Reprinted from the *Soil Science Society of America Journal*
Volume 49, no. 3, May–June 1985
677 South Segoe Rd., Madison, WI 53711 USA

Single Waterdrop Splash Detachment and Mechanical Properties of Soils

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ABSTRACT

This study was an assessment of the use of soil mechanical properties to predict soil detachment by single waterdrop impact. Soil mechanical properties were measured on four soils with a triaxial consolidated-undrained compression test and a Swedish fall-cone device. The weight of soil detached was measured for 5.7-mm diameter drops falling a distance of 13 m. The results indicated that strength and pre-failure deformational properties, as measured by the triaxial test alone, were not good predictors of soil resistance to splash. As previously reported, soil splash weight was a linear function of the ratio of waterdrop kinetic energy to fall-cone strength on a per soil basis, but the slope of the line differed among soils. The slopes were, however, greater for soils with greater consolidated, undrained friction angles as determined in the triaxial test and expressed in terms of total stresses. Therefore, the fall-cone strength term was reduced as a function of the triaxial friction angle, and detachment was plotted versus the ratio of raindrop kinetic energy to the corrected fall-cone strength term. The resultant relationship was linear with the same slope for all four soils. This result was explained in terms of our current understanding of the soil splash mechanism. The fall-cone alone predicts the initial splash phase of cavity formation upon impact, but overpredicts the resistance of the soil to subsequent lateral jetting of water.

Additional Index Words: **erosion mechanics, shear strength, soil deformation, soil erodibility, soil erosion, triaxial test.**

Nearing, M.A. and J.M. Bradford. 1985. Single waterdrop splash detachment and mechanical properties of soils. Soil Sci. Soc. Am. J. 49:547–552.

RECENT STUDIES have advanced our understanding of the soil splash process, but no method has yet been proposed to accurately predict the resistance of soils to raindrop splash detachment. Early attempts to predict splash based on soil particle size and soil chemical properties were not universally successful. Recently, the importance of soil mechanical properties to splash resistance has been recognized. Cruse and Larson (1977) related splash resistance to shear strength of a soil as measured by the unconfined compression test. Al-Durrah and Bradford (1981) developed a force-resistance model for waterdrop impact detachment based on soil shear strength measured with a Swedish fall-cone. They found a linear function between splash weight and the ratio of raindrop kinetic energy to the undrained shear strength for an Ida silt loam. Subsequent application of the model to nine soils from Iowa, Missouri, and Indiana showed that the fall-cone shear strength correlated well with the detachment for a specific soil, but that the linear relationship was not constant for the different soils (Al-Durrah and Bradford, 1982a).

One possible reason for the failure of the Al-Durrah and Bradford relationship to hold for all soils is that the relationship considered only strength properties of soils and not soil deformational properties. Huang et al. (1982), using a numerical technique to study the impact of a raindrop on a rigid surface, proposed three critical factors to define resistance to detachment by raindrop impact: (i) soil deformational characteristics, (ii) soil shearing strength, and (iii) surface microrelief. In a subsequent study, Huang et al. (1983) used a numerical technique to evaluate the effect of the elastic modulus on the soil splash process. The elastic modulus is the initial slope of the stress-strain curve. They suggested that the soil material near the edge of a cavity boundary is destabilized by tensile stretching due to soil deformation upon loading. They hypothesized that materials with lower elastic moduli are subjected to greater tensile forces at the cavity boundary, weakened more by impact, and thus more susceptible to erosion by the subsequent lateral jetting of water.

The purpose of this study was to develop an improved prediction relationship of soil detachment by a single waterdrop impact from soil mechanical properties. To overcome the limitations of the Swedish fall-cone test, used in the Al-Durrah and Bradford (1982a) study, the undrained triaxial compression test was used in this study to evaluate both strength and deformational properties. Relationships between triaxial strength and deformational parameters, fall-cone measurements, and splash measurements were evaluated for their value in predicting soil splash detachment. This investigation proposes a correction factor for the fall-cone shear strength in the force-resistance model of splash detachment and examines this factor relative to the mechanism of soil detachment by single waterdrop impact.

SOIL SHEAR STRENGTH

According to Mohr theory, a material fails along a plane when a certain optimum combination of normal stress and shearing stress occurs within a stressed body. The shear strength, τ_f, along any plane is therefore a function of the normal stress, σ_n, on that plane. The Coulomb equation,

$$\tau_f = c + \sigma_n \tan \phi \qquad [1]$$

represents a special case of the Mohr theory of strength in which the Mohr failure envelope is a straight line with slope $\tan \phi$ and intercept c on a shear versus normal stress diagram. The c and ϕ terms of the Coulomb equation denote cohesion and angle of internal friction, respectively. The Mohr-Coulomb failure hypothesis suggests that Eq. [1] is represented by the line which is tangent to the Mohr's circles of stress conditions at failure on the plot of shear versus normal stress. The c and ϕ parameters are determined by a geometric relationship. First, a regression line is determined for the points of maximum shear stress on the Mohr's circles. The slope of that line is equal to $\sin \phi$. The ratio of the regression line intercept to $\cos \phi$ is the value of c (Holtz and Kovacs, 1981).

Soil strength is expressed in terms of either total or effective stresses. For saturated soils effective stress, σ', is determined by the equation:

$$\sigma' = \sigma - u, \qquad [2]$$

[1] Contribution from the USDA-ARS in cooperation with the Purdue Agric. Exp. Stn. Journal no. 9938. Received 6 July 1984. Approved 16 Nov. 1984.

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Table 1. Classification of the soils.

Location	Series	Family	Subgroup
Indiana	Alford	Fine-silty, mixed, mesic	Typic Hapludalfs
California	Auburn	Loamy, mixed, thermic	Ruptic-Lithic Xerochrepts
Iowa	Dickinson	Coarse-loamy, mixed, mesic	Typic Hapludolls
Indiana	Zipp	Fine-mixed, nonacid, mesic	Typic Haplaquepts

where u is the soil pore water pressure and σ is the total applied stress. Shear strength is, therefore, expressed as:

$$\tau = c' + \sigma' \tan \sigma' \quad [3]$$

where c' and σ' are the effective stress cohesion and friction angle parameters (Hvorslev, 1960). The effective stress may be viewed as the amount of stress which is carried by the interparticle contacts within the soil; i.e., that which is carried by the soil skeleton. The remainder of the total applied stress is carried by the soil water. If the soil is allowed to drain, then total and effective stresses are equal.

Towner (1961) used an unconfined compression test to show that soil water suction acted equivalently to an externally applied isotropic pressure in strengthening kaolinite. The negative soil water pressure acts (via Eq. [2] and [3]) to increase the effective stress and shear strength of the soil at a constant value of total stress. This concept was used in the present study to increase the strength of the soil samples for the detachment measurements.

MATERIALS AND METHODS

The Soils

Four soils were selected on the basis of their having a greatly different linear relationship for soil detachment versus inverse fall-cone strength measurement, as determined by preliminary testing of several soils. The soils also represented a relatively wide range of chemical and physical properties. The classifications of the soils are given in Table 1, chemical characteristics are given in Table 2, and soil texture is given in Table 3. Organic C was determined by a modified Walkley-Black method and organic matter content was considered to be equal to the organic C content multiplied by 1.724 (Nelson and Sommers, 1982). Cation exchange capacity (CEC) was determined by the NH_4OAc method (Thomas, 1982) and sand, silt and clay fractions by the pipette method (Day, 1965).

Determination of Soil Splash

Soil for the drop detachment determinations was air-dried, ground, and sieved through a 2-mm screen. A 5-mm thick porous disk was pushed into the bottom of a 57-mm long and 76-mm diameter acrylic ring. Another ring of the same dimensions was placed on top of the first ring, the air-dried soil was poured into the rings, and the rings were lightly tapped until the level of the soil was even with the top of the lower ring. Soil was added to provide a bulk density of 1.20 Mg m^{-3}. The soil cores were placed on glass bead tension tables, saturated for 2 d, and equilibrated for two days to matric potentials of −0.1, −1.0, −2.0, and −3.9 kPa.

The splash measurement procedure and raindrop tower were the same as described by Al-Durrah and Bradford (1981). Waterdrops 5.7 mm in diameter were dropped a distance of 13 m onto a 16-mm diameter target area on the soil core surface. The kinetic energy of the drop was calculated from the results of Laws (1941) to be 4.06×10^{-3} J. The splash collector was an acrylic cylinder with an Al annular disk on one end which was placed on the soil surface. The disk had a beveled edge around a 16-mm diameter hole which prevented the soil from flowing back onto the soil core. Soil splash was collected, dried at 105°C, and weighed

Table 2. Soil chemical characteristics.

Soil	Organic matter	pH	Soluble salts	Cation exchange capacity	Exchangeable cations			
					Na^+	K^+	Ca^{2+}	Mg^{2+}
	g/kg		S 10^{-5}	cmole/kg				
Alford	14	5.4	62	14.8	0.02	0.62	4.04	0.47
Auburn	65	6.2	11	26.6	0.03	0.88	7.73	2.21
Dickinson	42	6.2	33	19.5	0.10	0.16	5.43	2.02
Zipp	22	7.5	22	24.0	0.07	0.24	10.98	0.89

Table 3. Soil texture.

Soil	Sand content (2.0–0.05 mm)	Silt content (0.05–0.002 mm)	Clay content (< 0.002 mm)
	g kg^{-1}		
Alford	35	762	203
Auburn	332	461	207
Dickinson	444	363	193
Zipp	102	670	228

to the nearest 0.01 mg. Six independent measurements of splash were taken per core at different locations on the surface. Four replicate cores were used for each of the four soil water matric potentials.

The Fall-Cone

Immediately after collecting the splash samples, soil surface shear strength was measured using a Geonor[3] model g-200 Laboratory Cone Penetration Apparatus. To use the cone, it is placed with its apex just in contact with the soil surface, then released freely into the soil surface and the penetration depth is measured. The undrained shear strength is determined using tables presented by Hansbo (1957). The depth of penetration, h, is related to shear strength, τ, by:

$$\tau = K \cdot (Q/h^2) \quad [4]$$

where K is a factor of proportionality determined empirically by Hansbo (1957) and Q is the weight of the cone. In this experiment, three fall-cone readings were taken per soil core.

The Triaxial Test

The consolidated-undrained triaxial compression test was used to measure soil strength and deformation parameters. Air-dried soil was ground, sieved through a 2-mm sieve, and wetted using a fine spray to a water content conducive to packing and subsequent preparation for the triaxial test. Water contents of packing, w, for the soils were: Alford, w = 0.200 kg kg^{-1}; Auburn, w = 0.295 kg kg^{-1}; Dickinson, w = 0.188 kg kg^{-1}; Zipp, w = 0.227 kg kg^{-1}. The soil was then compressed within a brass cylinder to a core radius of 19.1 mm and a height of 75.8 mm and bulk density of 1.20 Mg m^{-3}. After the core was formed, it was pushed from the brass cylinder and placed into an acrylic cylinder for transfer to the triaxial cell without breakage or crumbling.

The principles behind the consolidated-undrained triaxial test are discussed by Bishop and Henkel (1962). The method outlined here is given in detail by the U. S. Army Corps of Engineers (1970). The triaxial cell and control panel for back pressure saturation were made by Geotechnical Equipment Co.[3] of Chicago. Pore water pressure was measured with a pressure transducer. The soil specimen was placed in the triaxial cell between two porous plates and sealed in an impermeable rubber membrane. The cell was filled with water. A pressure of 34.5 kPa was added to the cell chamber to

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

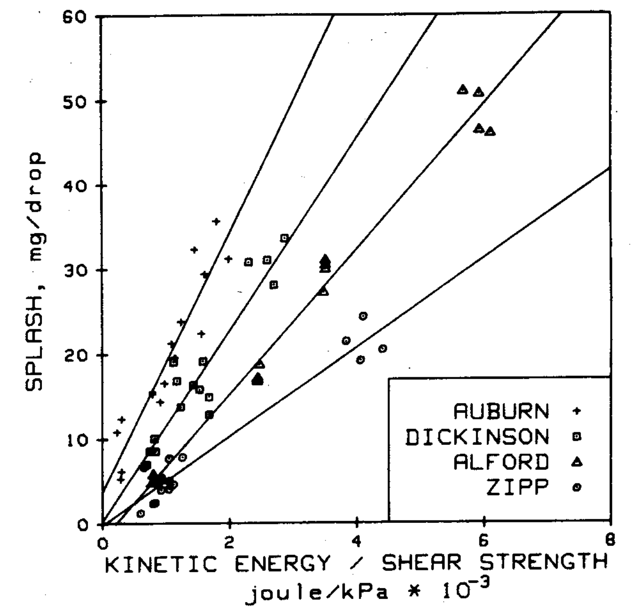

Fig. 1. Detachment vs. ratio of raindrop kinetic energy to fall-cone shear strength.

confine the specimen. Next, water was allowed to flow through the sample from the bottom under a low pressure head. Back pressure was used to achieve the high degree of soil saturation necessary for accurate measurement of pore water pressure. Back pressure refers to pressure within the sample which drives the soil air into solution (see Lowe and Johnson, 1960; Black and Lee, 1973). The pressure was increased simultaneously in the cell and sample while retaining a pressure differential of 34.5 kPa across the rubber membrane. The back pressure was raised slowly within the sample to avoid excessive pressure differentials within the specimen itself. Back pressure within the sample was raised to between 550 and 690 kPa, depending on what was necessary to achieve saturation. Complete saturation was verified by shutting off pressure lines to the sample, increasing the cell pressure, and measuring the rise in pressure inside the sample. A sample is considered saturated when the increase in pore water pressure immediately equals the increase in cell pressure.

Core samples were tested at five consolidation pressures: 50, 100, 200, 300, and 400 kPa. After saturation, the pressure in the cell was increased to provide a difference between cell and sample pressures of the desired consolidation pressure. The sample was then opened to a burette with the appropriate back pressure and allowed to drain. Consolidation continued until the level of water in the burette stabilized. Consolidation required about 10 minutes to an hour, depending on the soil and consolidation pressure. After consolidation, drainage lines to the sample were closed so that no additional volume change was allowed.

The samples were loaded axially with an Instron Universal Testing Instrument[3] at a constant rate of strain of 0.01 cm min^{-1}. Tests were run for 114 min until a strain of 15% was reached. Failure was considered to occur at the maximum axial stress observed during that time. Immediately following testing the cell was emptied of water and the sample was removed and measured for water content.

Table 4. Linear regression parameters of splash weight, D, (grams) vs. ratio of raindrop kinetic energy, KE, (joules) to soil shear strength, τ, (kPa) by fall-cone.†

Soil	Intercept (a_1)	Slope (b_1)	Coefficient of determination (r^2)
Alford	−1.76	8.53	0.98
Auburn	3.78	15.29	0.87
Dickinson	0.32	11.26	0.87
Zipp	−0.14	5.23	0.94

† Model: $D = a_1 + b_1(\mathrm{KE}/\tau)$.

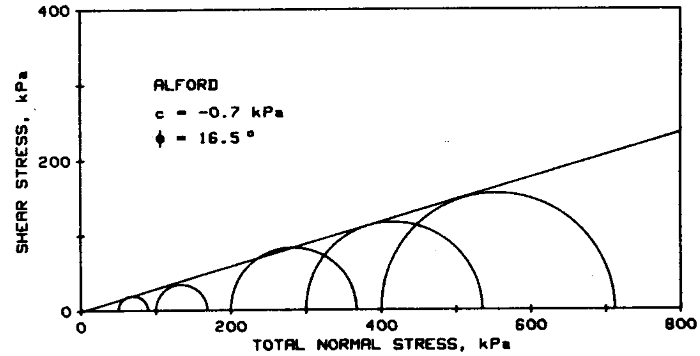

Fig. 2. Total stress strength envelope for the Alford.

RESULTS AND DISCUSSION

Detachment and Fall-Cone Results

The splash detachment and fall-cone results were plotted in Fig. 1 as detachment, D, versus the ratio of raindrop kinetic energy, KE, to fall-cone shear strength, τ. The results agreed with Al-Durrah and Bradford (1982a) in that all of the soils showed a linear relationship $D = a_1 + b_1(\mathrm{KE}/\tau)$ with a high correlation coefficient. The slopes and coefficients of determination are given in Table 4. The slopes of the regression lines differed greatly among the four soils; at a shear strength of 2 kPa, the amount of soil splash for the Auburn soil was about 3.5 times greater than that for the Zipp soil. The intercept did not in any of the four cases vary significantly (with a 0.95 confidence coefficient) from zero.

Triaxial Test Results

In order to evaluate the use of triaxial test results to replace the fall-cone strength term in Fig. 1, several strength-deformation parameters were calculated.

The Coulomb failure envelope expressed in terms of total stresses for the Alford soil is given in Fig. 2. Such plots were made for all of the four soils in terms of both total and effective stresses. Table 5 summarizes the strength parameters for the four soils. The coefficients of determination for all of the regression lines were above 0.99. The friction angles for the soils increased in the order of Zipp < Alford < Dickinson < Auburn. The value of cohesion was low in all cases. The reason for the negative values of cohesion is unknown.

Table 5. Total and effective stress strength parameters.

Soil	Total stress		Effective stress	
	Cohesion	Friction angle	Cohesion	Friction angle
	kPa	degrees	kPa	degrees
Alford	−0.72	16.5	0.19	31.5
Auburn	1.75	18.6	1.61	40.7
Dickinson	0.46	17.4	1.63	37.2
Zipp	0.80	14.8	−4.94	30.6

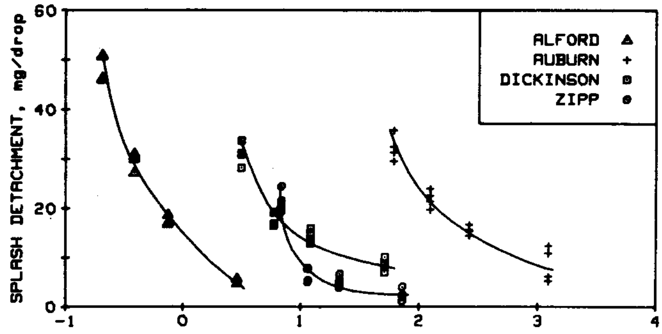

Fig. 3. Detachment vs. calculated corresponding triaxial shear strength.

A strength value based on the related value of strength as determined by the consolidated-undrained triaxial test was calculated for the samples used in the detachment experiment using Eq. 1 and 2. This is possible since the shear strength of a saturated soil is the same under an external confining pressure and an equivalent soil water suction (Towner, 1961). Figure 3 is a plot of detachment versus the shear strength as calculated from the triaxial test measurements of cohesion and friction angle expressed in terms of total stresses using Eq. [1]. The curves for the four soils were similar in general form, but were spaced widely on the strength axis. Since the suctions were low, the values of cohesion largely controlled the relative positions of the curves. The relative positions of the curves in Fig. 3 do not relate to the relative slopes of Fig. 1. Thus, it appears unlikely that the cohesion and friction parameters alone from a conventional triaxial consolidated-undrained test are sufficient to predict soil splash detachment differences among soils.

Huang et al. (1983) suggested that the elastic modulus has an effect on cavity formation upon impact, and hence subsequent detachment. Moreover, strain energy, the amount of work per unit volume required to deform a material, has been correlated to erosion resistance of metals (Thiruvengadam, 1963; Thiruvengadam, 1967; Heyman, 1970; Shanlev et al., 1967). Both elastic moduli and strain energy were calculated from the triaxial test stress-strain curves in this study. Statistically significant differences between the elastic moduli for the four soils did not exist. Therefore, the significance of the elastic modulus on splash detachment could not be evaluated.

Strain energy was computed by integration of the stress-strain curves. Regression lines were fitted to the relationship of strain energy versus confining pressure to estimate strain energy at pressures similiar in magnitude to the suction values of the splash detachment samples. Regression parameters are listed in Table 6 with the average amounts of detachments for the soils at 0.1 kPa soil water tension. The greatest splash amount for each soil was obtained at 0.1 kPa tension. Since strain energy was insignificantly different between 0.0 and 0.1 kPa confining pressure, a relationship between strain energy and detachment for the four soils would exist only if detachment at the 0.1 kPa suction correlated to the strain energy intercept. This was not the case. The Alford and Auburn soils had similar strain energy intercepts but very different splash amounts. The Auburn and Dickinson soils had similiar splash amounts but very different strain energy intercepts.

Table 6. Regression parameters of strain energy, SE, vs. confining pressure, σ_3.†

Soil	Intercept (a_s)	Slope (b_s)	Coefficient of determination (r^2)	Detachment at 0.1 kPa suction (D)
	kJ/m³	(kJ/m³)/kPa		mg
Alford	1.42	0.095	0.986	48.53
Auburn	1.45	0.123	0.999	32.17
Dickinson	0.73	0.117	0.996	30.91
Zipp	2.01	0.081	0.997	21.37

† Model: SE $= a_s + b_s \sigma_3$.

An attempt was made to relate detachment to a combination of triaxial total stress cohesion, friction angle, and strain energy terms at low confining pressures. While this approach may explain the low detachability of the Zipp relative to the other soils and the relatively high detachability of the Alford, it did not correlate for the Auburn and Dickinson. The Auburn and Dickinson have similiar splash amounts at 0.1 kPa suction, but the Auburn has significantly higher cohesion, friction angle, and strain energy.

Fall-Cone Strength, Triaxial Results, and Detachment

Figure 4 is a plot of the slopes of the regression lines for the force-resistance model of splash detachment versus the tangents of the total stress friction angles as determined by the triaxial test. Slope of detachment versus the ratio of kinetic energy to fall-cone strength increases with the friction parameter. This suggests that the fall-cone strength measurement is an overestimate of overall soil splash resistance, and that the causal factor is the friction term.

Figure 5 is a plot of splash detachment versus the ratio of kinetic energy to a corrected fall-cone strength term. The strength term is reduced as a function of the individual soil's total stress friction term. The coefficient of determination using the data for all four soils is 0.91. The results show that the empirically derived function of the total stress friction angle provides an adequate correction factor for the fall-cone based force resistance model of soil splash detachment.

The rationale for using the soil friction angle is based on our current understanding of the mechanism of soil splash detachment. The soil splash process consists of two components: (i) soil compression and cavity formation upon impact and (ii) lateral jetting of the water across the cavity boundary. Al-Durrah and Bradford (1982b) found for six soils that fall-cone shear strength relates directly to splash angle. Splash angle is a direct result of the shape of the impact cavity. Therefore, fall-cone measurements adequately predict the initial component of cavity formation. However, the relationship between detachment and fall-cone shear strength is not the same for different soils. Thus, fall-cone measurements do not predict the resistance of soil particles to shear by the lateral jetting of water. That the resistance of the soil to the jetting is more in the form of cohesion (strength at zero confining pressure) than friction (strength imposed with hydro-

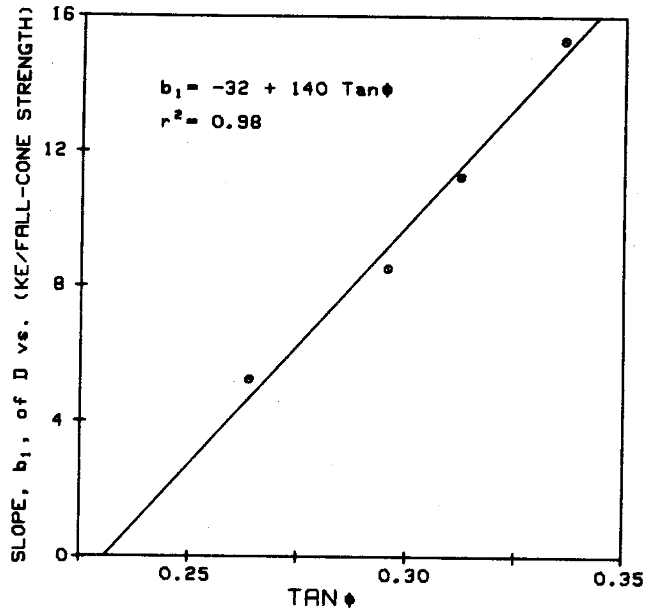

Fig. 4. b_1 **(Slope of detachment vs. ratio of kinetic energy to fall-cone shear strength) vs. the tangent of the total stress friction angle.**

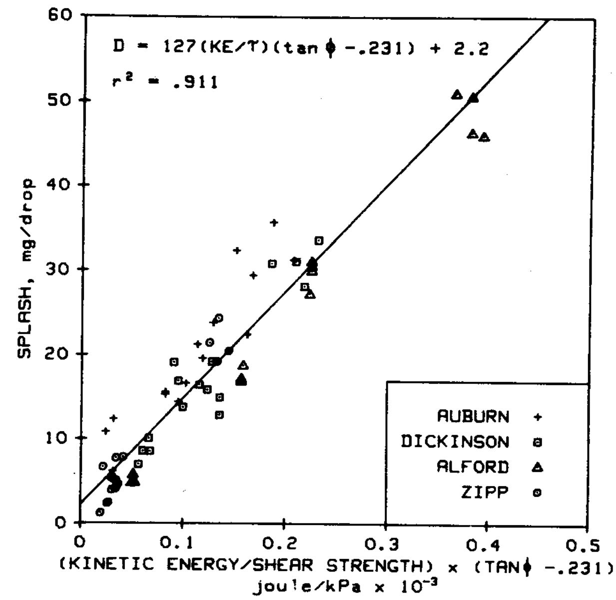

Fig. 5. Detachment vs. the ratio of raindrop kinetic energy to a corrected fall-cone strength term.

static pressure) has been suggested by Al-Durrah and Bradford (1982b). Huang et al. (1982 and 1983) showed that tensile failure occurs from the lateral jetting of water across the cavity boundary. Friction does not contribute to the resistance of a soil to tensile failure, but fall-cone strength does increase with soil water suction (i.e., it has a frictional component). If cohesional forces between soil particles provide the primary resistance of the soil to the lateral jetting of water, then the fall-cone strength may be an overestimate of the soil resistance to the jetting. Reduction of the fall-cone resistance term by the empirically derived triaxial friction term provides a measure of the overall resistance of the soil to both components of the splash detachment process.

CONCLUSIONS

Based on the experimental study of soil strength-deformation properties determined with the fall-cone device and triaxial compression test and of soil splash due to the impact of a single waterdrop, the following conclusions are drawn:

1. Strength and pre-failure deformation properties of soils, as measured with the triaxial test alone, are not good predictors of single waterdrop splash detachment.
2. Fall-cone measurements overpredict the resistance of a soil to detachment.
3. A unique linear function exists between detachment and a combined function of waterdrop kinetic energy, fall-cone shear strength, and the undrained total stress friction angle for the four soils tested.

REFERENCES

Al-Durrah, M.M., and J.M. Bradford. 1981. New methods of studying soil detachment due to waterdrop impact. Soil Sci. Soc. Am. J. 45:949–953.

Al-Durrah, M.M., and J.M. Bradford. 1982a. Parameters for describing detachment due to single waterdrop impact. Soil Sci. Soc. Am. J. 46:836–840.

Al-Durrah, M.M., and J.M. Bradford. 1982b. The mechanism of raindrop splash on soil surfaces. Soil Sci. Soc. Am. J. 46:1086–1090.

Bishop, A.W., and D.J. Henkel. 1962. The measurement of soil properties in the triaxial test. Edward Arnold Ltd., London.

Black, D.K. and L.L. Lee. 1973. Saturating laboratory samples by back pressure. ASCE J. Soil Mech. Found. Div. 99:75–93.

Cruse, R.M., and W.E. Larson. 1977. Effect of soil shear strength on soil detachment due to raindrop impact. Soil Sci. Soc. Am. J. 41:777–781.

Day, P.R. 1965. Particle fractionation and particle size analysis. *In* C.A. Black (ed.) Methods of soil analysis, Part 1. Agronomy 9:545–567.

Hansbo, S. 1957. A new approach to determination of the shear strength of clay by the fall-cone test. Proc No. 14. Swedish Geotechnical Institute, Stockholm.

Heymann, F.J. 1970. Toward quantitative prediction of liquid impact erosion. p. 212–248. *In* Characterization and determination of erosion resistance, ASTM Spec. Pub. 474. American Society for Testing and Materials, Philadelphia, PA.

Holtz R.D., and W.D. Kovacs. 1981. An introduction to geotechnical engineering. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Huang, C., J.M. Bradford, and J.H. Cushman. 1982. A numerical study of raindrop impact phenomena: the rigid case. Soil Sci. Soc. Am. J. 46:14–19.

Huang, C., J.M. Bradford, and J.H. Cushman. 1983. A numerical study of raindrop impact phenomena: the elastic deformation case. Soil Sci. Soc. Am. J. 47:855–861.

Hvorslev, M.J. 1960. Physical components of the shear strength of saturated clays. p. 169–273. *In* Research Conf. Shear Strength Cohesive Soils, Boulder, CO. June 1960. American Society of Civil Engineers.

Laws J.O. 1941. Measurements of fall-velocity of water-drops and raindrops. Trans. Am. Geophysical Union 22:709–721.

Lowe J. and T.C. Johnson. 1960. Use of back pressure to increase degree of saturation of triaxial test specimens. p. 819–836. *In* Research Conf. Shear Strength cohesive soils, Boulder, CO. June 1960. American Society of Civil Engineers.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. In C.A. Black (ed.) Methods of Soil Analysis, Part 2, 2nd ed. Agronomy 9:539–579.

Shalnev, K.K., J.J. Varga, and G. Sebestyen. 1967. Scale-effect investigation of cavity erosion using the energy parameter. p. 220–235. *In* Erosion by cavitation or impingement. ASTM Spec. Pub. 408. American Society for Testing and Materials, Philadelphia, PA.

Thiruvengadam, A. 1963. A unified theory of cavitation damage. Trans. ASME Ser. D, 85:365–373.

Thiruvengadam, A. 1967. The concept of erosion strength. p. 22–35. *In* Erosion by cavitation or impingement. ASTM Spec. Pub. 408, American Society for Testing and Materials, Philadelphia,

PA.
Thomas, G.W. 1982. Exchangeable cations. In C.A. Black (ed.) Methods of soil analysis, Part 2, 2nd ed. Agronomy 9:159–165.
Towner, G.D. 1961. Influence of soil-water suction on some mechanical properties of soils. J. Soil Sci. 12:180–187.
U.S. Army Corps of Engineers, 1970. Laboratory soils testing, Engineer Manual, EM 1110-2-1906. U.S. Government Printing Office, Washington, DC.