

The Mechanism of Raindrop Splash on Soil Surfaces¹

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ABSTRACT

From the results of high-speed photography of 4.6-mm-diam drops impacting various soil materials and from soil mechanics principles, a new concept in describing the mechanism of soil detachment from raindrops impacting on saturated soil surfaces is proposed. The impulsive loading caused by the impacting drop does not permit time for drainage; thus there is no change in total soil volume or bulk density. The soil surface is deformed under the impulsive load application of the drop; however, the vertical strain under the impact area is compensated by a bulge around the perimeter of the depression. The vertical force of the drop is transformed to lateral shear caused by radial flow of the impacting drop. Splash angle is determined by the depth of the cavity and the size of the bulge surrounding it.

Splash angle was highly correlated with soil shear strength as measured by the fall-cone method. Low soil strength resulted in (i) a larger cavity and surrounding bulge, (ii) a greater detachment of soil particles due to the shear stress of the radial flow, and (iii) a greater splash angle with the horizon.

Additional Index Words: mechanics of erosion, soil erosion, soil shear strength, soil splash, splash angle.

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MIHARA (1952) was among the first to describe the mechanism of soil detachment due to the impact of a single raindrop. Mihara, using a high-speed camera to photograph splash in sand, found that at early stages of impact a drop simultaneously penetrates the sand surface and outspreads. The depth of penetration depended on the sand surface conditions, especially the water content. Since Mihara's studies, little has been done to describe the mechanism and forces involved in the detachment process of soil materials. Studies of splash shapes and pressure distributions applied by an impacting drop on sand, water, or rigid surfaces, however, have been reported (Mutchler, 1967; Harlow and Shannon, 1967; DePloy and Savat, 1968; Heymann, 1969; Rochester and Brunton, 1974; Ghadiri and Payne, 1980; Huang et al., 1982).

High-speed photography has been used to measure

splash angles from drops impacting on rigid, water, sand, and soil-paste surfaces. Increasing the water depth from 0.01 to about 0.5 cm over sand surfaces increased the splash angle from 35 to about 85 degrees (Mihara, 1952), and over smooth glass, from about 50 to 90 degrees (Mutchler, 1967). Splash angles were found to increase throughout splash development (Mutchler, 1967). The splash angle of a drop impacting on a hard clean surface was about 11 degrees (Rochester and Brunton, 1974), whereas the splash angle on a soil-paste surface was about 49 degrees (Ghadiri and Payne, 1980).

Results from high-speed photography also indicated that splash duration from a drop impacting onto a saturated soil-paste surface was about 7 ms. For a sand surface at -2 kPa matric potential, splash lasted <3 ms but increased to >100 ms with 0.5-cm depth of water on the surface, and to >200 ms for a deep water pool (Ghadiri and Payne, 1980). Duration of splash was found to differ for various sand particle sizes (Mihara, 1952).

The depth, diameter, and volume of cavities caused by raindrop impact on sand surfaces were measured by Mihara (1952). The bottom surface of the cavity was found to be convex rather than flat. The cavity depth decreased with increasing sand compaction and decreasing velocity of impacting drop. The cavity diameter was slightly larger than the diameter of the drop and increased as the velocity of the drop increased.

Soil mechanics concepts have seldom been applied to soil detachment studies, with the exception of the studies by Cruse and Larson (1977) and Al-Durrah and Bradford (1982) in which models were tested that correlated the dry weight of soil material splashed from the soil surface (splash weight) to soil shear strength. Al-Durrah and Bradford (1982) showed high coefficients of determination ($r^2 = 0.88$ to 0.97) between splash weight and the ratio of raindrop kinetic energy and soil shear strength for nine soils. A maximum coefficient of determination of only 0.61 was found when soil properties other than shear strength [particle-size fractions, organic matter, cation exchange capacity (CEC), surface area, bulk density, matric potential, pH, total soluble salts, and exchangeable Na, K, Ca, and Mg] were used as independent variables to predict soil splash.

In this study we used high-speed photography to photograph splash from raindrops impacting various soil materials having variable water potential, bulk

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Table 1—General soil characteristics.

Series	Subgroup	Sand content,	Clay content,	Organic matter
		2.0–0.05 mm	<0.002 mm	
		%		
Avonburg	Aeric Fragiaqualfs	30.5	11.2	1.0
Menfro	Typic Hapludolls	4.5	14.0	2.7
Ida	Typic Udorthents	3.6	22.0	3.3
Marshall	Typic Hapludolls	2.7	29.3	3.7
Tama	Typic Argiudolls	3.8	30.8	4.6
Monona	Typic Hapludolls	4.0	31.2	3.8

density, and shear strength values. From the results of high-speed photography and from soil mechanics principles, we propose a mechanism of splash due to raindrops impacting onto saturated soil surfaces.

MATERIALS AND METHODS

Six soil materials were used in this study. General descriptions are found in Table 1; more detailed characteristics are given in Al-Durrah and Bradford (1982). Each soil was air-dried, ground to a maximum particle diameter of 2 mm, sieved through a 1-mm screen, and moistened by spraying water and mixing. The water content for different soils ranged from 15 to 18%. Each moist soil was then compressed into 5.7-cm-long and 7.6-cm-i.d. acrylic cylinders. The compression bulk densities ranged from 1,000 to 1,500 kg/m³. The soil samples were placed on glass bead tension tables and allowed to become saturated before matric potentials, ranging from -0.5 to -6.5 kPa, were applied. The soil shear strength was varied by changing the soil bulk density and the matric potential.

The shear strength of the upper 0.5 to 1.5 cm of the soil surface was determined with a Geonor model³ g-200 labo-

³ Trade names and company names, included for the benefit of the reader, do not imply endorsement or preferential treatment of the product listed by the USDA.

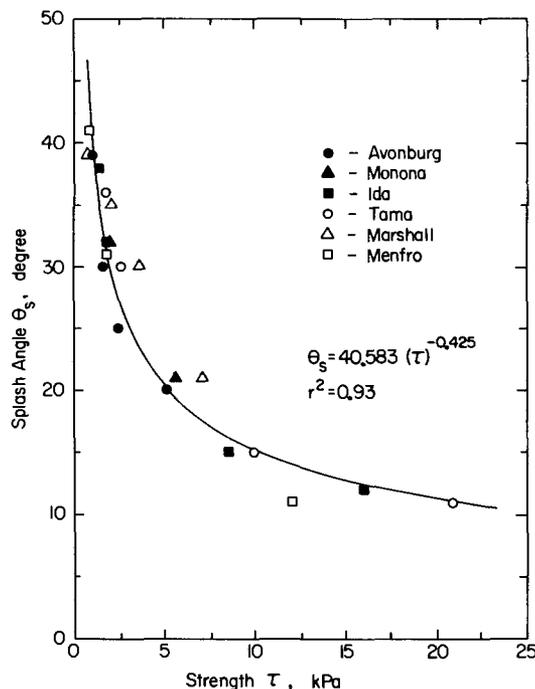


Fig. 1—The relationship between splash angle and soil shear strength.

ratory cone penetration apparatus. Theory and procedural details can be found in Hansbo (1957) and Al-Durrah and Bradford (1981).

The raindrop tower described by Al-Durrah and Bradford (1981) was used in this study to produce 4.6-mm-diam drops falling 890 cm onto the different soil surfaces. The soil splash collector was removed and a high-speed camera was placed at a horizontal distance of about 40 cm from the target area. The camera, a 16-mm Hycam³ model 40, was operated

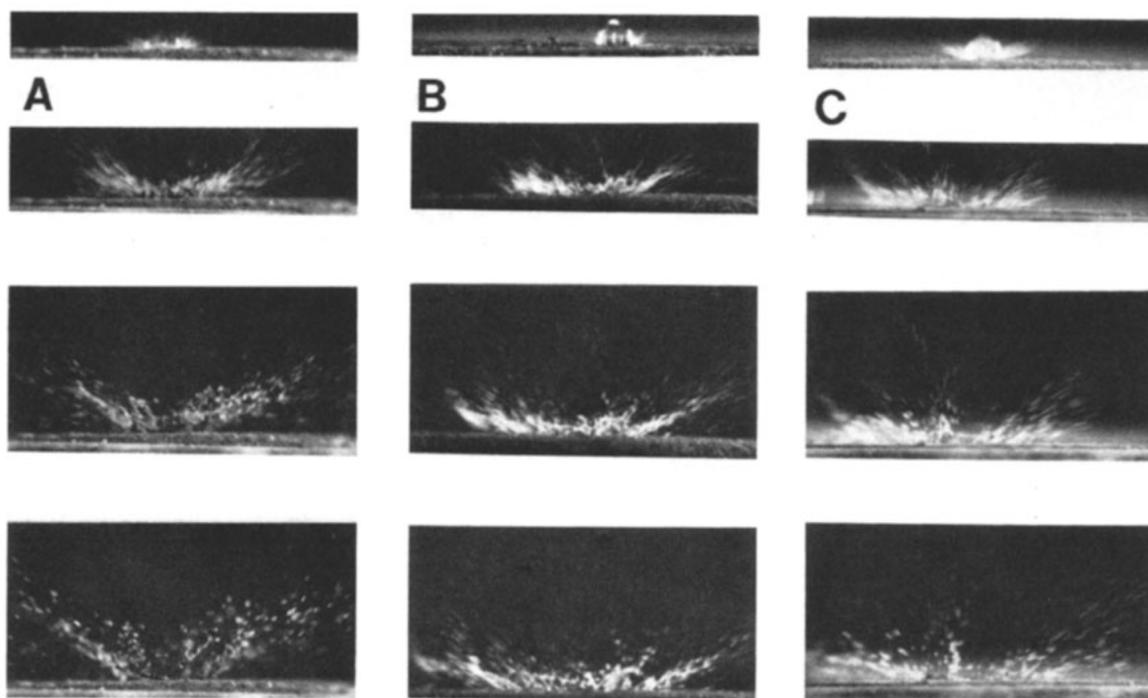


Fig. 2—A series of photographs of splash from Tama silty clay loam at three shear strength levels: (A) $\tau = 2.6$ kPa; (B) $\tau = 7.1$ kPa; and (C) $\tau = 20.9$ kPa.

at 2,000 frames/s. The target area was illuminated by six 1,000-W quartz spotlights.

Reversal film, 16 mm, 30.5 m, Kodak³ Tri-X, was used in the high-speed photography. After the film was devel-

oped, negatives and 12.5- by 17.5-cm prints were made from the frames that contained the splash action. Splash angles were measured on the prints using a protractor with an approximate accuracy of 2 degrees. Splash angles were re-measured on three soils at three randomly selected strength levels with a protractor on a projection of the original film on a 40- by 40-cm flat screen. No significant differences were found between the two methods of measuring splash angles. Splash angles, however, were found to increase with time after impact up to a certain value. In this study, the maximum angle between the horizontal soil surface and the lower line of splash was reported as the splash angle. For each specific soil condition, the reported angle is an average of three determinations on duplicate soil samples.

RESULTS AND DISCUSSION

Splash angles were highly correlated ($r^2 = 0.93$) with the soil shear strength as measured by the fall-cone method (Fig. 1). Splash angles ranged from about 11 degrees at a shear strength of 20 kPa to about 40 degrees at a shear strength of 1 kPa. The relationship between splash angle and shear strength was independent of the type of soil material used in this study. The clay percentage of the soil materials ranged from 11.2 to 31.2%, organic matter from 1.0 to 4.6%, CEC from 9.1 to 28.7 meq/100 g, and surface area from 40 to 110 m²/g (Al-Durrah and Bradford, 1982).

Selected pictures of splash from Tama silty clay loam at three shear strength levels are shown in Fig. 2. These pictures indicate that splash shape is influenced by soil surface shear strength. Analyzing these pictures and others from different soils, we found that, in addition to the splash angle, two other splash characteristics varied with soil shear strength. These were the velocity of the detached soil particles during a splash event and the size of the cavity (width and depth). Due to limitations in measuring equipment, the splash speed and dimensions of the cavity were observed only qualitatively. In general, splash speed was found to increase as the shear strength increased. In high-strength soils, the cavities were larger in diameter but much shallower in depth, resulting in smaller-volume cavities than with low-strength soils.

Figure 3 is a schematic diagram representing the mechanisms involved in soil detachment for both high-strength and low-strength cases. At the instant of impact, the pressure and shear stress distribution are symmetrical about the center of impact (Rochester and Brunton, 1974). According to the pressure distribution calculations of Huang et al. (1982), the peak pressure occurs at the circumference of the contact surface and diminishes in about 6 to 10 μ s. For high rates of load application on saturated soils, such as a force applied by an impacting drop, there will not be enough time for water drainage to take place; therefore, the soil bulk density or void ratio will remain constant (Holtz and Kovacs, 1981; Fig. 10.9c). In soils engineering, this type failure is termed "undrained." The undrained strength is defined as the state of stress at failure of a soil where drainage of pore fluid into or from the soil is not permitted during compression or shear. Under the extremely high rate of a waterdrop impact, the assumption of no drainage and no volume change seems valid since the external loads change at a rate much faster than the rate at which the pore pressures can dissipate. Under such conditions, the

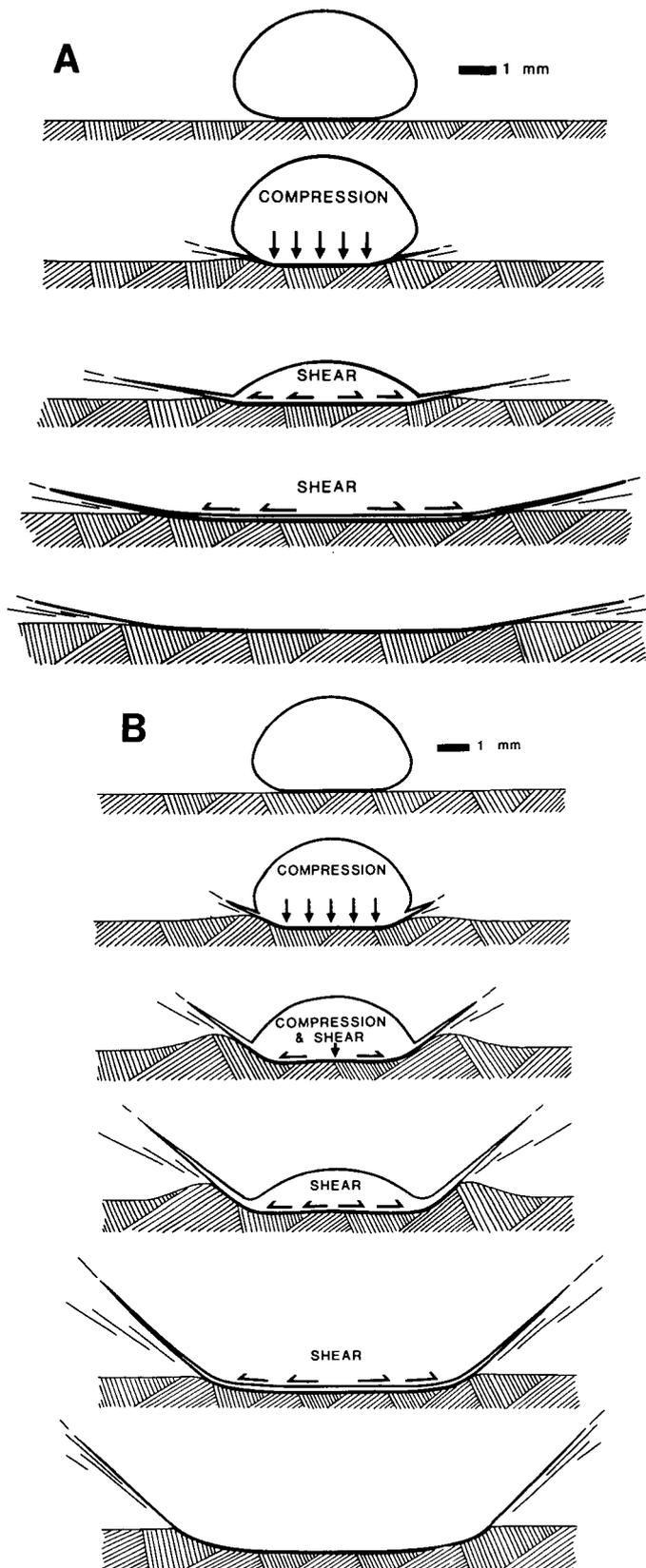


Fig. 3—Schematic diagram of the splash mechanism at (A) high- and (B) low-strength levels.

soil under the impact area will be strained vertically. This change in shape will be compensated by the development of a bulge around the perimeter of the depression (Fig. 3) such that the total soil volume remains constant. The magnitude of vertical strain is determined by the magnitude of load, the area of application, and soil deformation characteristics. The first two are determined by the raindrop size and velocity at the instant of impact. The latter is influenced by soil properties such as structure, shear strength, and stress history. Normally, as the soil shear strength increases, the soil becomes more resistant to change in shape under an applied force. Therefore, the depth and total volume of the cavity (and consequently the size of the surrounding bulge since the total soil volume is constant) is smaller for higher-strength surfaces.

The compressive stresses are then transformed to shear stresses, across the solid-liquid contact region due to the lateral jetting water. The radial flow velocity is greater than the drop impact velocity (Harlow and Shannon, 1967; Huang et al., 1982). At this stage, soil particle detachment is caused by the shear stresses of the radial flow acting on the bottom and sides of the cavity and on the circular bulge. The amount of soil detachment from the cavity sides will be determined by the magnitude of soil deformation that took place in the earlier stages of cavity development and by the cohesive forces resisting the shear stresses. By counting the number of film frames, the velocity of splash was found to be greater when the soil shear strength was higher. Thus, the shear stress of the lateral flow as a detaching force is greater when the soil surface shear strength is higher. However, since the soil resistance is much greater in high-strength soils, the sum of the soil detached by the two mechanisms combined (the interception of lateral flow by the cavity sides and the bulge, and the shear stress of the lateral flow) is always greater in the low-strength soil (Al-Durrah and Bradford, 1982).

A consequence of this concept for describing the mechanisms of soil detachment is that raindrops do not compact or densify the soil surface by the compressive forces of the drop. The formation of dense surface crusts is a result of the breakdown of soil aggregates and the packing of the splashed soil particles. The observations of Moldenhauer and Koswara (1968) support this process.

Figure 3 also represents the effect of the magnitude of soil deformation by raindrop impact on splash angle. The greater the depth of cavity and size of bulge, the larger is the splash angle as a result of the greater interception of lateral flow.

The relationship between splash angle and splash weight for the six soils was determined from the relationship between splash angle (θ_s) in degrees and shear strength (τ) in kilopascals in Fig. 1:

$$\theta_s = 40.5 \tau^{-0.425}, \quad [1]$$

and the relationship between splash weight (S) in mg/drop and the ratio of raindrop kinetic energy (KE) in joules to shear strength (Al-Durrah and Bradford, 1982):

$$S = a + b (KE/\tau). \quad [2]$$

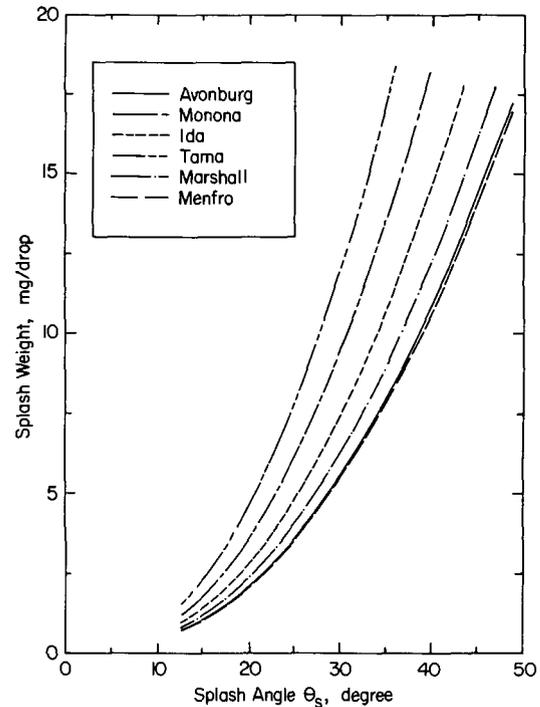


Fig. 4—The relationship between splash weight and splash angle.

In Eq. [2], a is a constant theoretically equal to zero, since splash weight must be zero when either KE is zero or τ is very large; b is a soil constant that represents the slope of the regression line that was forced through the origin; and $KE = 20.82 \times 10^{-4}$ J for a 4.6-mm-diam drop impacting at a velocity of 9.0 m/s. The results of these calculations for six soils were plotted in Fig. 4. Splash weight was not a unique function of splash angle for all soils. The differences among soils are due mainly to differences in strength-related soil properties. Both splash weight and splash angle are affected by frictional and cohesive forces between soil particles and by soil deformability, but each of these properties contributes differently in the determination of splash weight and angle. Soil deformability has a direct influence on splash angle but only an indirect influence on splash weight. Cohesive forces between soil particles, on the other hand, have the greatest effect on the determination of splash weight, since detachment is primarily caused by flowing water that shears the soil particles at the bottom and sides of the cavity.

SUMMARY AND CONCLUSIONS

The results of this study add to our understanding of the mechanics of raindrop splash. A unique relationship between splash angle and soil strength as measured by the fall-cone device existed for six mid-western U.S. soils; however, splash weight was not a unique function of splash angle for all soils. The explanation for this phenomenon is that under the impact of a high velocity, single waterdrop soil fails under an undrained condition. The volume of soil in the cavity created by the compression forces (only) of the waterdrop is offset by an equal volume of soil

in the bulge developed around the perimeter of the depression. The greater the depth of waterdrop penetration (or compression), the larger the bulge volume. As the bulge volume increases, the splash angle increases. Thus a unique relationship was experimentally found between splash angle and strength. We assume that splash angle is a function of depth of raindrop compression and bulge volume, and strength is a function of cone penetration. Splash weight is related not only to the process of soil compression by waterdrop impact but also to the process of detachment due to lateral water flow across the cavity boundary. Since a unique relationship between splash weight and splash angle was not found, we can conclude that the total soil shearing resistance estimated by the fall-cone device and the actual resistance of the soil to the jetting water are probably not equal. The process of detachment by lateral jetting water must be examined in close detail.

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