Erosion and Sediment Transport Measurement (Proceedings of the Florence Symposium, June 1981). IAHS Publ. no. 133.

A study of the dynamics of drop erosion under laboratory conditions

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ABSTRACT Drop erosion experiments on sand have been carried out by means of a Kazó type rainfall simulator, and quantitative data concerning the extent of drop erosion have been obtained. The linear correlation between rainfall energy and material displaced has been examined by least squares analysis, and this analysis has defined the energy range at which there is no material transfer (i.e. the range below the drop erosion threshold energy). The order of magnitude of material transfer corresponding to an infinite falling height has also been evaluated. The use of a plastic net stretched over the sand has been shown to decrease drop erosion significantly.

L'étude de la dynamique de l'érosion produite par les gouttes de pluie dans les conditions du laboratoire
RESUME Avec le simulateur de pluie Kazó, nous avons fait des expériences d'érosion de pluie sur sable et nous avons obtenu des données quantitatives sur cette érosion. Nous avons étudié la corrélation linéaire entre l'énergie de la pluie et la quantité de matière déplacée par la méthode des moindres carrés en utilisant un programme. L'estimation numérique a attiré notre attention sur le domaine d'énergie pour lequel le déplacement de matière ne se produit pas (domaine au-dessous du seuil d'énergie de l'érosion par la pluie). Nous avons étudié l'ordre de grandeur du déplacement de matière correspondant à une hauteur de chute infinie. A l'aide d'un filet de plastique étendu au-dessus du sable on a réussi à réduire dans une large mesure l'érosion dûe à la pluie.

INTRODUCTION

The aim of the experiments was to obtain data on the amount of material transfer brought about by the kinetic energy of raindrops on impact with the soil surface. In particular, what correlation can be found between the energy of impact and the quantity of transferred material? In what way is the material transfer influenced by the slope angle? Can the extent of drop erosion be influenced artificially?

The term "material transfer" is taken here to mean the displacement of soil particles only by raindrops moving in a trajectory and therefore separated from the soil surface. The term does not include transfers resulting from the massing of drops taking place as a result of the effect of impact, or changes in the position of the drops whilst in contact with the soil surface, although these are also mechanical forms of motion. Arising from the concept of drop erosion in a strict sense, however, the movement of drops in a trajectory is important.

METHODS AND EXPERIMENTAL MATERIAL

The experiments were carried out by means of the Kazó type rainfall simulator (Kazó, 1966) always in stagnant air. For catching the transferred drops recipient vessels of my own design were used (Fig. 1). The raindrops from the rainfall simulator fall on an area of 0.25 m^2. They leave the simulator under the effect of gravity and their velocity acceleration depends upon the height of fall. The simulator produces raindrops of uniform size, 3 mm in diameter.

The experiments were carried out using sand. Table 1 shows the grain size distribution. Because of the negligible cohesion between the grains, this material is suitable for investigating the mechanism of drop erosion since, even in the case of low energy raindrops, material transfer can be measured. Also, as a result of its good permeability, superficial flow can be excluded and thus the effect of raindrop impact can be clearly isolated.

The energy of impact of the raindrops is varied by placing the simulator at different heights. The experiments were carried out at fall heights of 0.6, 1.0, 1.7, 2.5, 3.2, 4.0 and 4.8 m. The velocity of the raindrops was determined by a phototechnical method. The experiments were completed for each fall height at slopes angles of 3°, 7°, 10°, 14° and 20°. A planar slope at the

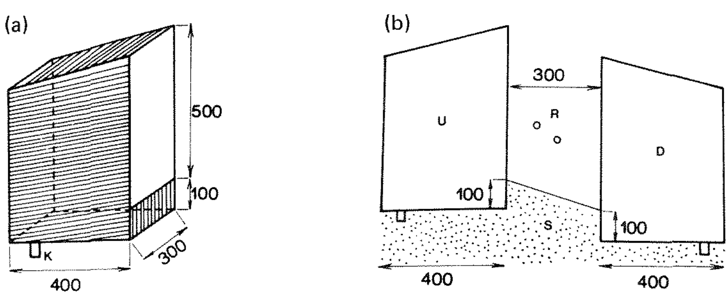

Fig. 1 (a) The recipient vessels and (b) their position in the experimental set up. Dimensions in millimetres. K = outlet tube, R = raindrops, S = sand, D = the vessel at the lower end of the slope, U = the vessel at the upper end of the slope.

Table 1 The grain size distribution of the sand used in the experiment

Diameter of grains (mm)	>0.8	0.8-0.63	0.63-0.32	0.32-0.2	0.2-0.1	0.1-0.05	0.05-0.02	<0.02
Weight %	0.03	0.05	2.07	15.53	66.21	13.91	0.80	1.4

appropriate angle was made up of sand. Recipient vessels were placed at the lower and upper ends of the slope at a distance of 30 cm from each other (Fig. 1(b)). The vessels caught the splashing raindrops over a width of 30 cm and up to a height of 50 cm (Fig. 1(a)).

In each case the intensity of rain used during the experiments was 35 mm h^{-1}. Each rainstorm was produced with distilled water and lasted for an hour. Four replications were used and thus the main series of experiments consisted of 140 measurements. When processing the data, mean values ($\bar{x}$), dispersion (s), coefficients of variation (s%) were calculated. The parameters of the regression lines were determined by the least squares method using a program prepared by Dr Ágoston Bába, physicist.

RESULTS

The first task was to determine the energy of the drops falling from various heights. Since the rainfall simulator produces only raindrops with a diameter of 3 mm, only the velocity of one drop needed to be determined. Altogether 170 measurements were made at the above listed heights as well as at intermediate heights. The results obtained by the phototechnical method are shown in Fig. 2. With the help of this figure drop velocities for any

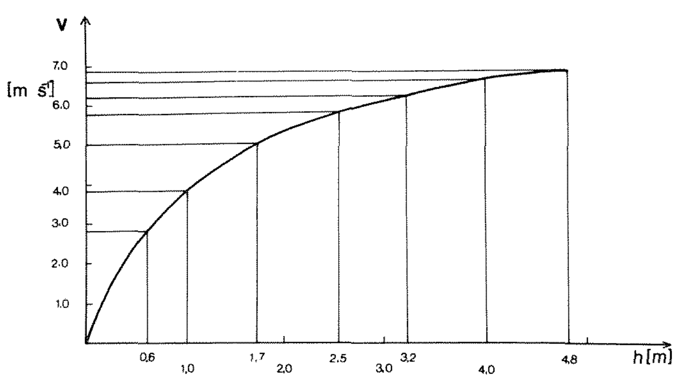

Fig. 2 The relationship between the height of fall (h) and the velocity of the raindrop (v) for drops of 3 mm diameter.

fall height between 0 and 4.8 m can be determined, and from these data both the energy of one drop and that of the rainstorm can be calculated. This information is used to study the correlations between the energy of rain and the quantity of the material transferred from the soil surface. In addition, the energy of single drops was examined in experiments described below to determine the threshold energy for drop erosion. Because of the nature of the drop erosion process and the form of the experiments, this approach enabled a more realistic assessment of energy thresholds than could be obtained using storm energy values. It should be noted here, however, that, because the simulated rain is homogeneous in drop size, the energy of one drop varies with height of fall in exactly the same way as the energy of rain

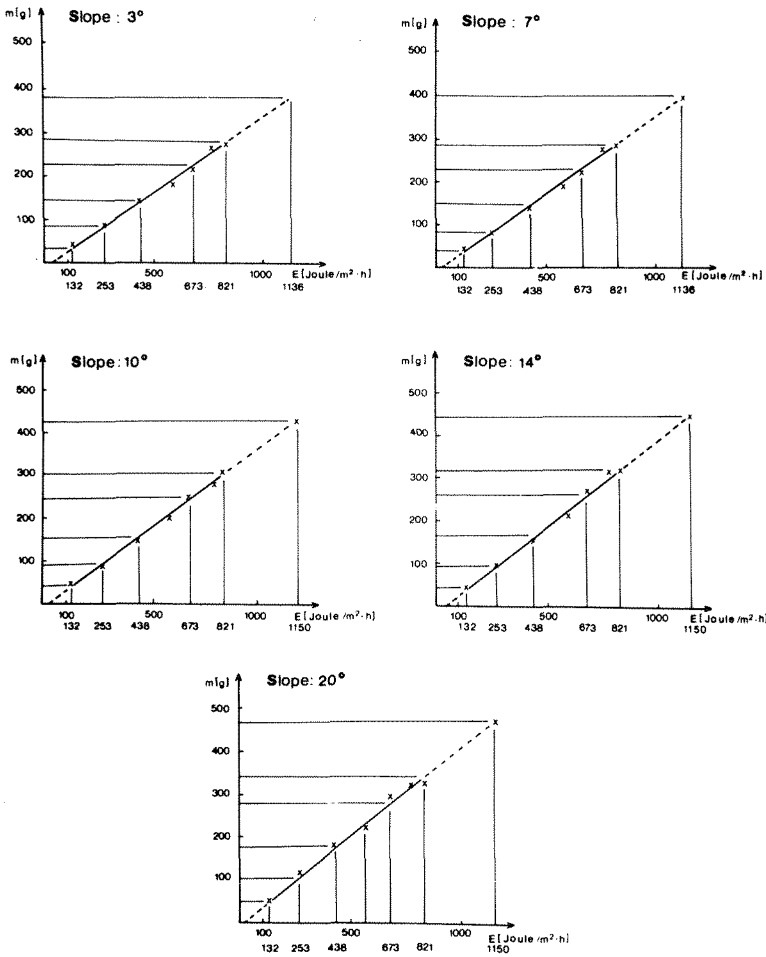

Fig. 3 The correlation between the energy of rain ($J\ m^{-2}\ h^{-1}$) and the quantity of the material transferred during drop erosion (g) in the case of an area of $0.09\ m^2$ at various slope angles.

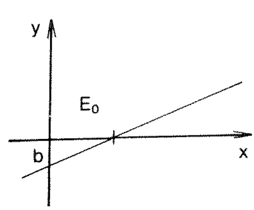

Fig. 4 Parameters defining a linear regression line (see text).

Table 2 Parameters of the best-fit regression lines between rainfall energy and material transfer (D+U) by the least squares method

Slope angle	3°	7°	10°	14°	20°
E_0	22.82	22.15	21.50	18.85	1.14
b	−7.98	−7.95	−8.09	−7.50	−0.47

falling within an hour, and thus this threshold energy value is also suitable for the study of correlations.

On reaching the surface of the sand, the raindrops resulted in the dispersion of sand grains. There was always more sand moving downwards (hereinafter: D) on the slope than upwards (hereinafter: U). The difference between the two values (D-U) expresses the extent of erosion whereas the D+U values are suitable for the study of the relationship between the energy of the rain (drop energy) and quantity of material transfer. Applying the least squares method, a linear relationship was found between the energy of the rain and material transfers (Fig. 3). The correlation between the quantity of the transferred material and the energy of the rain can be examined only for specific slope angles since the values of D, U, D-U and D+U vary with an increase in slope angle. The following parameters are identified for the best-fit regression lines: E_o, the point of intersection with the x-axis indicating energy = E-axis; and b, the point of intersection with the y-axis indicating the values of mass = m-axis (Fig. 4).

The regression lines for rainfall energy and material transfer (D+U) do not pass through the origin but, without exception, intersect the x-axis at positive values of energy (E_o parameter in Table 2). This indicates that there is a range of low energy values at which no material transfer occurs. The energy value at which the transfer of the soil grains first occurs will be called the threshold energy of drop erosion. To know this value is very important as far as the protection against soil erosion is concerned. If the energy of raindrops can be artificially reduced to below this value, then drop erosion can be stopped.

Because of its importance, additional studies were carried out for the determination of the threshold energy of drop erosion. These studies were undertaken not with rainfall simulators but by using a pipette to produce raindrops with a diameter of 3 mm. These were allowed to fall onto the soil surface through the mouth of a cone-shaped glass bell. Under the glass bell the surface was covered with a metal anchor-ring having an opening of 17 mm diameter which was placed exactly underneath the upper

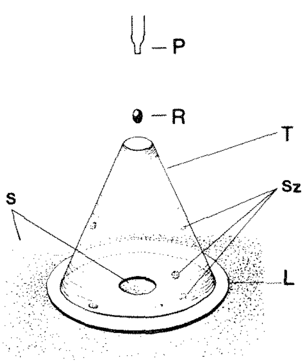

Fig. 5 Apparatus used to define the threshold energy of drop erosion. P = pipette, R = raindrop, T = glass bell with a mouth at the top, S = sand, L = metal plate, Sz = grains of sand transferred from the surface.

mouth of the glass bell (Fig. 5). Through the glass it was easy to see whether the falling raindrops caused material transfer or not. The fall height of the drops was increased in 2 or 3 cm increments from a height of 5 cm up to the point at which the first dispersing grains touched the metal plate or the wall of the glass bell. When the value of the threshold energy was reached, it was checked at 8-10 various points of the sand surface to allow for the inhomogeneity of the sand. During the measurements the influence of the moisture content of the sand on the value of the threshold energy was also examined. Because of the inhomogeneity of the sand, different values of threshold energy were observed for given states of humidity, and so it is more reasonable to express threshold energy as a range of values. The threshold energy for the sand maintained in a state of humidity which keeps balance with the atmospheric humidity (0.4 weight %) is 500-620 ergs, that is, only those raindrops having this energy or greater cause material transfer. The energy of the rain consisting of such drops is 124-153 J m^{-2} h^{-1}.

The drop erosion threshold energy for the same sand with a moisture content of 20 to 22 weight % is 50-120 ergs for a single drop. This corresponds to rain of an energy of 12.4-29.7 J m^{-2} h^{-1}. These values of threshold energies are for horizontal sand surfaces. Further studies are necessary to determine whether the slope angle influences the value of the threshold energy. Because the low moisture content of the surface layer is characteristic only of the initial minutes of a rainstorm, it is more reasonable to consider the lower energy values as the threshold energy of drop erosion. The moisture content of the top 2 cm layer was measured before each experiment. It was found to be 12.6-16.0% before rainfall was applied, whereas after a few minutes of rain it reached 20%, and at the end of each rainstorm was more than 22%.

The experiments have also shown that the resistance of the same material to drop erosion during one rainstorm changes significantly: namely, the more the moisture content increases the easier it is eroded. It has also been found that the extrapolation made by an exact mathematical method on the basis of results of numerous single drop tests indicates fairly well the threshold energy values for the simulated rainstorms obtained by direct measurements.

Furthermore, a calculation was made of the amount of material transfer which would result from rain consisting of 3 mm diameter drops falling from an infinite height. According to the data of Gunn & Kinzer (1949) raindrops with a diameter of 3 mm reach a terminal velocity of 806 cm s^{-1}, which is equal to an energy of 1136.9 J m^{-2} h^{-1}. On the basis of the data of the regression lines (Table 2), material transfers are determined for an area of 0.09 m^2 in the case of an energy of 1136.9 J m^{-2} h^{-1} and then these data have been converted into t ha^{-1} (Table 3). The D+U values indicate the total material transfer both upwards and downwards while the D-U values indicate the extent of the erosion. Concerning the data presented here, however, it should be noted that this extrapolation extends further beyond the data base than the previous extrapolations and there was no possibility of

Table 3 Material transfers calculated for a rain energy of 1136.9 J m^{-2} h^{-1} at various slope angles

Slope angle	D-U (g. 0.09 m^{-2})	D-U (t ha^{-1})	D+U (g. 0.09 m^{-2})	D+U (t ha^{-1})
3°	49.23	5.47	389.77	43.31
7°	121.62	13.51	400.27	44.47
10°	163.63	18.18	419.57	46.62
14°	221.97	24.67	444.91	49.43
20°	321.62	35.74	466.23	51.80

Table 4 Material transfers by drop erosion from a sand surface of 0.09 m^2 with and without a plastic net

		Quantity of transferred material (g)			
		On a surface without net		On a surface with net	
Slope angle	Fall height	D-U	D+U	D-U	D+U
7°	3.2	77.16	231.40	1.38	4.58
14°	4.0	156.48	306.28	4.67	7.95

control measurements. Thus the source of error has also been greater: it is likely to exceed the highest coefficient of variation calculated during the experiments of 17.9%. When comparing the values of Table 3 with the results of other soil erosion measurements, this source of error needs to be taken into consideration. Furthermore, in a comparison with the measurements carried out in nature, it should also be noticed that in nature a significant part of the surface is covered by plants, and depending on the extent of this cover the quantity of the material transferred by drop erosion decreases. Taking all this into account, however, on the basis of the data of Table 3 it is evident that the amount of the material transferred by drop erosion is not a negligible quantity in the case of rains of greater energy. The extent of the material transfer caused by rains of smaller energy can be seen in Fig. 3.

During the experiments an attempt was made to decrease drop energy by stretching a plastic net with a mesh of 1 mm at a height of 50 cm over the sand surface. First a rain with an energy of 672.7 J m^{-2} h^{-1} was produced followed by one with an energy of 762.3 J m^{-2} h^{-1} (falling heights: 3.2 and 4.0 m, respectively). Breaking against the net, the raindrops pulverized, and they were able to cause only slight drop erosion on the surface. Compared with the experiments without nets the extent of the material transfer was 33 to 55 times less (Table 4). The data in Table 4 are mean values.

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