

The Effect of Raindrop Kinetic Energy on Soil Erodibility

A. Moussouni, L. Mouzai, M. Bouhadef

Abstract—Soil erosion is a very complex phenomenon, resulting from detachment and transport of soil particles by erosion agents. The kinetic energy of raindrop is the energy available for detachment and transport by splashing rain. The soil erodibility is defined as the ability of soil to resist to erosion. For this purpose, an experimental study was conducted in the laboratory using rainfall simulator to study the effect of the kinetic energy of rain (E_c) on the soil erodibility (K). The soil used was a sandy agricultural soil of 62.08% coarse sand, 19.14% fine sand, 6.39% fine silt, 5.18% coarse silt and 7.21% clay. The obtained results show that the kinetic energy of raindrops evolves as a power law with soil erodibility.

Keywords—Erosion, runoff, raindrop kinetic energy, soil erodibility, rainfall intensity, raindrop fall velocity.

I. INTRODUCTION

THE rainfall erosivity is defined as the potential ability of rainfall to cause erosion of an unprotected field [22]. It depends on the physical rainfall characteristics, the drop height, the size of the drops and the terminal fall velocity [21]. For [33] and [3], the rainfall erosivity depends on the kinetic energy and the rainfall intensity. Morgan (1995) says that the kinetic energy is the most appropriate expression of rainfall erosivity (quoted in [6]).

The raindrop kinetic energy is the energy available for detachment and transport by rain splash ([31], [24], [25]). This is an important factor of detachment ([6]). It disperses the particles forming aggregates and clods ([27], [28]).

The soil erodibility is defined as the ability of the soil to resist to erosion. To investigate adequately the effect of the raindrop kinetic energy on the soil erodibility, we have to modify and to vary the parameters of this phenomenon.

For this purpose, an experimental study was conducted in the LEGHYD laboratory using a rainfall simulator to study the relationship between the raindrop kinetic energy and soil erodibility.

The simulator which was used is identical to that described in [18], [19], with a spray nozzle fixed on a gantry at a height of about four meters. Driven by a pendulum, the nozzle sprays a surface test of 1 m². The soil used is an agricultural remoulded soil.

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II. BASIC EQUATIONS

A. Raindrop Kinetic Energy

The raindrop kinetic energy is converted at the impact on the soil. This aggression can be considerable if the soil is not protected by a vegetable cover which absorbs some of this energy, which is calculated as follows:

$$E_c = \frac{1}{2} mV^2 \quad (1)$$

E_c : specific kinetic energy (J.m⁻².mm⁻¹), m : raindrop mass (kg) and V : raindrop fall velocity (m/s).

Indeed, it is normally necessary to know both the mass and velocity of each raindrop; we sum then the energies of each drop to know the total energy of a rain. It is therefore important to study the characteristics of the rain.

1. Drop Size

For [34], [5] was the first to think that the raindrop covers all aspects of the erosive rainfall effect. Reference [26] reported that just at the impact, the drop shape had a significant influence on the surface of the target on which the impact force is distributed, which directly affects the quantity of detached soil. Reference [13] studied the effect of the drop of water on the detachment for different raindrop diameters; he mentioned that the soil lost by the splash varies linearly with the square of the mass of the drop.

Several researchers [16], [31] have established relationships between the raindrops diameter and the rainfall intensity; the relationship is:

$$D_{50} = aI^b \quad (2)$$

D_{50} is the median raindrop diameter (mm) and I is the rainfall intensity (mm/h).

To determine the rainfall kinetic energy, we proceed as follows:

Calculate the median raindrops diameter.

Determine the raindrops velocity using the Laws' table.

Determine the raindrop mass, when the drop is assimilated to a sphere ($V = \pi d^3/6$).

2. Fall Velocity

The raindrop fall velocity depends on its mass, thus its diameter. It is not constant throughout the fall; it increases up to a speed limit or a terminal velocity [7]. According to [12], the terminal velocity depends only on the raindrop diameter. Reference [4] showed the importance of the diameter and the fall drop velocity in the detachment erosion by "splash".

Empirical formulas have been developed by several researchers in different conditions. Reference [34] gave the following formula in which D is the raindrop diameter:

$$V=10^{3\sqrt{D}} \quad (3)$$

Uplinger (from [30]) evaluated the velocity according to the median diameter D_{50} by:

$$V=48.54D_{50}e^{-1.95D_{50}} \quad (4)$$

Reference [16] expressed D_{50} by:

$$D_{50}=1.23I^{0.128} \quad (5)$$

Brandt (1989) (in [29]) expressed D_{50} by:

$$D_{50} = 1.466 I^{0.123} \quad (6)$$

Best (1950) (from [30]) suggests the following relation:

$$V = 10.30 - 9.65 e^{-0.6D} \quad (7)$$

This approach gives good results when the raindrop diameter is larger than 0.4mm, but gives negative velocities when the diameter is smaller.

In our case, the raindrops fall velocity is determined using the Laws abacus that uses the median drop diameter and the falling raindrops height.

B. Soil Erodibility

In the WEPP model (Water Erosion Prediction Project), interrill surfaces erosion is expressed as [14]:

$$E = KI^2S_f \quad (8)$$

E is the rate erosion interrill, K is the soil erodibility, I is the rainfall intensity and S_f is the slope factor, which is expressed by the equation:

$$S_f = 1.05 - 0.85 \exp(-4\sin\theta) \quad (9)$$

θ is the parcel inclination angle.

The runoff sediment concentration is expressed by:

$$C_s = q_s/q \quad (10)$$

q_s is the solid discharge, q is the liquid discharge.

The relation between E and q_s is:

$$E = q_s/L \quad (11)$$

L is the length of the eroded surface in the runoff direction.

The combination of (8)-(11) gives the expression of erodibility as follows:

$$K = q_s/LI^2S_f \quad (12)$$

The sediment concentration was defined as the ratio between the dry weight of the sediment and the runoff volume [10], [1].

$$C_s = \frac{m_s}{w_t} = \frac{m_s}{w_e + w_s} \quad (13)$$

Dividing the numerator and denominator by the width and time, (13) becomes:

$$C_s = q_s/q_{mel} \quad (14)$$

q_s is the unit solid discharge (kg/m.s) and q_{mel} is unit mixture discharge (m²/s).

Equation (12) becomes:

$$K = C_s q_{mel} / LI^2 S_f \quad (15)$$

III. EXPERIMENTAL PROCEDURE

The used simulator is of ORSTOM type with a spray nozzle fixed on a gantry at a height of about four (4) meters driven by a motor. The nozzle sprays a surface test of 1 m². The rotation velocity is controlled by the battery charger which produces different voltages by changing the rotational velocity of the motor. Therefore, in combination with the water pressure controlled by a manometer, one can change the rain characteristics (intensity, diameters of the raindrops), the falling speed of the raindrops and the raindrops kinetic energy. The pump supply is connected to the spray system by a PVC tube. Water aspiration is coming from a tank of 600 l. The control pressure supplied by the pump to the nozzles is carried out from two valves.

The soil tray used in this study has a length of 2m, width of 50 cm and a depth of 15 cm. It is fixed on a metallic frame serving as a support. On one end of this support is fixed an axis which allows the tray to pivot. On the other end, it is lifted via two threaded rods, provided with flywheels, to fix the desired inclination of the tray. The soil used is a sandy agricultural soil of 62.08% coarse sand, 19.14% fine sand, 6.39% fine silt, 5.18% coarse silt and 7.21% clay.

The procedure used to measure the rainfall intensities was the simple volumetric method and are as follows: 12.4 mm/h, 20 mm/h, 28.5 mm/h, 52 mm/h, 60.4 mm/h, 73.5 mm/h and 103 mm/h. The slope is fixed at 3%. The height between the nozzle and the soil surface is 3m. This simulator was already used by the authors [19] and [20].

The water volume collected in each beaker was measured using a graduated cylinder of 1000 ml; this operation is reproduced every 3 minutes until the end of the test. Thereafter, the beaker is stirred so that all the solids particles are suspended in water; we take a sample of 100 ml in a small glass beaker which we measured previously the empty weight. [8], [23]. Having noted the volumes of all the beakers and collected after cleared volumes of 100 ml of the mixture, we put these glass beakers in the oven at a temperature of 105°C for 24 hours [8].

The surface velocity U_s was measured using $KMnO_4$ (Potassium permanganate) as a dye tracer. One side of the soil tray was graduated in order to obtain time measurements. Four positions (0.5m, 1m, 1.5m and 2m) were selected to record the travelling time of the leading edge. A small amount of the colored liquid was injected in the middle of the surface flow at 0.5 m from the top end of the soil tray. Surface flow velocities were then measured visually by recording the time of the leading edge of the dye cloud travelling between the injection point and the bottom end of the soil tray. The mean flow velocity U_m is calculated from the surface velocity using the conversion factor of 0.67 (see [10]). The measurement of surface velocity was repeated every three minutes for each experiment and the same experiment was run five times.

The mean flow depth, h , was then calculated using the relation: $h = q_m/U_m$ where q_m is the unit overland flow discharge of water/sediments mixture and U_m the mean velocity.

For measuring the raindrop diameter, the used method was the stain method or method of absorbent paper [11]. The method is based on the principle that the falling drop on uniform absorbent surface produces a stain which is proportional to the raindrop diameter. For our experiments, we used blotting paper as absorbent surface with potassium permanganate ($KMnO_4$) powder which is a dye that changes the color when wet and becomes purple.

The treated paper is placed on a glass plate of the same size and is held horizontally, covered with another glass plate of a larger size. The paper is then simply submitted, a very short time, to the simulated rain. When the leaf is dry, the impact of the raindrop appears purple. We use a magnifying glass to measure the impact diameter. The number of drops varies from one sheet to another depending on the rainfall intensity. We then determine the median diameter and the raindrop kinetic energy.

IV. RESULTS AND DISCUSSION

From Fig. 1, for rainfall intensities between 12 mm/h to 103 mm/h, the median raindrops diameters vary between 1.75 mm to 3.07 mm. Our results show that the correlation between the median diameter (D_{50}) and rain intensity (I) is represented by a power law ($D_{50} = 0.945 I^{0.245}$) with a coefficient of determination $R^2 = 0.79$. This relationship is very close to those obtained by [2], [32] and [16].

The raindrops kinetic energy increases with increasing rainfall intensity. The function is represented by a power law with $E_c = 0.105I^{0.804}$ with $R^2 = 0.95$ (see Fig. 2).

Reference [18] studied the characteristics of rainfall simulators and the distribution of natural raindrops. It has been observed that natural precipitation consists of a series of drops which size is close to 0 to 7 mm in diameter. The median diameter of the droplet is between 1mm and 3mm for erosive rain. This median diameter range is much close to the results presented in Fig. 1. On the contrary, median diameters found by [21] in their studies in Ethiopia, are slightly higher than our results. Indeed, they found that for rainfall intensity between

12 mm/h to 96 m/h, the median diameter is between 3 mm to 4.4 mm.

The relationship between the raindrops falling velocity and the raindrop diameter is shown in Fig. 3. The relationship follows a polynomial function with a high coefficient of determination.

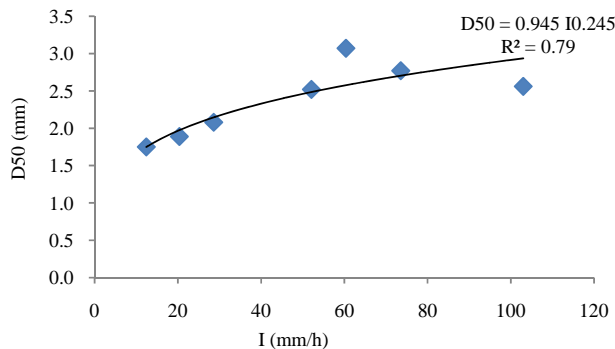


Fig. 1 Relationship between rainfall intensity and raindrop diameter

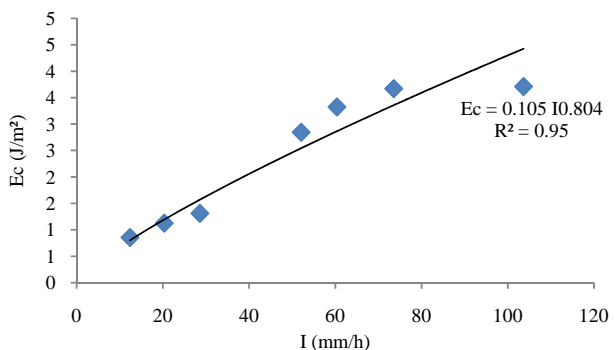


Fig. 2 The relationship between rainfall intensity and raindrop kinetic energy

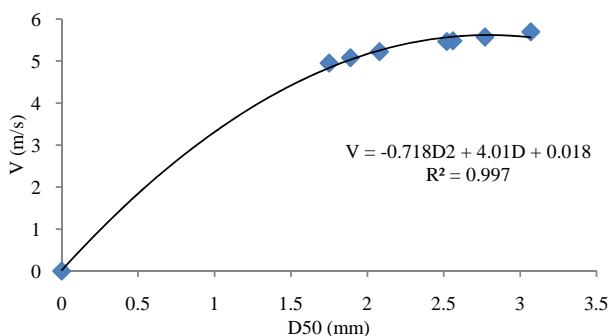


Fig. 3 Relationship between terminal velocity and median raindrop diameter

The relationship between the raindrop fall velocity and raindrops size is represented by a power law. According to [17], several studies on the parameterization of rainfall have emerged in recent years. Relations between the kinetic energy of rain and rainfall intensity were established. From a theoretical point of view, the best fit to the measured data is

obtained with respect to the power law (Steiner and Smith 2000; Salles et al. 2002 cited in [17]).

Using more sophisticated techniques, [15] and [9] determined the relationship between drop size and terminal velocity. This relationship is not linear because large drops tend to become flattened by resistance forces during their fall. Due to the air resistance, there is also a limit of the raindrops size above which they become unstable and tend to break. This limit appears to be about 6 mm to 8 mm (e.g. [16]).

The results obtained in this study show that the increase in soil erodibility follows that of the raindrops kinetic energy. The correlation between the kinetic energy of the rain and the soil erodibility, shown in Fig. 4, is fitted by a power law with a rather significant coefficient of determination.

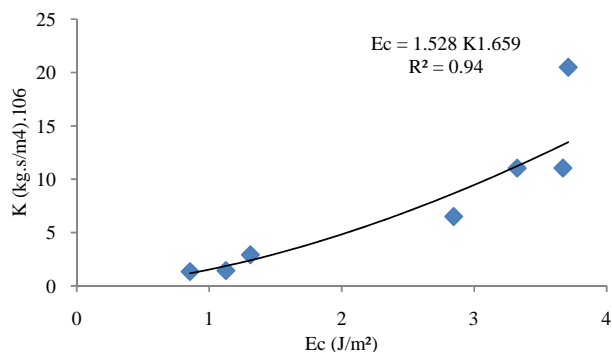


Fig. 4 Relationship between raindrop kinetic energy and soil erodibility

V. CONCLUSION

This experimental study allowed us to show the relationship between the raindrops kinetic energy and soil erodibility. Based on these results, we can conclude that:

- The raindrops kinetic energy is related to the rainfall intensity following a power law.
- The rainfall intensity is related to the median raindrops diameter by a power function.
- The raindrops kinetic energy has a significant effect on soil erodibility; the correlation is represented by a power law.

The terminal velocity is related to the median raindrops diameter by a polynomial law.

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