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Examining the Process of Soil Detachment from Clods Exposed to Wind-Driven Simulated Rainfall

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SOIL detachment from clods exposed to wind-driven rain is much greater than detachment caused by similar rainfall intensities without wind (6)*. Seemingly, changes in drop size or in the profile drag exerted by the wind account for the difference, but, until recently, insufficient data were available to support these hypotheses. One recent study revealed that waterdrops have less vector velocity when falling through a wind tunnel than when falling in still air (2). The present study explains further the process involved in soil detachment under wind-driven rainfall.

Ellison (3, 4), who was concerned with the total water-erosion process, reported that raindrop splash was the principal agent of soil detachment. Bennett et al (1) later modified this by saying raindrop splash was one of several important factors in the soil-erosion processes. He stated that drop impact mixed the soil with the surface water, thus contributing muddy water to the runoff. The effects of drop impact were observed in this study and compared with observations of Ellison and Bennett.

Soil loss resulting from rainfall in still air is closely related to the kinetic energy of the rain (10). The product of rainfall energy and intensity commonly is used to relate simulated rainstorms to natural rainstorms. If wind accompanying a rainstorm were to increase soil loss only by increasing the rainfall energy, this same rainfall index could be used to relate simulated wind-rainstorms to natural wind-rainstorms, if rainfall energy were determined in wind. But if wind contributes to soil loss in ways other than changing the rainfall energy — and this study indicates that it does — then the wind forces on the soil also must be considered.

This paper reports the results of the study in which wind shear stress and rainfall kinetic energy were considered as separate variables. The results of this study help to explain the effect each variable has in the soil detachment process.

This paper was submitted expressly for publication in TRANSACTIONS of the ASAE. Paper is a contribution from the Soil and Water Conservation Research Division, Agricultural Research Service, USDA, in cooperation with the Kansas Agricultural Experiment Station. Department of Agronomy contribution No. 1115.

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* Numbers in parentheses refer to the appended references.

Procedure

Field clods were formed by chisel tillage of a silt loam soil which was near optimum moisture for compaction. Samples collected for study were air dried and a size range of 1.27 to 3.81 cm in diameter was obtained by rotary sieving. One thousand grams of clod samples, placed on trays having 0.64-cm screen bottoms, were exposed for 30 min to simulated wind-rainstorms in a wind tunnel-raintower facility (2). The trays plus clods were weighed, exposed to simulated rainfall and wind, air dried, and reweighed to determine the quantity of soil material that had detached and passed through the screens. Three replications were made during each storm event.

Rainstorms were simulated in the facility by spray nozzles located 10.4 m above the wind tunnel floor. Drops falling this distance in still air will attain at least 95 percent of their terminal velocity (5), and rainfall intensity can be controlled by adjusting the number and size of spray nozzles used.

Rainfall-energy values were determined for various combinations of windspeed, nozzle number and size, and location of tests on the floor of the raintower. Drop size distributions were determined by the flour method (7). A prediction equation developed in a previous study (2) was used to calculate resultant velocities of drops in the various drop-size groups. To measure rainfall intensities in wind, shallow metal trays containing a water-absorbing polyurethane foam material of known area were exposed for a definite time period; they were weighed before and after exposure. Kinetic-energy values were determined (7, 9) by methods developed by Wischmeier and Smith (10).

Reference wind velocities of 0, 447, 671, and 894 cm/sec were measured in the center of the wind tunnel upwind of the test samples with a pitot-static tube and inclined alcohol manometer. Detailed velocity profiles obtained near and above the clods were plotted against $\log_{10}$ height. However, this velocity profile was not typical of a profile over a rough surface in the wind tunnel, because it did not develop fully over the length of the clod tray and was in a transitional state. Because of the nontypical velocity profile, the values for the effective roughness height, d, and the roughness parameter, Z_0, determined from a least-squares analysis using elevations within the "constant stress" layer, were not realistic. Values for the parameters determined in the wind tunnel in a fully developed boundary layer over a rough surface (unpublished data of Lyles) were used in the following relation to determine drag velocities:

$$U_* = \frac{\overline{U}_z}{5.75 \log \left(\frac{Z - d}{Z_0}\right)}$$

where U_* = drag velocity, cm per sec
$\overline{U}_z$ = mean velocity at height Z, cm per sec
Z = elevation above trays, cm
d = 2 cm
Z_0 = 0.08 cm

The wind shear stress was calculated from the drag velocities in the following relation:

$$\tau = \rho U_*^2$$

where τ = shear stress, dynes per sq cm
ρ = density of air, 0.001173 g per cu cm
U_* = drag velocity, cm per sec

To offset the many assumptions required in calculating wind shear stress, shear stress on the clods was measured. A 7.6-cm strip the width of the exposure tray was cut from one of the trays and attached to the small vertical cantilever beams at the ends of a heavy metal plate so that the strip was supported 6.4 cm above the plate. A nearness indicator was mounted on the plate under the screen so that it would sense movement of the screen. Soil clods were placed on the screen, and the probe was calibrated by hanging weights from a cotton thread attached to the screen over a "frictionless pulley" (Fig. 1a). After calibration, the screen and probe were placed in the wind tunnel, the exposure tray from which the screen had been cut was placed around the screen and probe, and soil clods were placed

This article is reprinted from the TRANSACTIONS OF THE ASAE (vol. 14, no. 1, pp. 90, 91 and 92, 1971), the Transactions of the American Society of Agricultural Engineers, Saint Joseph, Michigan

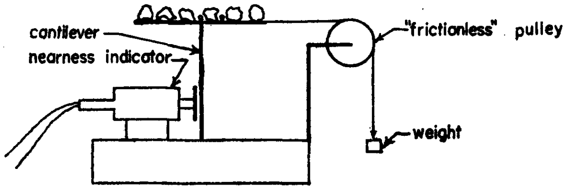

Fig. 1a Drag tray being calibrated

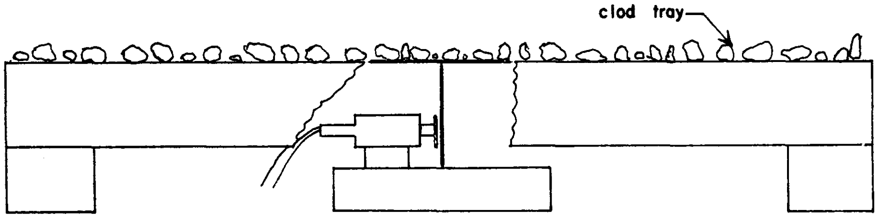

Fig. 1b Drag tray measuring wind drag

on the tray so that the surface resembled surfaces used for the soil-loss measurements (Fig. 1b). When the clods were exposed to wind, the proximity probe output was displayed on a millivolt recorder. From the chart records, the drag forces exerted by the wind on the clods were determined.

Time-lapse, closeup motion pictures were taken of individual soil clods exposed to simulated rain with and without wind to observe the soil-detachment processes.

Results

Table 1 compares the calculated shear stress with the measured shear stress.

The exposure conditions and average soil-loss measurements are summarized in Table 2.

The significance of wind shear stress as an independent variable affecting soil loss was determined by analysis of covariance. An F value of 13.49 (significant at the 99 percent level) was found to test the hypothesis that changes in windspeed did not change soil loss.

To derive a prediction equation for soil loss, a stepwise multiple curvilinear regression analysis was made, using the following variables:

Y = soil loss, g per 1,000 g

X_1 = rainfall kinetic energy, cm-Newtons per hr $\times 10^3$

X_2 = wind shear stress, dynes per sq cm

Table 3 summarizes the standard partial regression and multiple correlations for the various combinations of independent variables.

It can be seen from the standard partial regressions that an equation with only two variables, X_1^2 and X_2, can be used to predict soil loss almost as accurately as one using all four variables. The resulting prediction equation is:

Soil loss = 2.77 (rainfall energy)^2 + 33.60 (wind shear) — 61.48

Discussion

The estimated wind shear stress agreed quite well with the measured shear stress (Table 1). The measured values for shear stress were used in the regression analysis.

Kinetic energy per unit of rainfall intensity is a measure of the drop-size distribution. As the percentage of larger drops increases, the kinetic energy per unit rainfall increases. Although kinetic energy is a useful erosion index, drop size and velocity should be of similar magnitude for storms that are to be compared (8). The variability in kinetic energy per unit of rainfall among the exposure conditions used in the present study (Table 2, column 4) was small enough to be accounted for by the rainfall kinetic energy parameter.

The analysis of covariance showed that wind shear stress was a significant variable after the effects of rainfall energy were accounted for. Because rainfall kinetic energy is determined by drop size and drop velocity, the changes in drop size and velocity caused by wind were accounted for in the kinetic energy variable. Therefore, we concluded that wind accompanying the rain increases the soil removal from clods by means other than changing drop size or velocity.

The actions of raindrops in the water-erosion process described by Ellison and Bennett were found to apply to clods being exposed to rain; although some soil was splashed from the clod surface, drop impact contributed more to the detachment process by mixing the soil with the free water on the surface of the clod so that the surface soil was in a liquid state and would flow from the clod.

The flow of water and soil from the clod surface depends on the balance of forces. As long as the forces that attract the surface soil-water mixture to the clod are greater than the external forces on the surface, no soil will flow from the clod. But when the moisture content of the surface soil becomes great enough to reverse this relationship, the soil-water mixture flows from the clod. Thus, when clods are exposed to rain, gravity and the impact of the raindrops cause the surface soil to flow. If the rain is accompanied by wind, the drag forces of the wind on the clod surface add to the forces of gravity and drop impact, causing soil flow at a lower moisture

TABLE 1. COMPARISON OF CALCULATED SHEAR STRESS AND MEASURED SHEAR STRESS

Free-stream velocity, cm per sec	Friction velocity, cm per sec	Calculated shear stress, dynes per sq cm	Measured shear stress, dynes per sq cm
447	39	1.44	1.28
671	49	3.18	3.14
894	62	5.62	5.32

TABLE 2. SUMMARY OF EXPOSURE CONDITIONS AND SOIL LOSS MEASUREMENTS

Windspeed, cm per sec	Wind shear stress, dynes per sq cm	Rain intensity, cm per hr	Kinetic energy per unit rainfall, cm-Newtons per sq m-cm	Rainfall kinetic energy, cm-Newtons pr hr x 10^3	Soil loss, g per 1,000 g
0	0	1.93	20.43	1.511	36
0	0	3.56	23.27	3.170	82
0	0	6.07	23.01	5.348	221
447	1.28	2.21	20.50	1.736	33
447	1.28	3.51	23.12	3.104	163
447	1.28	3.94	28.31	4.268	306
671	3.14	1.78	25.43	1.732	53
671	3.14	2.95	27.70	3.126	184
671	3.14	4.04	33.35	5.157	533
894	5.32	2.03	29.26	2.278	88
894	5.32	4.70	24.45	4.397	424
894	5.32	3.89	30.77	4.578	472

TABLE 3. SUMMARY OF STEPWISE MULTIPLE CURVILINEAR REGRESSION ANALYSIS

Independent variables used	Standard partial regressions b_{X_1}'	b_{X_2}'	$b_{(X_1)^2}'$	$b_{(X_2)^2}'$	Multiple correlation R
X_1, X_2, X_1^2, X_2^2	0.3703	0.8322	0.4417	-0.4703	0.9324
X_2, X_1^2, X_2^2		0.8585	0.8062	-0.4829	0.9308
X_2, X_1^2		0.3956	0.7901		0.9216
X_2		0.4822			0.4822
X_1^2			0.8334		0.8334

content and increasing the total soil removal.

Figs. 2 and 3 show the flow of water and soil from clods exposed to rain and to wind and rain, respectively. Fig. 2 shows a buildup of the liquid before it flows from the clod surface. In Fig. 3 the wind drag causes the liquid to accumulate on the lower downwind side and be removed at a much lower water content than in Fig. 2. With wind it takes less water to start soil removal than with no wind.

The prediction equation used in this study shows the importance of wind shear stress as an independent variable, and the standard partial regressions indicate the relative importance of each independent variable. We concluded that wind shear stress was above half as important as rainfall kinetic energy in predicting soil loss.

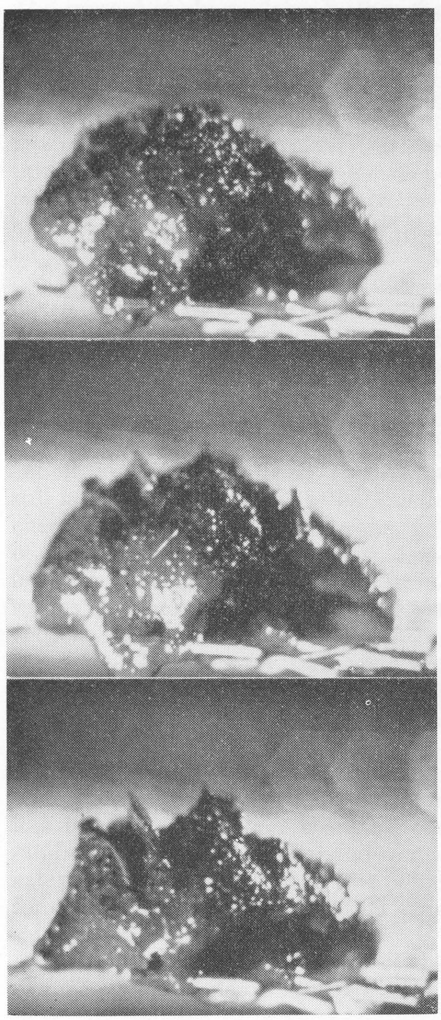

Fig. 2 Successive pictures from time-lapse motion picture of a soil clod exposed to 7.9 cm per hr of rain without wind: top (a) 15 min after rain started, liquid is beginning to accumulate on the bottom of clod; center (b) 25 min after rain started, more liquid has accumulated on the bottom of clod; bottom (c) 35 min after rain started, the liquid accumulation has detached from the clod

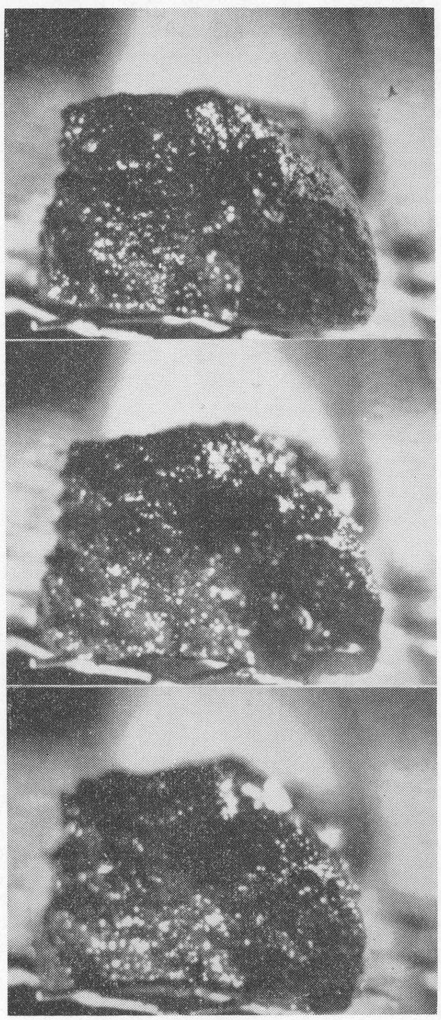

Fig. 3 Successive pictures from time-lapse motion picture of a soil clod exposed to a 5.8 cm per hr rain with 894-cm per sec wind. Wind is from left to right: top (a) 10 min after rain started, free liquid has not accumulated on the downwind side due to drop angle of impact; center (b) 20 min after rain started, some liquid has accumulated on the lower downwind side; bottom (c) 30 min after rain started, some of the liquid accumulation has been detached from the clod

Conclusion

When soil clods were exposed to simulated wind-rainstorms, the increase in soil detachment corresponding to increases in windspeed could not be attributed totally to changes in drop size or rainfall velocity. The wind shear stress was about half as effective as rainfall kinetic energy in causing soil detachment. We concluded that wind drag on the saturated surfaces of the clods increased the flow of water and soil from the clods. Therefore, wind forces on the soil surface must be considered when estimating the soil-erosion potential of a wind-rainstorm.

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