 mm to about 7 mm), increasing with the intensity to 2.25 mm median drop size for high intensity storms (Laws and Parsons, 1943). Most design standards were based on Laws and Parson's (1943) studies.

Unfortunately, most of the rainfall studies were in Illinois, Washington DC,

Washington, or locations in the south, outside California. The mountains and ocean add to the variation in the rainfall characteristics (McCool, 1979). California has both topographic and marine influences. No studies of rainfall characteristics, (Drop size, storm intensity in microclimates, etc.) were completed in the state of California. Parameters can be approximated using the studies from other regions, but an accurate simulation of California rainfall is difficult without adequate research studies of California conditions.

Drop velocity is important in designing a rainfall simulator. Drops from natural rainfall are at terminal velocity when they hit the soil surface (Meyer and McCune, 1958). Therefore, a rainfall simulator must create drops of adequate size and velocity to simulate the same condition, indicating the importance between an adequate and related fall distance and drop size distribution. A direct relationship exists between drop diameter and fall distance (Laws, 1941).

A reproducible storm pattern is easy to simulate when a simulator can be adjusted to the desired intensities and duration. Since computers are inexpensive, a simulator can be driven by specialized software controlling the intensity and duration of the storm. The Vegetative Establishment and Maintenance Study (VEMS) team controls their simulators in a manner creating bell shaped storm patterns, simulating the intensity variation inherent in nature.

Previously Developed Rainfall Simulators

Simulators can be separated into two large groups (drop-forming simulators and pressurized nozzle simulators) (Thomas and El Swaify, 1989). Drop-forming simulators are impractical for field use since they require such a huge distance (10 meters) to reach terminal velocity (Grierson and Oades, 1977). The drop-forming simulators do not produce a distribution of drops unless a variety of drop-forming sized tubes are used. Another negative of the drop forming simulator is their limited application to small plots (Bubenzer, 1979b). Several points of raindrop production must be closely packed to create an intense enough downpour of rain. Drop forming simulators use small pieces of yarn, glass capillary tubes, hypodermic needles, polyethylene tubing, or metal tubing to form drops (Bubenzer, 1979b).

Pressurized nozzle simulators are suited for a variety of uses. They can be used in the field and their intensities can be varied more than the drop forming type (Grierson and Oades, 1977). Since drops exiting the nozzles have an initial velocity greater than zero due to the pressure driving them out, a shorter fall distance is required to reach terminal velocity. Nozzle intensities vary with orifice diameter, the hydraulic pressure on the nozzle, the spacing of the nozzle and nozzle movement (Meyer, 1979).

Pressurized nozzle simulators can produce variable storm intensities. A continuous spray from a nozzle creates an unnaturally intense storm. Some method of starting or stopping the spray is needed. The solutions have been a rotating disc, a rotating boom, a solenoid-controlled simulator (Miller, 1987) and an elaborate sprinkler system (Sumner

et al., 1996). The simplest to use is a rotating or oscillating boom (Bubenzer, 1979b).

The most popular nozzle is the Veejet 80100 nozzle run at 41 kPa (6psi). It was chosen because it most closely resembles the drop size distribution of erosive storm patterns in the Midwest (Bubenzer, 1979a). Accurate testing of nozzles must be done to ensure adequate spray coverage and uniformity in the plot.

The Norton Simulator

The Norton Ladder Type Rainfall Simulator is a spray boom that oscillates across a test plot at varying speeds to produce variable-intensity storms. Scott McAfee and Darrel Norton designed the Norton Ladder Type Rainfall Simulator for use at the USDA National Soil Erosion Research Lab at Purdue University. Boxes around each nozzle regulate the spray for proper nozzle overlap and swath width. A clutch brake starts and stops the boom as regulated by a signal from the control box. A small gear motor drives the clutch brake and the boom. The four nozzles are supplied with water in sets of two; each set of nozzles has its own hose and pressure gauge to adjust for differences in elevation, hose orientation, etc.

The rainfall simulator uses a Spraying systems Veejet 80100 nozzle. Typical, manufacturer specified uses for this nozzle include, dust control, industrial washing applications and fire control. Its uses are high-pressure, high-velocity- high-volume water applications; all things rainfall is not. The pressure range of the nozzle is quite large, from 34 to 3400 kPa (5 to 500 psi) yielding flow rates of 13.2 to 132 Liters per minute (3.5 to 35 gpm). A pressure of 41 kPa (6 psi) produces drop size and intensity similar to natural rainfall (Bubenzer, 1979a).

Most nozzles tend to produce irregular spray when used at its capacity limits due to machining differences. Thus, any differences between nozzles are amplified by the small psi used leading to a reduced uniformity. A new nozzle was needed, one with a narrower operation range, but similar drop size and intensity.

IMPORTANT SIMULATOR CHARACTERISTICS

Based upon the use and study of the ladder type rainfall simulators used by the Cal Poly Vegetative Establishment and Management study (VEMS), a few design goals and parameters were considered. Above all, a rainfall simulator must be accurate and must meet all six criteria for properly simulating rainfall. Any other criteria are a matter of convenience for the user. These include weight, ease of use, reliability, accuracy and economy.

The simulator and support structure should be as light as possible. Since most of the use of the simulators is in the field and on slopes, researchers should easily place them in position. Conditions in the field lead to the necessity of strong and lightweight equipment.

In addition to being lightweight, the simulator should also be easy to use and set-up. The support system should be adequately strong to withstand any wind and all movements of the simulator. Ease of use also includes easily readable instrumentation and control systems. Proper instrumentation must be used to monitor the flow of water to the nozzles. These should be placed in such a position as to accurately measure and help regulate the inflow of water to the nozzles. Flow gages are preferred for the rainfall simulator because of the elevation differences between the points and the

difficult correlation of flow rate and pressure. The control box should be built to withstand the electronic loads placed on it with a safety factor to prevent burnout. A computer-driven labview set up is highly desirable.

Reliability ties in with strength and proper instrumentation of the rainfall simulator. Reliability relates to the repeatability of storm events. A computer-derived storm is the most reliable because it eliminates the human error involved in altering intensities. Also, when properly monitored by the correct instrumentation, the reliability will increase or at least be as high as possible.

Accuracy is achieved by creating uniform rainfall across the test plot. When a nozzle with good drop size distribution for simulating rainfall is chosen and is placed in series with adequate spacing to allow adequate overlap lateral uniformity is achieved. When this laterally-uniform boom is swept back and forth across an area, the spray will be uniform. Properly designing and testing the boxes used for cutting off the spray is critical for creating uniform rainfall.

Without question the most desirable characteristic of a rainfall simulator is its cost; it should be as low as possible. Designing a simulator must be done with cost in mind. The goal is to design and build a rainfall simulator for less than ten thousand dollars.

TESTING

Different nozzles require different lateral spacing, to create uniformity spray overlap. The overlap is necessary to achieve lateral uniformity thus uniformity of spray up and down the test plot. Since the variation between points is more important than amount of spray, standard deviation of

points (6-inch cans capturing the spray) was found. Several different lateral spacings were tested.

Nozzle choice

The nozzle tested was the Floodjet SS3/8k-45 with an orifice diameter of 5.51 mm (0.221 in). These were agricultural nozzles that closely resemble the Veejet 80100 flow rates (12.1 L/min at 34 kPa for the floodjet as compared to the 13.2 L/min at 34 kPa for the Veejet) as specified. The optimum range of the Floodjet is much narrower than the Veejet nozzle; its range is from 20.5 to 410 kPa (3 to 60 psi). The drop size distribution of the Floodjet nozzles were specified to be similar to natural rainfall in the catalogue (Figure 1).

Figure 1. Spraying Systems Company



Floodjet SS3/8k-45 nozzle.

The basis for boom length tests and drop-size tests is the nozzle. The Floodjet SS3/8k-

45 nozzles are far superior for rainfall simulation than the Veejet nozzles. Veejet nozzles are industrial spray nozzles, used for cleaning tanks and other high-pressure applications whereas Floodjet nozzles are used for agricultural spraying practices. The Veejet that is presently used on the rainfall simulator has a much wider pressure range than the Floodjet nozzle. Thus, if there were a small pressure imbalance or fluctuation in the boom, the amount of rainfall applied to the test would vary significantly less with the Floodjet than with the Veejet.

Lateral uniformity testing

Several boom sizes were tested. The tests were conducted on calm, sunny days. The lateral uniformity was tested under a nozzle pressure of 48 kPa (7 psi). A spray angle of 53° was determined by geometry and the outside of the spray was cut off by boxes around the nozzle. The spray was captured by a grid-work of 6 inch stainless steel cans on the ground, 8-feet below the nozzles. The volume in each can was measured with a 1000 ml graduated cylinder and recorded. This process was repeated three times for each boom. The standard deviation of the spray was determined and a regression analysis was performed (Table 1).

The results indicate there are a number of boom lengths that can be used with the Flood Jet nozzle. The 48-inch boom had the lowest standard deviation; thus choosing this nozzle spacing will give the best uniformity for simulating rainfall. However, the 36, 39, 48 and 60-inch booms were not statistically different. So a design choice was made. The smaller lateral spacing gives a much more intense storm, which may or may not be appropriate for the test site climate.

Table 1. Standard deviations for the tested booms.

Nozzle Spacing	Average Standard Deviation
in	ml
60	62.34
54	77.66
51	98.92
48	62.54
42	82.62
39	55.16
36	56.63
Norton	139.19

Drop Size Test

Proper drop size is critical for simulation of rainfall. The drop size distribution was tested using Eigel and Moore's (1983) oil method. This entails mixing 1 part STP oil treatment and 1 part Swan brand mineral oil. Drops with ranges from 0.5- 7 mm (0.02 to 0.28 in) are caught in a petri dish of oil and held there for enough time to count and measure them. This approach was much simpler and easier to perform than the other methods, which include using flour and time-lapse photography.

The found drop size distribution is that of natural rainfall. Drop size ranges from less than 1 mm to about 7 mm (0.04 to 0.28 in) in diameter. The average drop size is 1.71 mm (0.067 in). The average drop size is smaller than the standard of 2.25 mm (0.089 in) used on previous simulators but, agrees with the literature for drop size for lower intensity storms (less than 50 mm, 2 in, per hour).

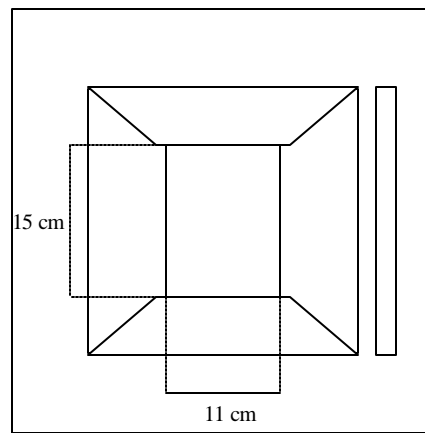
The drops were assumed to be at terminal velocity due to their size and the height of the boom. No tests were performed to find drop velocity or energy due to several

previously conducted studies in the literature.

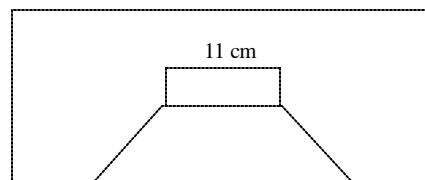
Final Dimensions

The tests performed led to the final, critical dimensions for the rainfall simulator. The nozzles are spaced 99 cm (39 in) apart. The simulator is approximately 3.56 m (140 in) long and 41 cm (16 in) wide. The box opening was determined by geometry and the opening as seen by the nozzle is 15 cm (6 in) wide, to cut off the spray for the desired spray angle, by 11 cm (4.5 in) long, to allow a large swath width (figure 2).

Figure 2. General spray box dimensions



Spray Box, Overhead View



Spray Box, Side View

CONCLUSIONS AND FINAL DESIGN

The final design of the rainfall simulator is similar to the original rainfall simulator with a few critical changes. The framework supporting the boom and machined components of the control box are made from aluminum. Since the nozzle was changed to the Floodjet SS3/8k-45 nozzles, the lateral spacing of the nozzles was changed to 99 cm (39 in). The box dimensions also changed to a wider, shorter opening to regulate the spray. The gear motor drives same clutch-brake assembly which regulates the oscillations of the spray boom. The water source is mounted on a trailer with a pump to feed the simulator. A network of hoses bring the water to the simulator and a gutter along the side of the simulator leading to hoses return unused water to the tank to be used again, thus using the water efficiently.

Flow gages at the inlet to the water manifold are used in addition of pressure gages on top of the water inlet manifold to regulate and monitor the flow of water to the nozzles. A laptop drives the system, bypassing many issues created by the control box and human-designed storms. The support system is made of aluminum rods and therefor are lightweight, strong and easily broken down. The design is based on a tent design utilizing a network of poles and connectors to support the simulator in six positions along the length.

Goals Achieved

The final simulator designed and built by the VEMS research team achieved the goals set forth. The chosen nozzle produces drop sizes and distribution near to natural rainfall for California storm conditions. Due to the height of the simulator and initial velocity of

drops from the nozzle, the drops are at terminal velocity. Uniformity of rainfall is greater than 90% over the entire test plot (for one simulator the test plot is 3.56 m long and 1 m wide). The angle of impact of the drops from the nozzle is vertical. The computer-driven set up creates reproducible storm patterns that can be varied over a range of intensities.

The goals for the other more convenient considerations were also met. The designed simulator cost approximately seven thousand dollars. The flow gages at the source of water into the simulator help keep the nozzles flowing at the same rate, thus increasing both reliability and accuracy of the design storms. The software drives the system, thus eliminating human error and increasing the usability of the entire system. The freedom the computer provides allows for fewer people to run experiments and more time to observe the effects of the rainfall on the test plot. Few people are required to run the testing because the simulators are light and easy to set up and run.

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