Relationships Between Waterdrop Properties and Forces of Impact[1]

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ABSTRACT

Waterdrop impact forces cause detachment of particles from soil surfaces and are an important component of soil erosion. This study was undertaken to determine the effects of waterdrop properties on waterdrop impact forces. Forces of impact were measured with a piezoelectric transducer for 3.31-, 3.83-, and 4.51-mm-diam drops falling from heights of 0.5, 1.4, 3.3, 6.4, and 14.0 m. Mean peak force of impact was determined to be a function of both drop kinetic energy and momentum for individual drop heights, but the relationship varied with height. Mean peak force was proportional to the diameter squared times velocity cubed for all drop sizes and fall heights. Also, the peak forces were related to drop oscillation during fall. A nondimensional representation of impact force vs. time duration of impact was determined.

Additional Index Words: **erosion, erosivity, raindrop, splash.**

Nearing, M. A., and J.M. Bradford. 1987. Relationships between waterdrop properties and forces of impact. Soil Sci. Soc. Am. J. 51:425–430.

SOIL DETACHMENT by raindrop impact is a function of raindrop size, velocity, and shape (Hudson, 1981; Riezebos and Epema, 1985). Likewise, surface sealing of soils is known to be some function of raindrop parameters (Thompson and James, 1985). The forms of the functions relating raindrop parameters to soil detachment and sealing are still debated. Both soil detachment and sealing are largely mechanical processes. Soil detachment, in particular, has been correlated with soil strength parameters (Cruse and Larson, 1977; Al-Durrah and Bradford 1981, 1982a, b; Nearing and Bradford, 1985). Mechanical behavior of soils, including shear strength, can be described in terms of stresses, or forces per unit area, on a soil mass. The relationship between waterdrop impact forces and drop properties has not been clearly established, but is necessary for gaining a more complete understanding of the processes of soil splash and surface sealing.

Several parameters have been suggested as a measure of erosivity due to raindrop impact. Drop momentum, P, and kinetic energy, KE, have been suggested many times (Ekern, 1950; Rose, 1959; Bubenzer and Jones, 1971; Hudson, 1981). Al-Durrah and Bradford (1982a) measured a linear relationship between soil splash detachment and the ratio of KE to soil shear strength, using a Swedish fall-cone device, for nine soils. Equally good results were obtained with P in place of KE in their model. All of their data were collected for a drop fall height of 8.9 m. Similar results were obtained by Nearing and Bradford (1985) for four soils at a drop height of 14 m. A relationship between breakdown of the soil aggregates and a product of drop diameter, d, and the square of its velocity was found by Ghadiri and Payne (1977). For constant density of drops, this term is proportional to the ratio KE/d^2. Impact stresses were calculated from a simplified mechanical model assuming incompressible mechanics of the waterdrop. A high correlation was found by Riezebos and Epema (1985) between sand splash amount and KE, P, KE/d^2, and KE/d.

Drop shape affects the amount of soil splash (Riezebos and Epema, 1985). By changing the height of fall from 0.57 to 0.62 to 0.67 m, the amount of splash loss was changed from 0.78 to 0.28 to 0.88 g/drop. The drop shape at 0.57- and 0.67-m fall height was prolate, and at 0.62-m fall height the drop shape was oblate. The shape of falling raindrops tend to oscillate between a prolate and oblate shape (Jones, 1959; Epema and Riezebos, 1984). The theoretically derived oscillation frequency, ϕ, is (Lamb, 1945, p. 475)

$$\phi = [\ 2\sigma\, n(n - 1)(n + 2)\ /\ \pi^2 \rho\, d^3\ ]^{1/2} \qquad [1]$$

where σ is surface tension, ρ is water density, and n is a constant equal to 2 for the principle mode of vibration. Equation [1] becomes

$$\phi = 11.0\, d^{-1.5} \qquad [2]$$

for waterdrops, where d is in centimeters, and ϕ is in hertz. Equation [2] was verified experimentally by Nelson and Gokhale (1972).

The amplitude of oscillation, A, of the drop decreases exponentially with time due to viscous damping effects (Lamb, 1945, p. 640) according to the equation

$$A = A_o \exp(-t_f/\tau) \qquad [3]$$

where t_f is the time of fall of the drop before impact

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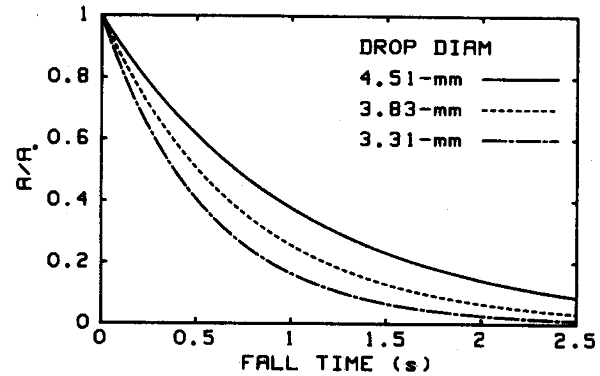

Fig. 1. Theoretical decay of drop oscillation amplitude, *A*, as a function of time.

and A_o is the oscillation amplitude at time $t_f = 0$. The time constant τ can be computed from (Lamb, 1945)

$$\tau = \frac{(d/2)^2}{(n - 1)(2n + 1)\,\nu} \qquad [4]$$

where ν is the kinematic viscosity and $n = 2$ for the principle mode of vibration. Note that τ is not the time required to damp the amplitude completely as was stated by Epema and Riezebos (1984). At time $t = \tau$ the amplitude is damped to $1/e$, or 37%, of its original value. The drop oscillation effect may be particularly important in laboratory studies since laboratory methods of drop formation do not provide for an initially spherical nonoscillating drop. Epema and Riezebos (1984) made recommendations for minimum drop heights for use in laboratory splash studies. Figure 1 is a plot of the ratio of oscillation amplitude, A, to initial amplitude, A_o, (calculated using Eq. [3]) vs. time of fall for 3.31-, 3.83-, and 4.51-mm-diam drops. The distance of fall for any time during fall may be calculated from the fall velocity vs. fall height curve for a drop.

From our present knowledge of the impact process, a functional relationship, h, can be proposed for waterdrop impact force, f, of the form

$$f = h\,(\rho, \sigma, C, K, S, d, v, t) \qquad [5]$$

where C is the velocity of a compressional wave in water, K is the bulk elastic compressibility of water, S is a drop shape effect, v is velocity of the drop immediately before impact, and t is the time during impact after initial fluid-solid contact. If C, K, ρ, and σ are constant, and if shape effect can be eliminated or neglected, then the function becomes

$$f = h_1\,(d, v, t)\,. \qquad [6]$$

The functional relationship between forces of waterdrop impact and drop properties are not known. Determination of these relationships is necessary in order to evaluate the erosivity of storm events and artificial rainfall used in erosion experiments. These relationships will also help in designing and interpreting laboratory measurements of waterdrop splash detachment. Therefore, this study was undertaken to measure the forces of waterdrop impact for a range of drop sizes and drop heights. The results will be used to develop a functional relationship between peak impact forces and waterdrop properties. The effect of drop size and velocity on the impact force vs. time during impact will be discussed briefly.

Table 1. Waterdrop properties.

Drop diameter† d	Drop mass m	Oscillation frequency f	Oscillation time constant t
mm	mg	Hz	s
3.31 ± 0.01	19.0 ± 0.2	57.8	0.55
3.83 ± 0.02	29.4 ± 0.4	46.6	0.73
4.51 ± 0.02	48.0 ± 0.7	36.3	1.02

† Calculated from the drop mass assuming spherical drops.

MATERIALS AND METHODS

The methods of data collection used in this study were similar to those used by Nearing et al. (1986). Briefly, the forces to waterdrop impact were measured using a Kistler[3] 607C1 piezoelectric pressure transducer which was calibrated in force units. The transducer had a 6.45-mm-diam sensing area. Although an equivalent force version of the transducer was available, the pressure transducer was chosen because its casing was sealed to prevent fluid from entering the internal electronics.

The signal from the transducer was amplified by a Kistler model 5004 charge amplifier. A plug-in filter was used on the amplifier to dampen parasitic high frequency noise from the input signal. The resonant frequency of the transducer was 250 000 Hz and the filter frequency was 68 000 Hz. The rise time of the system was 5.1 µs. The force input signal was recorded on a Hewlett-Packard[3] model 5182A waveform recorder at a rate of 1 point µs for a period of 512 µs for each impact.

The transducer was calibrated in a shock tube (Bowersox, 1958; Schweppe et al., 1963), which provided pressure steps with rise times on the order of 1 µs (Bowersox, 1958). The transducer had a highly linear response to applied force over the range of forces encountered in this experiment. The rise time response to the pressure steps was between 5 and 6 µs.

Many of the drops that impacted the transducer did not fall completely on the sensing surface. The drops that fell partially on the edge of the sensing area could be determined from the splash pattern on the Al block on which the transducers were mounted. Those drops that fell completely on the sensing area formed a single ring centered around the transducer after impact. Erroneous data due to drop impingement on the sensor edge were eliminated in this way during data collection.

Forces of impact were measured for 3.31-, 3.83-, and 4.51-mm-diam drops. The mean and standard deviation of the drop weights were determined by weighing 10 drops to the nearest 0.1 mg. The raindrop tower designed by Al-Durrah and Bradford (1981) was used to produce the drops. The heights of fall used were 0.5, 1.4, 3.3, 6.4, and 14.0 m. The characteristics of the drops, including the drop oscillation frequencies, ϕ, and decay of amplitude of oscillation parameter, τ, are given in Table 1.

Table 2 gives the impact velocities and time of fall for each drop size and fall height as computed from the data of Laws (1941). The length, L, which a drop falls during the time of one drop oscillation, is given by

$$L = v/\phi \qquad [7]$$

where v in this equation is the average velocity over a single oscillation length. The oscillation lengths in Table 2 were calculated from Eq. [7] using drop velocities at impact. Also in Table 2 are the kinetic energy and momentum of each drop size and fall height.

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[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.

Table 2. Waterdrop velocities, oscillation lengths, times of fall, kinetic energies, and momentums.

Fall height h_f	Drop diameter d	Velocity† v	Oscillation length L	Fall time t_f	Kinetic energy KE	Momentum P
m	mm	m/s	cm	s	mJ	g m/s
0.5	3.31	3.02	5.2	0.25	0.09	0.057
	3.83	3.04	6.6	0.25	0.14	0.091
	4.51	3.07	8.5	0.25	0.23	0.150
1.4	3.31	4.80	8.3	0.47	0.22	0.091
	3.83	4.91	10.6	0.46	0.35	0.144
	4.51	5.03	13.8	0.46	0.61	0.241
3.3	3.31	6.37	11.0	0.80	0.39	0.121
	3.83	6.59	14.2	0.78	0.64	0.194
	4.51	6.82	18.8	0.78	1.12	0.327
6.4	3.31	7.72	13.4	1.23	0.57	0.147
	3.83	8.28	17.8	1.19	1.01	0.243
	4.51	8.45	23.2	1.18	1.71	0.405
14.0	3.31	8.32	14.4	2.15	0.66	0.158
	3.83	8.75	18.8	2.07	1.12	0.257
	4.51	9.07	24.9	2.03	1.97	0.435

† From Laws (1941).

The peak forces of impact for all drop sizes were measured at five subheights over approximately one calculated (from Eq. [7]) oscillation length, L, for each drop height in order to test for possible differences in measured force due to a drop shape effect. Ten to 15 impacts were measured at each subheight and peak impact forces were averaged for those impacts. A representative force vs. time curve having approximately the average peak force value was recorded for each drop size at heights of approximately 1.4, 3.3, 6.4, and 14.0 m. From the data, nondimensional curves of impact force vs. time duration of impact were obtained.

RESULTS AND DISCUSSION

The peak force, f_p, at each subheight, h, approximated a relationship of the form

$$f_p = F + a \sin(2\pi h/L) \quad [8]$$

over one oscillation length, L, at each drop height tested where F was the mean of the sinusoidal function at any drop height and the parameter, a, was the amplitude of the sine function at any height. Both F and a varied with drop height, but the variance of F and a within each oscillation length was not large enough to be detectable from the data. Therefore, F and a were considered to be essentially single valued over each L. Sine curves of period L were fitted visually to each plot of peak force vs. drop subheight. Figure 2 is such a plot for the 3.31-mm diam drop at the 1.4-m fall height. A mean value of peak force, F, for each drop height was determined from the mean value of the sine curve over the oscillation lengths associated with the respective fall heights, and a was determined from the amplitude of the plotted curve. Force, F, and amplitude, a, of the sine function of force vs. subheight are listed in Table 3.

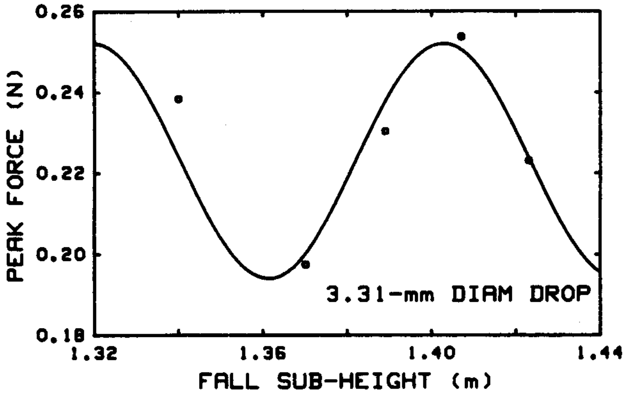

Fig. 2. Peak force vs. fall subheight for the 3.31-mm-diam drop at a fall height of approximately 1.4 m.

Table 3. Peak forces of impact.

Fall height h_f	Drop diameter d	Peak force mean F	Peak force amplitude a	Ratio of amplitude to mean R
m	mm	N	N	
0.5	3.31	0.096	0.018	0.19
	3.83	0.112	0.029	0.26
	4.51	0.125	0.041	0.30
1.4	3.31	0.223	0.029	0.13
	3.83	0.289	0.055	0.19
	4.51	0.420	0.088	0.21
3.3	3.31	0.429	0.030	0.07
	3.83	0.670	0.068	0.10
	4.51	0.990	0.150	0.15
6.4	3.31	0.715	0.032	0.05
	3.83	1.240	0.084	0.07
	4.51	2.000	0.210	0.11
14.0	3.31	1.020	0.017	0.02
	3.83	1.630	0.040	0.03
	4.51	2.540	0.150	0.06

From the above it appears that impact force is related to drop oscillation frequency, ϕ. To further test the hypothesis that drop oscillation is a factor affecting impact force, we proposed that a normalized force amplitude, $R = a/F$, was proportional to the oscillation amplitude A. If that is true, then R should follow a decay curve similar to that described for A in Eq. [3]. Hence, we hypothesized that

$$R = R_o \exp(-t_f/\tau) \quad [9]$$

where $\ln R_o$ is the intercept of the line of $(-\ln R)$ vs. t_f/τ, which has slope equal to 1. In order to determine R_o, $(-\ln R)$ vs. t_f/τ was plotted in Fig. 3 for the three drop sizes and five drop heights. A regression for the line of best fit with a forced slope of 1 was made, and the intercept, $-\ln R_o$, was determined to be 1.066. Hence, $R_o = 0.344$. With R_o established, values of R/R_o vs. t_f and the curves generated from Eq. [9] were plotted in Fig. 4 for each drop size tested. R decayed

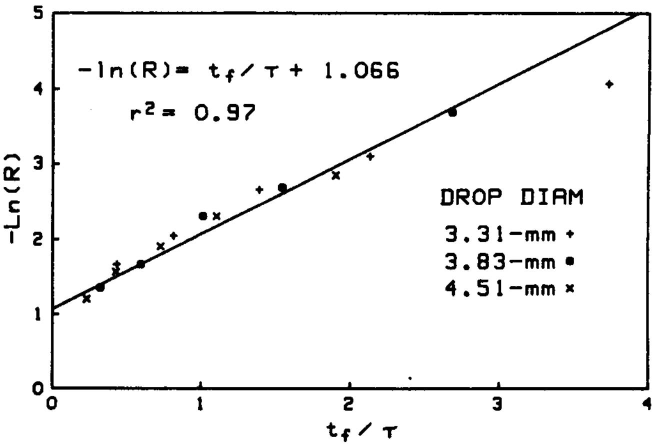

Fig. 3. The negative logarithm of the ratio, $R = a/F$, vs. the ratio of the fall time, t_f, to decay of oscillation time constant, τ.

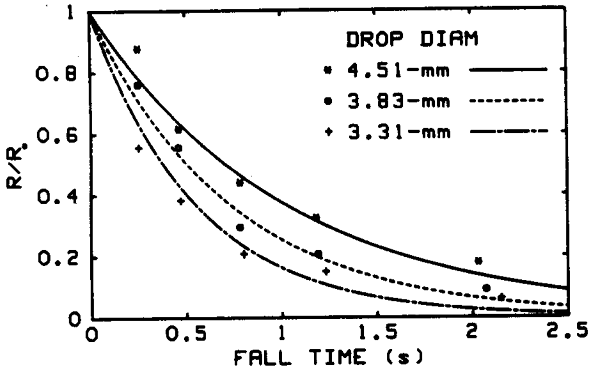

Fig. 4. The exponential decay of the ratio, R/R_o, with time for the 3.31-, 3.83-, and 4.51-mm diam drops.

exponentially with time according to Eq. [9] where the time constant, τ, was the same as that computed from Eq. [4]. Thus, the data do support the hypothesis that impact force is a function of drop oscillation.

P and *KE* are commonly suggested erosivity parameters for raindrops (Hudson, 1981). The mean peak force, *F*, of waterdrop impact at each of the 15 combinations of drop size and height was plotted as a function of *P* and *KE* in Fig. 5 and 6, respectively. A unique relationship between mean peak force and momentum or between mean peak force and kinetic energy for all drop sizes was not found. However, for any particular drop height the relationship between *F* and *P* or between *F* and *KE* was nearly linear over the ranges tested. These results help to explain why in studies such as Al-Durrah and Bradford (1982a) and Nearing and Bradford (1985), in which only one fall height was used, splash was linearly correlated to kinetic energy or momentum, whereas in studies such as that by Ghadiri and Payne (1977), in which several drop heights were used, the kinetic energy term alone did not correlate to impact stress or to the breakdown of soil aggregates. Our results indicate that mean peak force of waterdrop impact may be described as a linear function of either kinetic energy or momentum for any given drop height, but that the function is not the same for each height.

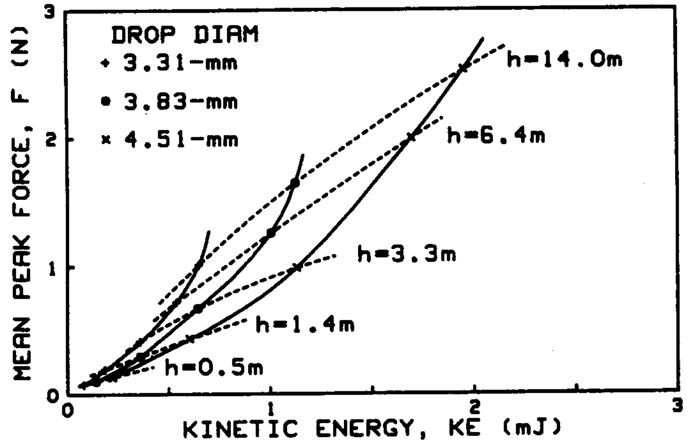

Fig. 6. Mean peak force, *F*, vs. kinetic energy, *KE*, of the drops.

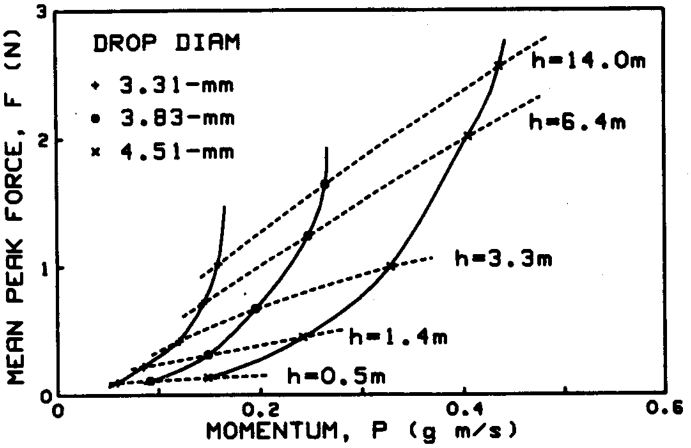

Fig. 5. Mean peak force, *F*, vs. momentum, *P*, of the drops.

KE/d and *KE/d*² have also been suggested as possible erosivity parameters for raindrops (Riezebos and Epema, 1985). The relationship between *F* and *KE/d*, plotted in Fig. 7, was more nearly a unique function than the one between *F* and *P* or between *F* and *KE*. The relationship, however, was not exactly the same for the three drop sizes tested. The relationship between *F* and *KE/d*² was apparently independent of drop size or fall height (Fig. 8). The regression equation of best fit for *F* vs. *KE/d*² was

$$F = 0.0626 + 0.00246\,(KE/d^2) + 0.000237\,(KE/d^2)^2 \qquad [10]$$

where the units of KE/d^2 are kilograms per square second and *F* is in newtons. The coefficient of determination, r^2, of the regression was 0.99.

We suggested previously that for constant ρ, *C*, σ, *K*, and *S*, the independent variables describing waterdrop impact forces are *d*, *v*, and *t* (Eq. [6]). Hence, we propose that

$$F = g(d,v) \qquad [11]$$

where *g* represents some function to be determined. Actually, the appropriate shape factor for *F* may not be the same for every drop velocity and size, but we can reasonably assume that at equilibrium conditions the shape factor, *S*, is some function of *d* and *v* (Pruppacher and Beard, 1970). Likewise, the time after impact of the peak force can also reasonably be considered a function of *v* and *d* and the water properties ρ,

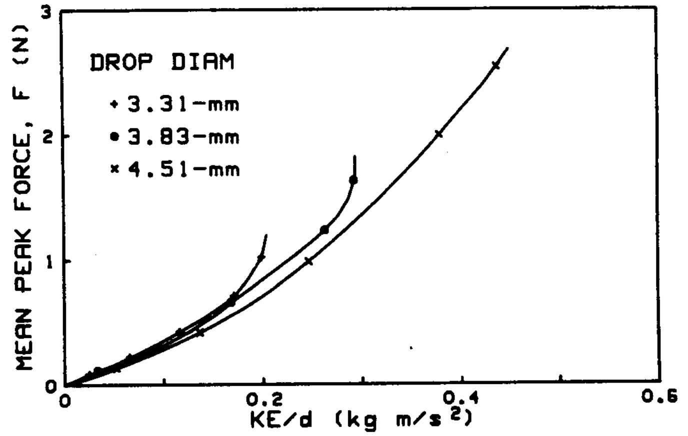

Fig. 7. Mean peak force, *F*, vs. the ratio of kinetic energy, KE, to drop diameter, *d*.

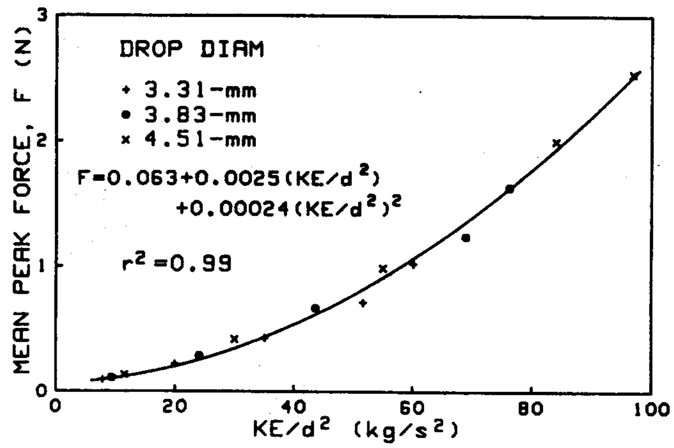

Fig. 8. Mean peak force, F, vs. the ratio of kinetic energy, KE, to drop diameter, d, squared.

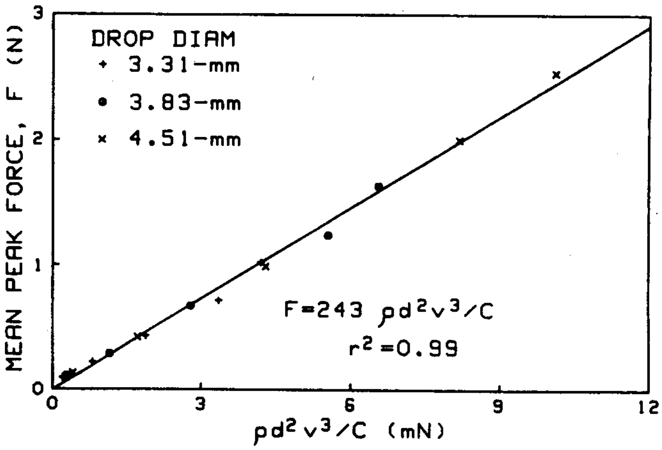

Fig. 9. Mean peak force, F, vs. $\rho d^2v^3/C$.

C, σ, and K. Correlation coefficients were calculated for 25 functions, g_{ij}, for $i,j = 1, 2, 3, 4, 5$ where

$$g_{ij} = a_{ij} + b_{ij}\, d^i\, v^j\,. \qquad [12]$$

The terms a_{ij} and b_{ij} are the coefficients determined by the regression. Two of the regression equations had coefficients of determination, r^2, values of over 0.990. They were

$$F = 0.0 + 162\, d^2v^3 \qquad [13]$$

and

$$F = 0.1 + 17.6\, d^2v^4\,. \qquad [14]$$

Note that for constant ρ the term d^2v^4 is essentially a constant times $(KE/d^2)^2$. Thus, Eq. [14] is essentially the same as Eq. [10] where the second term of Eq. [10] is not included. The logical value for F at $d = v = 0$ is zero. The F intercepts for Eq. [14] and [10] were significantly different (at significance level $\alpha = 0.05$) from zero. Equation [13], however, had an F intercept that was not significantly different (at $\alpha = 0.05$) from zero. We concluded, therefore, that Eq. [13] was a better representation for F than were Eq. [14] and [10]. To obtain the same units on both sides of Eq. [13], the constants ρ and C may be included, hence, Eq. [13] may be rewritten as

$$F = (k\,\rho/C)\, d^2\, v^3 \qquad [15]$$

where $a_{23} = 0$ and $k = b_{23}C/\rho$. The units of both sides of Eq. [15] are kilograms per meter square second. The values of F vs. $\rho\, d^2v^3/C$ and Eq. [15] are plotted in Fig. 9. Equation [15] is not based on fundamental mechanics of impact and we do not suggest, thereby, a cause and effect relationship. It was, however, the best statistical correlation between the mean peak forces of waterdrop impact and the pertinent waterdrop properties.

Dimensional analysis was performed on the force vs. time of drop impact curves in an attempt to find a nondimensional force vs. time relationship. The parameters included in the analysis were f, t, d, v, ρ, C, K, and σ. The best results were obtained for plots of $(fC/\rho d^2v^3)$ vs. (tvK/σ). Representative results are shown in Fig. 10 and 11. The results for the drop height of 6.4 m for all three drop sizes are shown in Fig. 10. The results for the 3.83-mm-diam drop for fall heights of 1.4, 3.3, 6.4, and 14.0 m were plotted in Fig. 11. The nondimensional curves were approximately uniform for all but those at the drop height of 1.4 m. At low (tvK/σ) values, the curves for the 1.4-m fall height matched adequately. The differences occurred at times after the peak forces had occurred.

The nondimensional analysis suggested that the relative force values at nondimensional time during impact could be normalized by the term $\rho d^2v^3/C$. That was the same normalizing factor determined for the

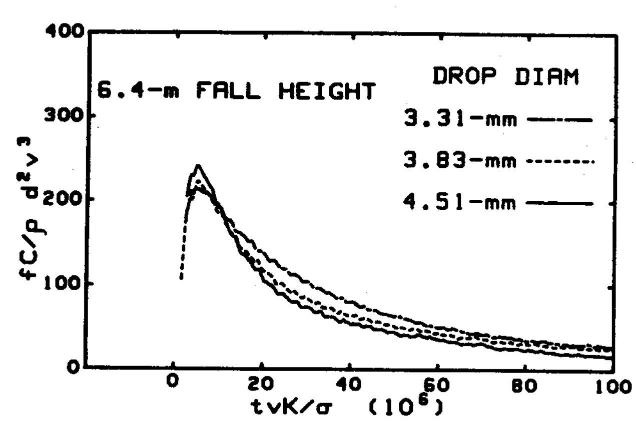

Fig. 10. Nondimensional curves of impact force vs. time of impact for the 3.31, 3.83, and 4.51-mm diam drops at a fall height of 6.4 m.

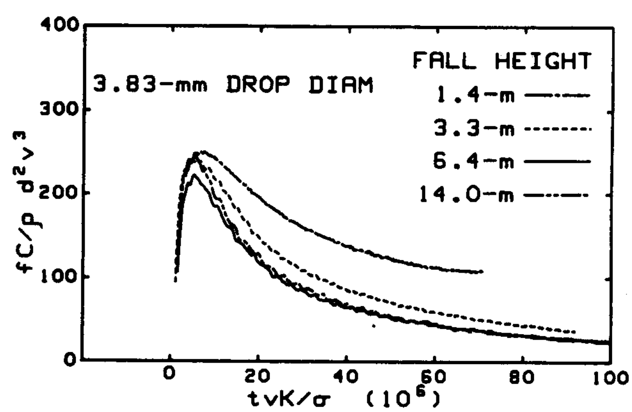

Fig. 11. Nondimensional curves of impact force vs. time duration of impact for the 3.83-mm-diam drop for fall heights of 1.4, 3.3, 6.4, and 14.0 m.

peak force, F, in Eq. [15]. The time of the normalized force is related to σ/vK. The higher the velocity of impact, the less was the time duration of impact to a particular value of nondimensional force. The nondimensional curves may be used to provide a basis for creating a loading function for modelling the impact for an arbitrary drop size and height.

CONCLUSIONS

The following conclusions may be made from this study.

1. Mean peak forces of waterdrop impact were unique functions of either kinetic energy or momentum of the impacting drop for individual fall heights, but the relationship varied for the different heights tested. Mean peak force was a unique quadratic function of KE/d^2 for all of the fall heights and drop sizes tested.
2. Mean peak forces of waterdrop impact were linearly related to the term $(\rho/C)\, d^2v^3$. The regression equation representing that function had an F intercept of zero and an r^2 of 0.99.
3. Peak forces of impact varied sinusoidally with small changes in drop height. The wavelengths of the sine curves on the force vs. subheight plots were approximately the same as those calculated from the theory of oscillating waterdrops. The normalized amplitude of the sine waves decreased as an exponential function of fall time. The time constant for the decay function was approximately the same as that calculated from the theory of viscous damping in oscillating waterdrops.
4. The curves of impact force vs. time during impact were nondimensionalized to the form $(fC/\rho d^2v^3)$ vs. (tvK/σ). The nondimensional curves were approximately uniform except for those of the lower velocity drops at time of impact greater than the nondimensional time of peak force.

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APPENDIX

List of Symbols

A = oscillation amplitude of waterdrop
A_o = oscillation amplitude of waterdrop at $t_f = 0$
C = velocity of compressional wave in water
F = mean of peak force, f_p, over one oscillation length
K = bulk compressibility of water
KE = kinetic energy of waterdrop
L = length that drop falls during one oscillation period
P = waterdrop momentum
R = normalized force amplitude ratio, a/F
R_o = value of R at $t_f = 0$
S = drop shape parameter
a = amplitude of f_p vs. drop subheight
d = waterdrop equivalent spherical diameter
f = waterdrop impact force (a function of t)
f_p = peak impact force at fall subheights
h = drop subheight
h_f = height of fall of drop before impact
n = constant related to mode of vibration of oscillating drop
t = time during impact after initial liquid-solid contact
t_f = time of fall of drop before impact
v = velocity of drop immediately before impact
α = statistical level of significance
ν = kinetic viscosity
ρ = density of water
σ = surface tension of water in air
τ = decay constant of oscillation amplitude
ϕ = waterdrop oscillation frequency

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