THE KINETIC ENERGY FIELD UNDER A RAINFALL SIMULATOR

Randy B. Foltz[1], A.M. ASCE, Charles H. Luce[1], Aff. M. ASCE, and Paul Stockton[2] Abstract

Rainfall simulators are commonly used to estimate erodibility parameters for physically based erosion models. Rainfall produced by the simulators should have kinetic energy delivery rates comparable to natural rainfall and the kinetic energy field under the simulator should be uniform. We used a calibrated piezoelectric crystal-based instrument to measure the raindrop splash power of a modified Purdue rainfall simulator. Measurements were taken at several points for three intensities (30, 50, and 100 mm/hr) and on a large grid at an intensity of 50 mm/hr. Raindrop power varied linearly from 0.116 W/m^2 at a rainfall intensity of 30 mm/hr to 0.391 W/m^2 at an intensity of 100 mm/hr, about half of that theoretically predicted for natural rainfall. On a closely spaced grid under 50mm/br rainfall, power varied from 0.103 W/m^2 to 0.292 W/m^2, a ratio of 1:3. The difference between the measured power and the power of natural rainfall and the high variability in the kinetic energy field raises questions about the validity of erodibility values derived from the simulator. Further testing of the piezoelectric crystal instrument will help validate these results.

Introduction

Process based models of erosion generally consider two types of erosion, flow induced erosion and raindrop splash-induced erosion (Foster and Meyer, 1972). Flow induced erosion is based on either the shear stress or the stream power of the flowing water (Govers, 1992).

Rain drop-splash erosion models are based on regressions of measured erosion from short plots compared to rainfall intensity under a rainfall simulator. Most researchers have found that erosion from interill areas is approximately proportional to the square of the rainfall intensity. The concept that rainsplash power is a function of rainfall intensity is an interpretation of the regression results; power is seldom directly measured.

Rain drop-splash erosion models require detailed information about soil erodibility relative to flow and rain drop splash. Data to estimate erodibility parameters are frequently collected using rainfall simulation. Consequently, a great deal of care has been given to ensuring that the rainfall power under simulators is comparable to natural rainfall.

The potential problem in using these methods to develop, validate, and estimate parameters for erosion models is that the relationship of rainfall intensity to power under a rainfall simulator can be substantially different from that of natural rainfall. Simply ensuring that the simulators have rainfall power comparable to natural rainfall is not enough to establish parameters for rain splash-induced erosion as a function of intensity.

Because of the use of rainfall simulators for these purposes, we examined the assumption that rain splash power under simulators varies with rainfall intensity in a manner that is similar to natural rainfall. Raindrop splash erosion incorporates both the direct movement of particles by raindrop splash and the effect of the raindrop splash on the thin film of flowing water in short interrill areas. Raindrop splash erosion is usually calculated as a function of the assumed power of raindrop impact times the rainfall intensity (Meyer and Wiscbmeier, 1969; Foster and Meyer, 1972; Meyer, 1981).

The objective of our research was to measure the kinetic energy under a Purdue type simulator at 25 mm/h and 50 mm/h intensities. We wished to compare the kinetic energy to published values of natural rainfall energy. Additionally, we wanted to test the assumption that rainfall energy varies with the square of the rainfall intensity.

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Methods

To accomplish our objectives, we used a Sensit Company rain sensor placed in several locations under a Purdue-type rainfall simulator. The methods are described in this section.

Rain Sensor

The rain sensor is a 100-mm diameter, synthetic piezoelectric ceramic crystal made from lead zinconate titinate with associated electronic circuitry. Piezoelectric crystals produce a charge proportional to the force applied to them in the direction of polarization. This principle has been used to measure the energy of blowing sand grains. Sensit Company modified the existing sand grain erosion device to measure the kinetic energy of rain drops.

The initial rain drop impact produces a predominately positive spike followed by a damped oscillation. The positive signal is amplified and fed to a squaring amplifier to produce an output pulse representative of the number of particle impacts. A differential integrator integrates currents proportional to the voltage amplitude resulting from the impact. The output of the integrator is a single voltage, increasing in a stair step manner until the voltage reaches a reference voltage, generating a kinetic energy pulse output. Each kinetic energy pulse represents a fixed total amount of integrated kinetic energy.

We calibrated the rain sensor using water drops formed with hypodermic needles of different sizes. With a constant water pressure at the needle, the number of drops were counted, collected, and weighed. The number of drops was typically 30 to 50, and the number of repetitions was typically 12 to 14 for each needle size. From the measured weight, the drop diameter was calculated. For the range of needle sizes used, #28 to #8, the drop diameters ranged from 2.14mm to 4.75 mm.

We selected four needle sizes to provide a drops ranging from 3.33 mm to 4.75 mm. Drops were allowed to fall *1.5* m onto the rain sensor. The drop velocity was calculated at 0.01-second time steps including a drag coefficient to determine velocity at impact Results from the program agreed well with published values of terminal velocity. We integrated the number of pulses over a 1-mm interval, while drops were falling at a controlled rate. By varying the needle size and the drop rate, we achieved a range of kinetic energy values from 123,100 to 1,125,000 ergs/min. Since the crystal also responds to wind noise and internally generated noise, a background noise measurement was made before and after the drop impacts. A regression of pulse counts and kinetic energy yielded the following equation

$$KE = 64698C + 52868$$

where *KE* was the kinetic energy in ergs/minute, and *C* was the number of counts per minute above the background. The regression had an r^2 of 0.899, a p-value of <0.0001; both the slope and the intercept had p-values < 0.0001. The calibration points and the regression are shown in Figure 1.

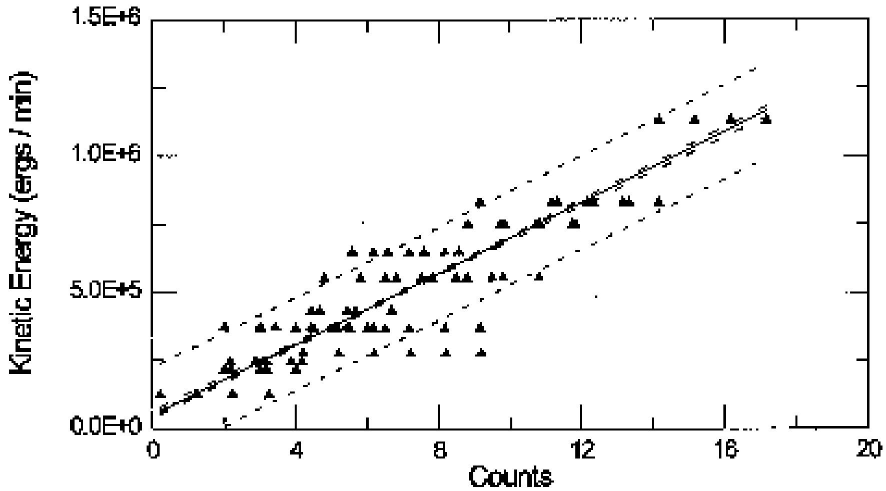


Figure 1 - The measured kinetic energy of drops and rain sensor counts used for calibration. The solid line is the equation of best fit, the dashed lines are the 95% confidence interval around the mean, and the dotted lines are the 95% prediction confidence interval.

We considered the intercept of equation (1) to represent the measurement threshold of the rain sensor. This value of 53,000 ergs/min corresponds to a rainfall rate of 2 mm/hr intensity of 2-mm drops falling at terminal velocity.

Although the sensor was calibrated with single drops striking the crystal, we assumed that it would respond properly to multiple drops. A more rigorous test of the instruments response to multiple drops is planned.

Rainfall Simulator

This study examined a modified Purdue simulator similar to that described by Meyer and Harmon (1979). This simulator has a continuously spraying nozzle that swings back and forth over a narrow slot between recirculation troughs on either side of the slot. Intensity was controlled by altering the time the nozzle spends spraying into the side trough instead of through the slot. The simulator had Spray Systems VeeJet 80150 nozzles operated at 41 kPa.
Rainfall energy measurements were made with the simulator set for 30 mm/hr ,50 mm/hr, and 100 mm/hr. Previous tests of the equipment showed that the settings gave consistent intensities and that the intensity field was uniform.

When operating on large plots, the rainfall simulator consists of regularly spaced nozzles located at the corners of equilateral triangles. We took measurements at three locations inside the triangles. One point was located beneath a nozzle, another was in the center of the triangle, and the third was midway between two nozzles (Figure 2). With these points we believed we could characterize the entire simulator energy distribution pattern.

The rain sensor was covered with foam for 10 minutes while recording background noise levels. The foam was then removed, and for another 20 minutes the background noise and raindrop splash were recorded at each point on the grid. Afterward, the background noise was measured for another 10 minutes. This gave 20 1-mm samples of raindrop energy at each point. The accumulated energy was converted to power per unit area by dividing by the area of the rain sensor and the time.

For the second study, we used a grid of 101 points on 0.422 m centers to take a systematic sample of rainfall power. The grid was oriented at a 22° angle to the primary axes of the simulator (Figure 3). This maximized the number of different locations relative to the regular pattern of the simulator nozzles, while still retaining a convenient, repeatable grid. For each point, measurements were taken in the same manner as before.

Results

For the power versus intensity study, the average raindrop power measured during the 30-mm/hr simulation was 0.116 W/m^2. The average raindrop power measurements during the 50-mm/hr simulations were 0.190 W/m^2 and 0.204 W/m^2. The average raindrop power during the 100 mm/hr simulation was 0.391 W/m^2. These averages suggest a linear relationship of rainfall power with intensity (Figure 4) and are approximated by the equation

$$P = (3.92 \times 10^{-3})\, I \qquad (2)$$

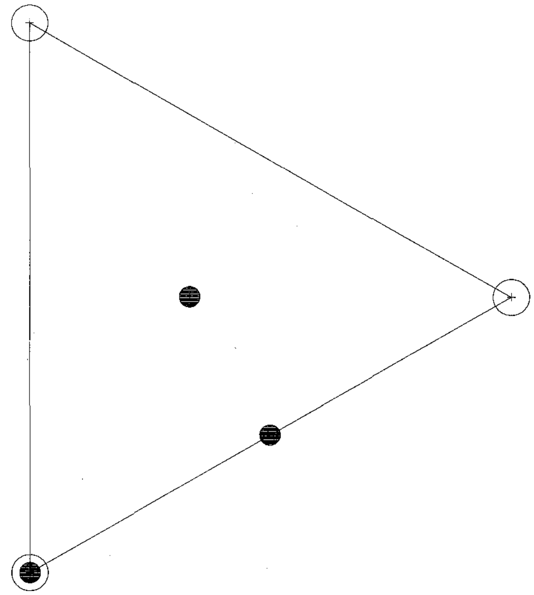


Figure 2 - The location of points used to measure rain drop power at 30, *50,* and 100 mm/hr rainfall intensities. The corners of the triangle were under simulator nozzles.

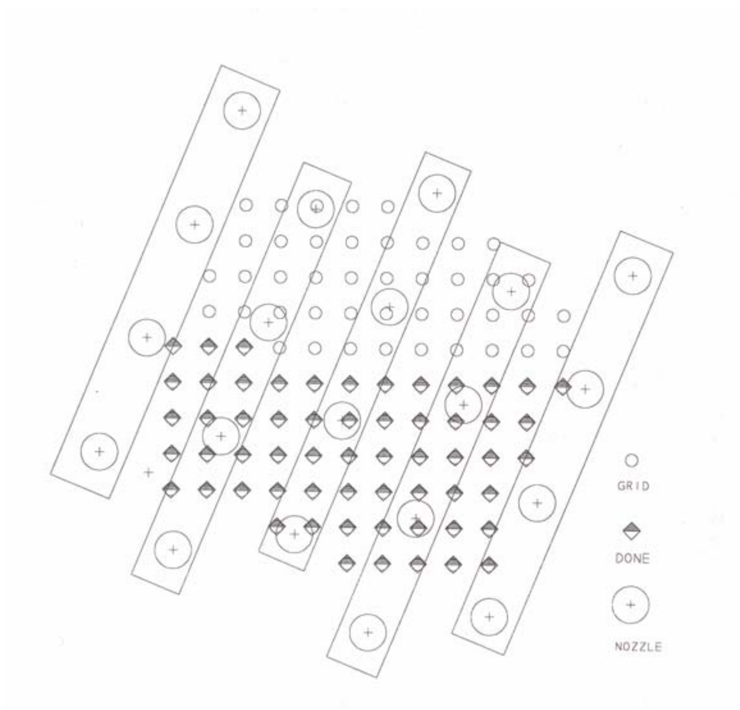


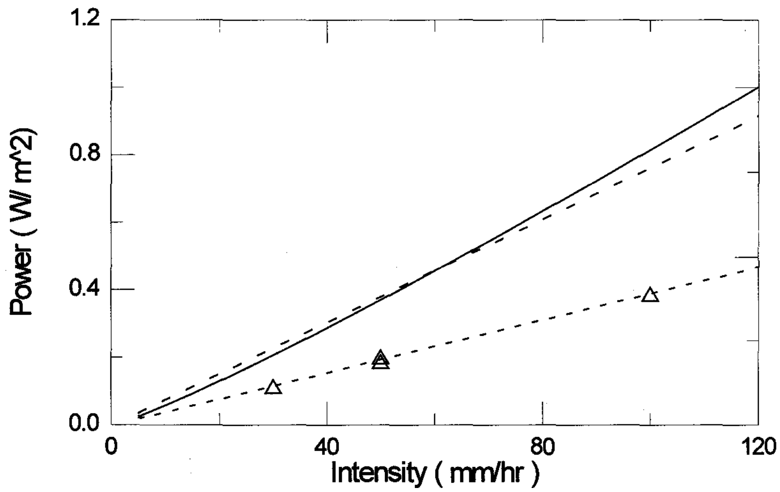
Figure 3 - The location of grid points under a Purdue-type simulator showing modules and nozzles. Fifty-one of the one hundred points were measured.

with Pin W/m^2 and In mm/hr. Such a relationship makes sense when considering the design of the simulator. To achieve a higher intensity, the Purdue type simulator simply increases the number of passes per unit time across its window. In the paper discussing the design of this simulator, Meyer and Harmon (1979) stated that the VeeJet 80150 nozzle with 41 kPa water pressure gives power at the rate

$$P = (7.63 \times 10^{-3})\, I \qquad (2)$$

with P in W/m^2 and *I* in mm/hr. They do not explain how the power was measured. The values we measured are about half of those given by Meyer and Harmon.

Figure 4-The relationship between rainfall intensity and power per unit area. The solid line is Wischmeier and Smith *(1958);* the dashed line is Meyer and Harmon (1979); the triangles are values we measured with rain sensor under a modified Purdue-type simulator. The dotted line is the best fit equation of our measured data.



To determine natural rainfall energy per unit dept Wischmeier and Smith (1958) recommended

E 916 331 + $\log_{10}(I)$ (4)

with E in foot-tons/acre-inch and I in in/hr. To obtain units of power per unit area, E must be multiplied by I. Converting units to SI gives

$P = (3.3 x 10^{-3} + 2.42 x$ 10~ $\log_{10} I) I$ (5)

with Pin W/m^2 and I in mm/hr. This gives a nearly linear relationship of power with intensity. Wischineier and Smith's (1958) curve agrees well with Meyer and Harmon's (1979) statement but both estimate about twice as much power as our measurements show.

The relationship between energy and intensity for this simulator would still give approximately the same form for the equation of intensity versus erosion as found by other researchers. However, it would probably yield lower estimates of erodibility than would be appropriate for natural rainfall since the values are still within an order of magnitude, they may be acceptable.

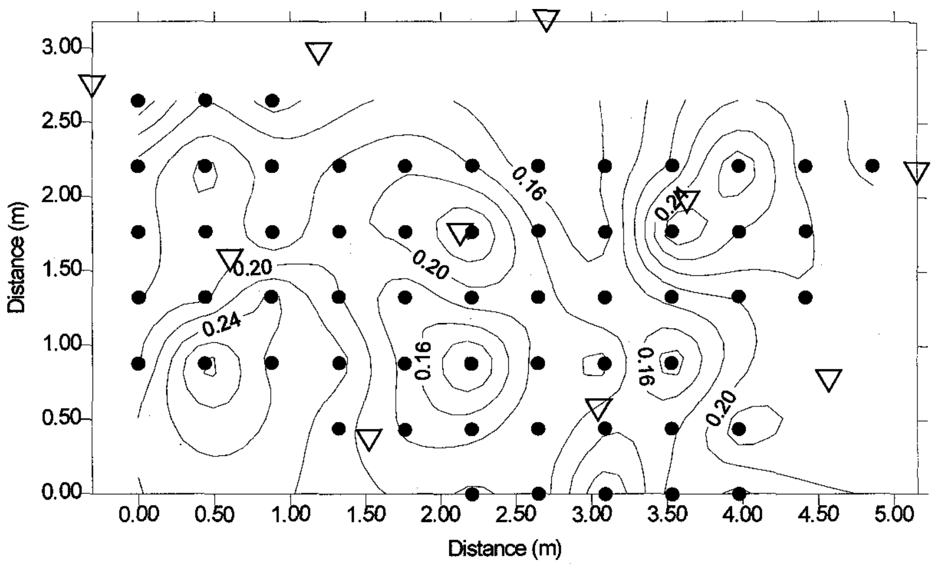
The data presented by Meyer and Harmon (1979) suggest that they examined the characteristics of the nozzle drop size distribution in a steady state condition. From the drop size characteristics, they calculated the raindrop power. The differences we found may be due to the fact that the nozzle does not point in a steady direction while in use so exit velocities are not directly downward.

In the second study, we found that variation under the simulator is high. It does not follow a pattern that we can determine with the partially completed grid at *50* mm/hr (Figure *5).* Measured values range from 0.103 to 0.292 W/m^2 within 2 m. This range is between *50%* and 150% of the average values measured under the single pattern of the simulator. Such a range was much greater than expected, especially considering the relatively uniform intensity distribution. These variations in energy with location imply differences in the relationship between I and P among those locations. The variations from point to point can be quite large.

Figure 6 shows the *95%* upper and lower confidence intervals for the measured power based on equation (1). This figure shows that there are differences at the *95%* significance level among the observed power values. A x^2-test at the *95%* significance level of the measured power values failed to reject the hypothesis that a normal distribution describes this data.

The variability from point to point raises the question of whether plot location relative to the simulator affects the results. When this type of simulator is used with more than one plot, results between plots may not be comparable. When this simulator is used with one large plot, the integrated effect of this variation in raindrop power would be difficult to estimate. Despite the variability in measurements, the raindrop power measured at any one point still did not reach the values predicted by Meyer and Harmon (1979) and Wischmeier and Smith (1958) for 50 mm/hr rainfall intensity.

Figure 5 - Contour plot of power per unit area in W/m^2 for an intensity of 50 mm/hr under a modified Purdue-type simulator. Contour interval is 0.02 W1m^2. Locations of simulator nozzles are shown as triangles. The measurement grid is shown as black circles. Distances are from an arbitrary point.



Conclusions

These results suggest that this simulator gives rainfall powers that are about half the theoretically derived estimate of natural rainfall. They are also about half what the equipment is expected to give. In addition, the simulator shows a high degree of variability in the power distribution. The power measurements do not show any pattern in the variability, and the variation is from one-half to one and one-half times the mean power output, which is greater than expected.

If the instrument is accurate, the variation in power under the simulator raises questions about the validity of erodibility data estimated using the simulator. The variation may also raise questions about the validity of model testing using this type of simulator. Further testing of the instrument under natural rainfall is needed for additional evaluation and to gain confidence in the instrument.

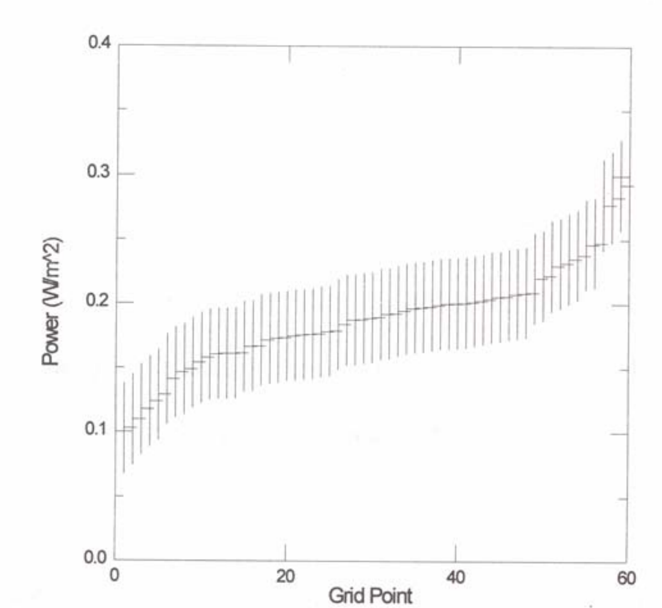


Figure 6 - Power per unit area in W/m2 for an intensity of 50 mm/hr under a modified Purdue-type simulator. The upper and lower 95% confidence intervals and the mean are shown for each grid point. The values have been sorted from low to high to illustrate the range of measured values

Appendix - References

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