Kinetic Energy of Water Drops Measured by a Dynamic Rain Gage System

Luiz A. Lima, Associate Professor

Departamento de Engenharia - Universidade Federal de Lavras, Lavras-MG, 37200, Brazil. Email: lalima@deg.ufla.br

Abstract: *Kinetic energy is very important to predict erosive potential of any rain, natural or artificial. Few equations used are empirical and based on measurements of drop size and velocity. This presentation is focused on a set of moving rain gages to measure velocity of drops and rain intensity. The equipment was used at NSERL (National Soil Erosion Research Laboratory) at Purdue University. It was observed that values measured by this new system are easily obtained. The equipment is easy to build and can evaluate the kinetic energy of sprinklers and sprayers with no need to measure drop sizes.*

Keywords: kinetic energy, dynamic rain gage system, erosivity, DRGS

Introduction

Rain drops have been investigated in order to understand their dynamics and characteristics to estimate, mainly, soil losses caused by rain erosivity. Accordingly to Heidorn (2000), the first attempts to evaluate size of rain drops were made in 1892 by E. J. Lowe. Later, Laws (1941) used laboratory procedures and measured the velocity of rain drops and related it to diameter and height of fall. Few years later, Gunn and Kinzer (1949) used sophisticated equipment, involving pressure and electronics, to measure the velocity of drops at stagnated air, in diameter ranging from 0.07 to 5.76 mm, while the minimum size worked out by Laws was 1.2 mm. According to Niu et al (2009), data obtained by Gunn and Kinzer, although from 1949, are still used as reference at rain drop studies.

Accordingly to Eigel and Moore (1983), the most common method to determine the kinetic energy of rain, natural or artificial, requires calculation of drop physical properties, requiring knowledge of terminal velocity, drop diameter and size distribution of drops.

Several techniques were developed in the past to measure drop size and velocity. For example, Laws and Parson (1943) used the flour method to evaluate drop diameter; Eigel and Moore (1983) created the photographic method of oil immersion to evaluate drop diameter; Solomon et al. (1991) used a LASER probe to measure the diameter and velocity of artificial rain drops. Recently, Niu et al (2009) measured the velocity and diameter of convective and strati form rains at different altitudes in China. They used the LASER disdrometer technique, equipment with parallel narrow beams that, once interrupted by a drop, can identify its diameter accordingly to the number of beams intercepted. Another type of equipment had been used by Caracciolo et al (2012), referred as Joss-Valdwogel disdrometer. These authors evaluated the accuracy of kinetic energy estimated based on rain rate, as proposed by Wischmeyer and Smith (1958) and empirically calculated by equation 1, especially under high rain rate values when its value is underestimated. Bradley and Bjorneberg (2011) evaluated kinetic energy of center pivot sprayers (47.3 to 165.3 mm/h intensity) and found values to vary from 9.1 to 13.2 J/Kg.

Based on rain drop diameter, Lima et al (1993) worked out equations related to drop falling from zero initial velocity. Drop velocity at any value of time (t) can be calculated as

$$v = \sqrt{\frac{g}{C_2}} \tanh\left[t\sqrt{gC_2}\right] \qquad (1)$$

where g is the gravity acceleration (9.81 m/s^2) and C2 the air drag coefficient. In an alternative form, based on the height (z), the impact velocity can be calculated as

$$v = \sqrt{\frac{g}{C_2}} \tanh\left[\cosh^{-1}(\exp[zC_2])\right] \qquad (2)$$

where z is the falling height in meters. Considering a high value for z, equation 3 can be reduced to

$$v_t = \sqrt{\frac{g}{C_2}} \qquad (3)$$

where v is referred as terminal velocity, known as the maximum velocity a rain drop can reach. Since natural rain drops fall from large height values, it is also considered as soil impact velocity. Several equations have been proposed to estimate C_2 based on Laws data (drop size larger than 1.2 mm).

Considering importance of erosion studies, high cost of disdrometers and inaccuracy of equations to predict drag coefficient (C_2) for small drops, this research considers that an equipment must be developed to estimate velocity and, therefore, kinetic energy of rain drops. Thus, this research investigated a dynamic rain gage system, from which kinetic energy of natural or artificial rain can be evaluated.

Theory background

A set of rain gages in which water can enter through an inclined (45 degrees) square cross section turns around a fixed circular rain gage. Based on such arrangement, although under rotational movement, the center gage (circular) is able to collect drops with vertical velocity larger than zero. The remaining gages will be filled by drops with velocity according to their position. The system is shown at figure 1.

Figure 1 – Dynamic Rain Gage System

The horizontal velocity of a rain gage positioned at a distance “r” can be calculated as:

$$Vh_r\,(m/s) = \frac{2\pi Rr}{60} \qquad (4)$$

where R is the rotation speed (rpm: rotations per minute) and r is the distance from the center. Since the cross section of each square gage is inclined at 45 degrees, the vertical velocity of rain drops that can enter at a given gage is larger than 1.414 Vh_r.

Exposed to any rain, the water collected at all gages can be plotted versus the velocity of rain drops, in histogram form. The cumulative frequency can be adjusted to

$$F(V) = \frac{1}{[1+(bV)^n]^{\,m}} \qquad (5)$$

where b, n and m are fitting coefficients. The first derivative of equation 6 can be easily calculated to estimate the relative frequency of rain drops falling with a given velocity.

Material and Methods

The developed system was set to turn at 123 rpm powered by a 12VDC motor under a rain simulator positioned three meters above the rain gages, at National Soil Erosion Research Laboratory (NSERL) at Purdue University. The rain simulator used works with an oscillating spray nozzle that oscillates and throws water on top of rain gages through an opening passage. Two intensity rains were used for evaluations, approximately 55 and 107 mm/h. Five rain events with duration of 7.5 minutes were evaluated for each rain intensity value. The water collected at each rain gage was used to build a histogram which data was fitted to equation 5. The rain gages had square opening section, 32 x 32mm. The central gage was circular with 32mm diameter. The water volume was measured by weighting the water collected at each rain gage and estimating the water volume considering water density equal to 1.0 g/cm^3.

Results and Discussion

Several tests were carried and the results obtained are listed at table 1.

Table 1: Velocity and Kinetic Energy of artificial rain events

Test		Velocity(m/s)			Kinetic Energy (J/Kg)		
	I(mm/h)	Right side	Left side	Mean	Right side	Left side	mean
1	56.32	3.69	3.30	3.50	6.80	5.45	6.12
2	56.84	3.46	3.67	3.56	5.99	6.72	6.35
3	56.23	3.97	3.36	3.67	7.89	5.65	6.72
4	55.35	3.46	3.84	3.65	5.98	7.37	6.66
5	53.57	3.74	3.65	3.70	7.01	6.66	6.83
Mean	55.66	3.66	3.56	3.62	6.73	6.37	6.54
CV	2.31	5.84	6.37	2.30	11.83	11.59	4.48
6	106.73	4.11	3.51	3.87	8.46	6.17	7.48
7	108.23	4.05	3.80	3.94	8.22	7.23	7.77
8	105.14	4.06	3.75	3.93	8.24	7.03	7.74
9	111.21	3.88	3.57	3.75	7.52	6.36	7.02
10	107.03	3.98	3.72	3.88	7.93	6.92	7.52
Mean	107.67	4.02	3.67	3.87	8.07	6.74	7.51
CV	2.10	2.22	3.38	1.95	4.49	6.74	4.01

CV: coefficient of variation (%)

Kinetic energy of rain was calculated as well as velocity considering rain gages at both sides of the central gage. Values listed on table 1 allows to conclude that despite the fact that intensity has approximately doubled, the velocity slightly increased from 3.62 to 3.87 m/s while the kinetic energy increased from 6.54 to 7.51 J/kg. In fact, this was expected (velocity would remain similar) since the rain intensity is increased simply by increasing the number of oscillations per minute at the rain simulator, i.e., the rain is the same, only the number of pulses (oscillations) has changed.

A histogram of rain drops can be built as plotted at figure 2. Observed and fitted values of cumulative frequency are plotted as well as the relative frequency – f(V). As can be observed, good fittings were obtained and all drops fell with velocity under 10 m/s.

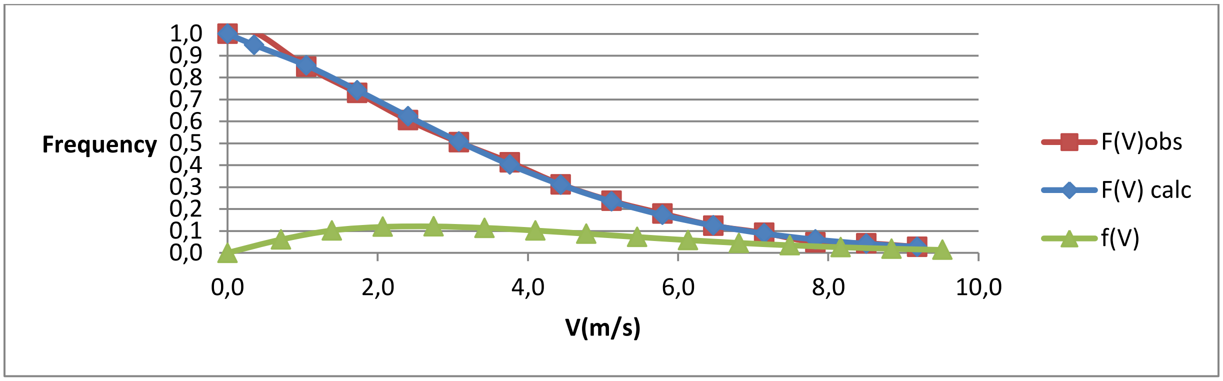

Figure 2: Histogram of cumulative (F) and relative (f) frequencies of rain drops

Comparatively to data found by Bradley and Bjorneberg (2011), the rain generated by the rain simulator tested has lower kinetic energy than that of center pivot nozzles (Nelson D3000, S3000 or R3000) with approximate flow rates of 2.5 m3/h, when KE varied from 9.1 to 13.2 J/Kg.

Conclusions

The dynamic rain gage system allowed the measurement of kinetic energy with no need to measure the drop size. It is simple to build and avoid empirical estimates of kinetic energy subject to errors.

Acknowledgments

This research was supported by CNPq (Brazilian Research Council Agency) and FAPEMIG (Minas Gerais Research Funding Agency). The author also expresses gratitude to The National Soil Erosion Resarch Laboratory, especially to Dr. Huang Chi-Hua for his support.

References:

BRADLEY, A. K. & BJORNEBERG, D. L. 2011. Infiltration Model for Center Pivot Sprinkler Irrigation. Irrigation Association Show 2011. Technical Conference. San Diego-CA.

CARACCIOLO, C.; NAPOLI, M.; PORCU, F.; PRODI, F.; DIETRICH, S.; ZANCHI, C. and ORLANDINI, S. 2012. Rain drop size distribution and soil erosion. In: Journal of Irrigation and Drainage Division. p. 461-469. American Society of Civil Engineers.

EIGEL, J. D.; MOORE, I, D. 1983. A simple technique for measuring raindrop size and distribution. **Transactions of ASAE**, St Joseph, v.26, n.4, p.1079-1084. Jul./Aug.

GUNN, R. and KINZER, D. G. 1949. The terminal velocity of fall for water droplets in stagnant air. Journal of Meteorology, Vol. 6, p. 243-248.

HEIDORN, K.C. 2000. Brushing the teardrops from rain. In: Weather people and history. The weather doctor.

HILLS, D. 1988. **Advanced Sprinkler Irrigation**. Course Notes. UCDavis.

LAWS, J. O. 1941. Measurements of the fall velocity of water drops and raindrops. Transactions of American Geophysics Union, Vol. 22, p. 709-721.

LIMA, L. A.; SILVA, M. L. N.; MARQUES, J. J. G. S. M. 1993. O salpicamento de latossolos provocado por gotas de chuva. In: CONGRESSO BRASILEIRO DE CIÊNCIA DO SOLO, 24, Goiânia, 1993. **Anais...** Goiânia: Astro Gráfica e Editora. v.13, p.163-164.

MATTHEWS, G. A. 1975. Determination of droplets size. **Pans***,* v. 21, p. 213 25.

NIU, S., X. JIA, J. SANG, X. LIU, C. LU, Y. LIU. 2009. Distributions of raindrop sizes and fall velocities in a semi-arid plateau climate: convective VS. stratiform rains. Submitted for publication in Journal of Applied Meteorology and Climatology. Brookhaven National Laboratory (www.bnl.gov). Accessed on July 15th.

NIU, S.,JIA, X, SANG, J, LIU X, LU, LIU Y. 2009. Distribution of rain drop sizes and fall velocities in a semi-arid plateau climate: convective versus stratiform rains. Journal of Applied Meteorology and Climatology.

SOLOMON, H. K.; ZOLDOSKE, D. F.; OLIPHANT, J. C. 1991. Laser optical measurement of sprinkler drops sizes. **In**: ASAE winter Meeting, Chicago, 1991. Proceedings...Chicago: ASAE, St. Joseph, p.87-96. Dec.

WISCHMEIER, W. H. and SMITH, D.D. (1958). Evaluation of factors in the soil loss equation. Agricultural Engineering, 39. 458-462.