Splash of a Waterdrop at Terminal Velocity

Abstract. *High-speed movies of splash formation caused by waterdrop impact at terminal velocity in thin water layers show that splash size increases with drop size. For increasing water depth, splash size increases to a maximum at a depth of one-third drop diameter; splash then decreases to a constant size for depths greater than three drop diameters.*

Much of the previous research on waterdrop impact has been done either with high impact velocities related to aircraft surface erosion or with low velocities produced by a short fall in conventional laboratories. All raindrops impact on the land surface at terminal velocity plus or minus some velocity increment because of wind and air turbulence. If a crop canopy covers all or part of the land, many of the raindrops are intercepted, and the rainwater falls on the soil at greatly reduced velocities. In terms of soil erosion potential, only waterdrops impacting at near-terminal velocity have much importance in soil detachment.

The research reported here is part of a larger project (*1*) conducted to further the understanding of raindrop splash erosion of soil. The work was done in a 12.2-m high drop tower built especially to study splash of raindrops impacting at terminal velocity.

A large waterdrop (diameter >2 or 3 mm) becomes measurably flattened on the bottom during its fall, and its fall path is somewhat comparable to that of a piece of flat paper (*2*). Thus, terminal velocity for such a falling body may not be constant. In this study, the average velocity of waterdrops after a free fall of 9.75 m will be called terminal velocity.

Drops of deionized water were formed from tubing tips with an outside diameter suitable to the formation of waterdrops with diameters of 2.9, 3.5, 4.2, 4.8, and 5.6 mm. The splash shapes caused by these drops falling into water depths of 0.1 to 90 mm were photographed at approximately 4000 frames per second. Surfaces of various roughness and softness were used. However, the only results to be discussed here are those obtained when a smooth and hard surface (plate glass) was used.

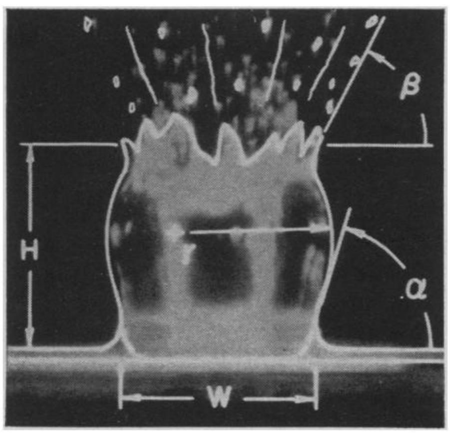

Fig. 1. Splash parameters for describing the geometry of splash shapes.

To study and analyze splash shapes, a set of parameters was developed (see Fig. 1), which are explained in detail elsewhere (*3*). The photograph in Fig. 1 was outlined to show a cross section of the splash shape. The splash parameters are suitable to describe shape changes and splash droplet travel with time. However, to compare effects of the splash variables of waterdrop diameter and water depth, a characteristic splash shape was defined when splash height was maximum. This definition made the parameters single-valued for any combination of splash variables. Splash parameters for the characteristic shape are designated by adding an *m* to the parameter designation (for instance, *Hm*).

Water depth has a major effect on splash shape and magnitude; in general, increased drop size increased splash dimensions. These effects on the parameters of the characteristic splash shape are shown in the dimensionless graphs of Fig. 2. The independent variable is water depth (*d*) divided by waterdrop diameter (*D*). The characteristic time variable (*Tm*) is included in a dimensionless group with waterdrop diameter and kinematic viscosity of water (ν). The characteristic shape parameters of height (*Hm*), crater width (*Wm*), and sheet curvature (*Rm*) are given with respect to waterdrop diameter. Characteristic sheet angle (αm) and splash angle (βm) are dimensionless by themselves.

The curves show that splash size increases to a maximum and then decreases to a constant with increasing water depth. The time required to attain the characteristic splash shape at maximum splash height also follows this trend. The sheet and splash angles increase from low values to maxima with depth. Splashes on thin water layers are straight-sided. Only those on greater depths acquire a curved-sheet shape.

The data in Fig. 2 are described by the following dimensionless equations:

$$Tm/\nu D^2 = 5.3 + 26.4 \exp(-4.8\, d/D) - 31.7 \exp(-6.6\, d/D) \quad (1)$$

$$Hm/D = 3.8 + 4.5 \exp(-2.2\, d/D) - 8.3 \exp(-12.0\, d/D) \quad (2)$$

$$Wm/D = 5.0 + 3.7 \exp(-1.3\, d/D) - 4.5 \exp(-5.9\, d/D) \quad (3)$$

$$\alpha m = 98 - 48 \exp(-4.75\, d/D) \quad (4)$$

$$\beta m = 80 - 34 \exp(-6.3\, d/D) \quad (5)$$

$$Rm/D = 2.8 + 30 \exp(-8.3\, d/D) \quad (6)$$

A splash shape is not formed by waterdrop impact on a smooth, hard surface that is dry and horizontal; the waterdrop merely spreads horizontally without forming splash droplets. For this reason, the value of *Hm* is zero for a zero water depth. However, the zero intercept for the other parameters could not be measured. Both time (*T*) and crater width (*W*) existed during the zero depth impact, but a characteristic

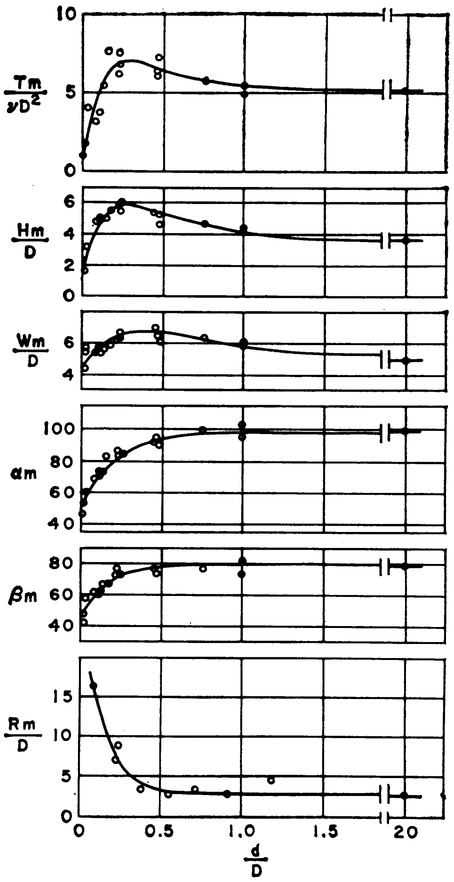

Fig. 2. Variation of characteristic splash shape parameters for various depths of surface water over smooth glass.

shape could not be determined with a zero splash height (H).

The other shape parameters, α, β, and R, did not exist for zero water depth. Because of the inability to measure the shape parameters at zero depth, Eqs. 1 through 6 can be used only for $d/D \geqslant 0.02$, which is the lower limit of the experimental independent variable.

Asymptotes for the above equations were estimated from measurements of splashes in deep water, $d = 9$ cm, by reasoning that the effects of depth on splash shape would be negligible for depths greater than the asymptotic value. Values of d/D corresponding to 99 percent of the asymptotic value of the dependent variable for Eqs. 1 through 6 are 1.3, 2.2, 3.3, 0.8, 0.6, and 0.8. Thus, depth likely has a negligible effect on splash for depths greater than three waterdrop diameters.

The parameters describing splash-shape size and time reach maxima at water depths of 0.28 D, 0.24 D, and 0.37 D for Eqs. 1, 2, and 3, respectively. Thus it can be inferred that water depth has its greatest effect on raindrop splash at depths of about one-third drop diameter.

If water depths greater than three waterdrop diameters have little effect on splash shapes, then it may be assumed that waterdrop impact has little effect on the underlying soil surface covered by such water depths. This depth is 8.7 mm for the smallest waterdrop diameter used and is not likely to occur over a significant portion of an agricultural field. However, rainfall may consist of drops much smaller than 2.9 mm. Laws and Parsons (*4*) give

$$D_{50} = 2.23\, I^{0.182} \qquad (7)$$

where I is rainfall intensity in inches per hour and where D_{50} is defined as the median raindrop diameter. The volume of drops larger than the median is 50 percent of the total volume. For a rainfall of 2 inches (5.08 cm) per hour (which is a highly erosive rainfall intensity), $D_{50} = 2.5$ mm. Most of the raindrops are smaller than the median diameters. Therefore, if Eqs. 1 through 6 may be assumed valid for drop diameters somewhat smaller than the range of waterdrops used, the required thickness of a protective water layer becomes small enough so that it could feasibly form over substantial portions of a field. This reasoning is supported by the observed effectiveness of only a small amount of mulch in reducing erosion on bare soil. Although mulch undoubtedly impedes sediment transport in runoff, it also increases the depth of surface water storage during a rainstorm. Thus, any method of maintaining a thin water layer may greatly reduce soil detachment due to raindrop impact and, hence, may reduce soil erosion.

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References and Notes

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5. This research was performed in cooperation with the Minnesota Agricultural Experiment Station, St. Paul, and is designated as Paper 7251, Scientific Journal Series.

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Insulin Levels in Primates by Immunoassay

Abstract. *Only trace amounts of insulin were detected by an immunoassay system with guinea pig antibody to pork insulin in the New World primates* Cebus *and* Saimiri. *The system found insulin levels in the Old World primates rhesus and chimpanzee which were quite like those of human beings. The findings suggest important structural differences in the insulins of the two primate divisions.*

Insulin could not be detected in the plasma of two species of New World primates either before or after administration of glucose when an immunoassay system that detects the expected amount of insulin in Old World primates and human beings was used. In this immunoassay system, insulin from subprimate species is used for the production of antibodies to insulin in another species (*1*). This is usually done in a small laboratory rodent with bovine or porcine insulin. The reference standard also is typically beef or pork insulin. Since in the assay the sample and added isotopically labeled insulin compete for the antibody to insulin, the antibody must not distinguish between insulin of different species if the measurements are to be valid. The usual procedure is to use the available porcine insulin as the working standard after comparing its recovery by the system with the primary standard, human insulin. This use of nonhuman materials for assaying insulin in human plasma is possible because of the cross-reaction of many mammalian antigen systems. The structures of human, beef, and pork insulin differ in only a few amino acids (*2*). These insulins, as well as those of horse, whale, dog, cat, rabbit, hamster, and man have all been shown to be neutralized by guinea pig antibodies to beef insulin (*3*). However there are insulins derived from other species which do not react with this antibody; for example the insulin from guinea pig, coypu, and capybara are not bound by antibody to beef insulin (*4*).

In the assay method of Hales and Randle (*5*) the complex of insulin and antibody is precipitated (for counting) by still another antibody, which is made to react with gamma globulin of the species in which the antibody to insulin was produced. In some other methods, including the one used here, the insulin–antibody complex is separated by ethanol precipitation.

During studies of the long-term effects of diets on glucose tolerance in *Cebus* and in rhesus monkeys, intravenous glucose tolerance tests were done. When plasma insulin was measured during these tests, only negligible amounts could be found in the *Cebus* monkeys although the insulin content of the plasma of rhesus monkeys was quite like that of human subjects. Since the glucose tolerances were not abnormal in the *Cebus* monkeys, it was assumed that the assay was not detecting insulin in this species. Investigation of additional species suggested that Old World primates have humanlike responses of insulin level while the New World primates have no measurable response of plasma insulin to glucose. There appear to be important immunological differences in the insulins which account for these findings.

The *Cebus* monkeys were jungle-born *Cebus apella* that had been fed purified diets for 8 to 10 years for studies of sterol metabolism and atherogenesis (*6*). These diets were formulated to contain marginal amounts of the essential, sulfur-containing amino acids, and supplementary cholesterol was added. The ani-