Measurement of Waterdrop Impact Pressures on Soil Surfaces[1]

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ABSTRACT

Limited data on pressures induced by waterdrop impact on soil surfaces restricts our understanding the mechanism of soil detachment due to raindrop impact. Impact pressures on rigid surfaces are known but their application to soil surfaces is questionable. This study was undertaken to measure vertical pressures of waterdrop impact on soil surfaces. A 1-mm diam piezoelectric transducer was developed and measurements of impact pressures as a function of radial distance from drop center were made. Dickinson loam (coarse-loamy, mixed, mesic Typic Hapludoll) and Ida silt loam (fine-silty, mixed [calcareous] mesic Typic Udorthent) with bulk densities of 1.0 and 1.2 Mg/m^3 and with matric potentials of -0.5 and -2.5 kPa were used. The waterdrop had a diameter of 5.6 mm and a fall height of 14 m. Average peak impact pressures were greatest at a distance of 1.8 to 2.3 mm from center of impact and of the order of 190 to 290 kPa. These stress levels are almost two orders of magnitude less than those for impact on a rigid surface. Much of the difference between soil and rigid cases was due to nonrigid, nonhomogeneous nature of the soil material. The remainder of the difference in stress levels was thought to be due to the effect of soil granularity or to the presence of surface and shear waves generated by impact.

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

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RESPONSE OF A MATERIAL SURFACE to the dynamic loading caused by waterdrop impact is a function of stress induced during impact and dynamic material properties of the surface. For the important case of impact of waterdrops on soil surfaces, stresses induced during impact have not been measured and are not known. Impact stresses caused by waterdrops are

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spatial and temporal functions of properties and geometry of waterdrops (Nearing and Bradford, 1987) and of mechanical properties of material being impacted (Nearing, 1987). Therefore, measurements of impact stresses on rigid surfaces are not necessarily valid for soil surfaces. Vertical impact stress distributions are responsible for shape of raindrop impact crater, for development of destabilizing tensile forces at crater boundaries (Huang et al., 1982) and for velocity of lateral jet during splash. Each of these factors affect the amount of soil that is detached by impact of a raindrop. The purpose of this study, therefore, was to measure vertical stresses caused by waterdrop impact on a soil surface.

An equation for maximum pressures induced by the one-dimensional impact of a semi-infinite body of water onto the surface of a semi-infinite, nonrigid solid can be derived from consideration of conservation of momentum (Springer, 1976; Adler, 1979). Maximum pressure, P_w, on the water-solid interface is given by

$$P_w = \rho_w C V/[1 + \rho_w C/\rho_t U_t] \qquad [1]$$

where C is velocity of compressional waves in water, V is relative velocity of the two materials at time of impact, ρ_w is density of water, ρ_t is density of the solid target, and U_t is velocity of the compressional wave in the solid. Equation [1] was derived in detail by Springer (1976). In the case of a rigid solid $\rho_t U_t \gg \rho_w C$ and Eq. [1] reduces to the classical "water hammer" equation

$$P_h = \rho_w C v \qquad [2]$$

where P_h is water hammer pressure (Adler, 1979). Equations [1] and [2] do not take drop geometry into account.

Numerical computations and laboratory experiments have been performed for impact of waterdrops on essentially rigid (i.e., where $\rho_t U_t \gg \rho_w C$) surfaces (Hwang and Hammitt, 1977; Johnson and Vickers, 1973; Rochester and Brunton, 1974; Rosenblatt et al., 1977). Figure 1, taken from Adler (1979), shows peak pressure of impact as a function of radial distance from center of impact from four studies. Rosenblatt et al. (1977) and Hwang and Hammitt (1977) performed finite difference computations for impact of spherical drops. Johnson and Vickers (1973) experimentally measured pressures of impact under a water jet. Rochester and Brunton (1974) measured impact pressure on a water disk held between two plexiglass plates. Impact pressures from Fig. 1 were of the order of magnitude as that computed from Eq. [2], i.e., of the order of P_h.

Description of impact on a soil surface is complicated by nonhomogeneity of the material. Nearing (1987) developed theoretical equations for one dimensional pressures of impact of water onto soil surfaces. The equation for total vertical stress, P_f, on the soil skeleton was

$$P_f = \rho_w CV/[\beta_f + \beta_p(\rho_p U_p/\rho_f U_f) + (\rho_w C/\rho_f U_f)] \qquad [3]$$

where β_f is volume fraction of soil in which the frame wave (compressional wave in soil skeleton; Biot, 1956) propagates, β_p is the volume fraction of soil in which the fluid wave (compressional wave in soil pores; Biot, 1956) propagates, ρ_f is density of material displaced by the frame wave, ρ_p is density of material displaced by the fluid wave, U_f is velocity of the frame wave, and U_p is velocity of the fluid wave. Nearing's results indicated that bulk density and matric potential will affect soil dynamic properties and hence pressures induced by impact of water.

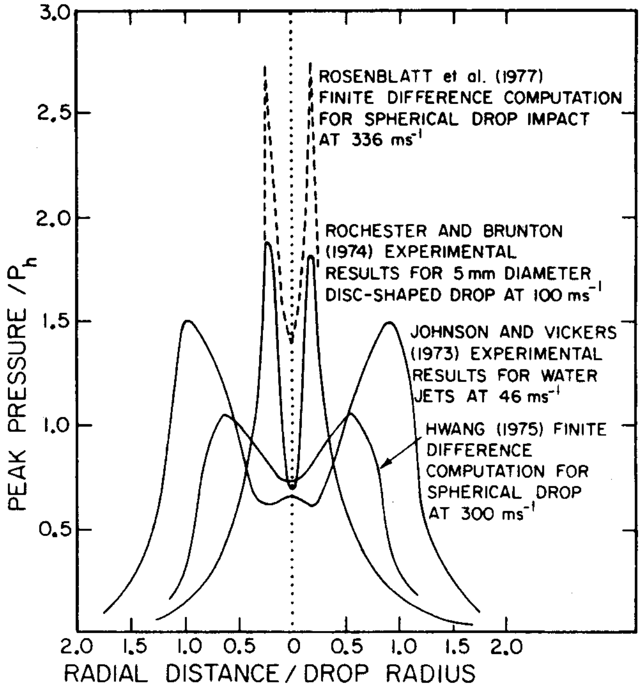

Fig. 1. Results of peak water impact pressures on rigid surfaces from past studies (from Adler, 1979).

Many experiments have been conducted to measure impact pressures on rigid surfaces, but few have measured the pressures induced by waterdrops impacting soil surfaces. Data from studies on rigid surfaces are not directly applicable to soils. Data for soils are necessary to understand the mechanism of soil splash detachment and to evaluate the soil properties that resist erosion. The present study was undertaken to measure the pressures of impact of waterdrops on soil surfaces. A sand-sized (1-mm diam) piezoelectric transducer was developed and calibrated, and a method for measuring the impact pressures on soil surfaces as a function of radial distance from the drop center was developed. The results indicated that the level of vertical stress induced on a soil surface is almost two orders of magnitude less and much more variable than the level of stress induced on a rigid surface.

MATERIALS AND METHODS

A 1-mm diam piezoelectric lead zirconate titanate crystal (PZT-5A) with a resonant frequency of 10 MHz was used in this study to measure waterdrop impact pressures on soil surfaces. Resonant frequency of piezoelectric crystals is dependent upon thickness (approximately 0.20 mm in this case) and composition of the crystal. Surfaces of the crystal were coated with gold electrodes, and very thin and highly flexible "Cooner" wires were used as leads. The wires were placed at an angle of about 60° from each other. They allowed free vertical movement of the transducer during the drop impact but restrained the transducer from moving laterally in most cases. The force required to bend the wires was not great enough to be measured with the transducer equipment available, and thus was considered negligible. The crystal was then coated with electrical resin to insulate and prevent loss of charge into the soil.

The transducer was calibrated against a Kistler model 607C1 piezoelectric transducer, which had a known calibration constant (see Nearing et al., 1986). The 1-mm transducer was placed on the sensing surface of the Kistler transducer, and a force was applied by tapping a metal rod onto the top of the 1-mm transducer. The same force was thus transmitted to the second transducer. Outputs of the two transducers were recorded simultaneously and compared. Peak output from our transducer was determined to be highly linear ($r^2 = 0.99$) with peak force applied as measured with the transducer with a known calibration.

Two soils were used in the study. Dickinson loam (coarse-loamy, mixed, mesic Typic Hapludoll) had 450 g sand/kg, 360 g silt/kg, 190 g clay/kg, a liquid limit of 30, and a plastic limit of 20. Ida silt loam (fine-silty, mixed [calcareous], mesic Typic Udorthent) had 50 g sand/kg, 710 g silt/kg, 240 g clay/kg, a liquid limit of 43, and a plastic limit of 28. Both soils have been used previously in single waterdrop detachment studies (Al-Durrah and Bradford, 1981, 1982; Nearing and Bradford, 1985). The method of forming soil samples was the same as that used by Al-Durrah and Bradford (1981). Briefly, soil was ground and passed through a 2-mm sieve, then moistened by spraying lightly with water until the water content was about 140 to 160 g/kg for Dickinson and about 190 to 205 g/kg for Ida. Cores were formed by static compaction of a preweighed mass of soil with known water content into acrylic tubing 57 mm in length and 76 mm in diameter to bulk densities of 1.0 and 1.2 Mg/m^3. A 5-mm thick porous stone was pushed into the bottom of the tubing and soil was trimmed from the other end. Soil cores were placed onto glass bead tension tables and saturated for 2 d. Matric potentials, Ψ, of -0.5 and -2.5 kPa were then applied for 2 d prior to performing the tests.

The raindrop tower designed by Al-Durrah and Bradford (1981) with a 5.6-mm diam drop, falling from 14 m was used. The resulting velocity for the drop was 9.3 m/s (Laws, 1941), which was essentially terminal velocity. A large drop size was selected in order to obtain as large of a ratio of drop size to transducer size as possible.

A plexiglass plate was placed approximately 2 cm above the soil surface. The plate had a 25-mm diam hole, and the transducer was placed carefully on the soil surface at the center of the hole. This center thus marked the original transducer location. A set of crosshairs were made that could be slipped into the hole in the plexiglass to mark the exact center. The crosshairs were removed to allow the drop to impact and could be replaced to locate the transducer's original position. Care was taken to create as little disturbance to the surface as possible, while making the top of the transducer flush with the soil surface. A drop was allowed to fall onto the soil and transducer, and the signal from the transducer was recorded with a Hewlett-Packard model 5182A waveform recorder at a rate of one point per 500 ns over a period of 512 μs. The output was stored on a computer disk for later analysis.

The radial distance of the transducer from the center of impact was measured by visually determining the center of the crater impact and measuring outward (to the nearest 0.1 mm) to the center of the original location of the transducer (i.e., the center of the hole in the plexiglass, as marked by the crosshairs, over the soil core). The transducer did not, in general, move far laterally from its original location, as discussed above. In the cases when the transducer did move appreciably, the data were discarded.

Between 37 and 51 impacts were recorded for each combination of matric potential, soil density, and soil type. The peak pressures were determined for each impact and plotted as a function of radial distance from the drop center. Representative pressure vs. time curves were also plotted.

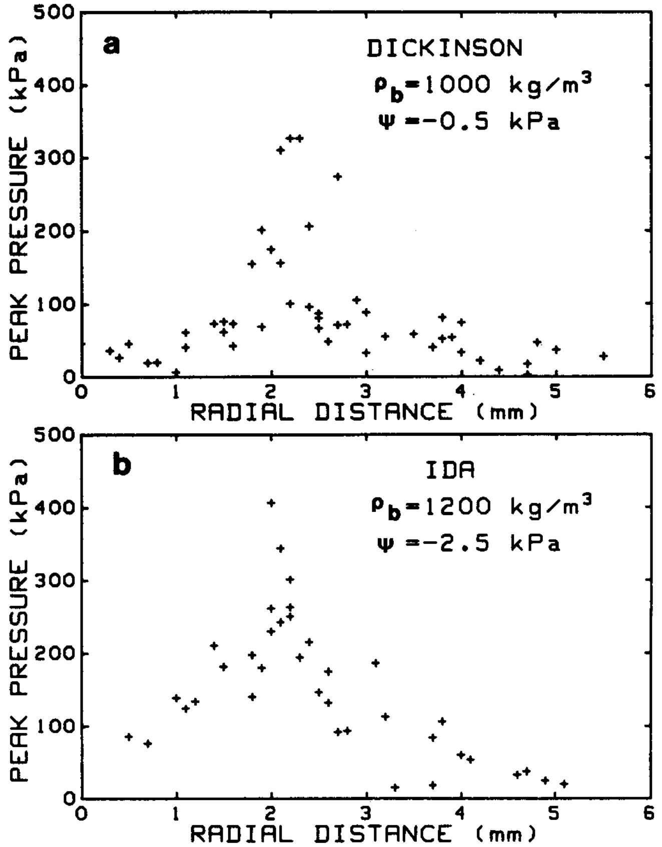

Fig. 2. Peak pressures vs. radial distance from the center of impact (a) for the Dickinson soil at $\rho_b = 1.0$ Mg/m^3 and $\Psi = -0.5$ kPa, and (b) for the Ida soil at $\rho_b = 1.2$ Mg/m^3 and $\Psi = -2.5$ kPa.

RESULTS

The average measured peak pressure for all of the data was 106 kPa. Examples of peak impact pressure vs. radial distance from the drop center (i.e., for the Dickinson at ρ_b= 1.0 Mg/m^3 and $\psi = -0.5$kPa and for the Ida at ρ_b= 1.2 Mg/m^3 and $\psi = -2.5$ kPa) were plotted in Fig. 2. Mean and standard deviation for the peak pressure values for the radius ranges of 0 to 1.7, 1.8 to 2.3, and 2.4 to 6.0 mm were listed in Table 1. Statistical analyses of the peaks showed that for each combination of soil type, density, and suction, average of the peaks in the range of radius from 1.8 to 2.3 was significantly higher (at $\alpha = 0.10$) from either of the other two radius ranges. Ranges of 0 to 1.7 and 2.4 to 6.0 mm were not significantly different from each other in any case. Mean peak pressures in the range of 1.8- to 2.3-mm radius ranged between about 190 to 290 kPa. Mean peak pressure outside of that radius range was between 44 and 135 kPa.

Representative voltage output with time curves for each of the three radius ranges were plotted in Fig. 3. Impact pressures were higher and lasted longer for the radius range of 1.8 to 2.3 mm. For the radius range of 2.4 to 6.0 mm, a negative voltage was often present after the peak. These negative voltage output values were probably due to a combination of forces on the

Table 1. Peak pressures of impact on soil surfaces for a 5.6-mm diam drop falling from 14 m.

Soil type	Bulk density	Matric potential	Distance from crater center	Mean peak pressure	SD	No. of impacts
	Mg/m³	kPa	mm	kPa		
Dickinson	1.0	−0.5	0.0–1.7	44	22	14
			1.8–2.3	201	98	9
			2.4–6.0	66	56	28
		−2.5	0.0–1.7	91	75	16
			1.8–2.3	209	82	8
			2.4–6.0	78	74	25
	1.2	−0.5	0.0–1.7	79	44	14
			1.8–2.3	209	102	10
			2.4–6.0	59	59	15
		−2.5	0.0–1.7	83	38	13
			1.8–2.3	249	70	8
			2.4–6.0	77	70	18
Ida	1.0	−0.5	0.0–1.7	98	51	9
			1.8–2.3	200	86	7
			2.4–6.0	69	56	26
		−2.5	0.0–1.7	97	47	9
			1.8–2.3	190	58	11
			2.4–6.0	57	52	28
	1.2	−0.5	0.0–1.7	113	52	9
			1.8–2.3	289	168	8
			2.4–6.0	68	48	33
		−2.5	0.0–1.7	135	48	7
			1.8–2.3	250	74	12
			2.4–6.0	91	63	18

side of the crystal and aerodynamic lift, both caused by high velocity jetting across the soil surface at the crater edge.

A significant ($\alpha = 0.10$) increase in measured vertical stress with increased soil density and increased soil-water suction was observed. Average peak vertical stress for the tests at $\rho_b = 1.0$ Mg/m^3 was 95 kPa, whereas the average peak vertical stress for the tests at $\rho_b = 1.2$ Mg/m^3 was 119 kPa. Impact pressure was 99 kPa and 113 kPa at $\Psi = -0.5$ and -2.5 kPa, respectively.

DISCUSSION

Observations that peak impact pressures ocurred in an annular ring around the center of the impact area were consistant with the observations of Mihara (1952), who discussed the shape of waterdrop impact craters in sand. Mihara observed that the central part of the crater was always shallow compared with a deeper annular ring away from the center. Our results were also consistent with observations of higher peak pressures located away from the center of impact on rigid surfaces (Fig. 1).

Measured peak pressures of impact were smaller by almost two orders of magnitude and more variable than previously measured on rigid surfaces. The water hammer pressure associated with a water velocity of 9.3 m/s is, from Eq. [2], about 14 000 kPa. This compares with the average measured waterdrop peak pressure, which was 106 kPa.

Nonrigidity of surface and multiphase nature of material accounts for a large portion of the difference between soil and rigid surfaces. Theoretical equations for one-dimensional pressures of impact of water onto soil surfaces were developed by Nearing (1987). Using those equations, calculated theoretical one-dimensional pressures for the soils used in this study were between 700 and 1400 kPa. From these calculations, it was apparent that nonrigid, multiphase properties of material were responsible for a large degree of difference between measured values of pressure on soil surfaces and those on a rigid surface.

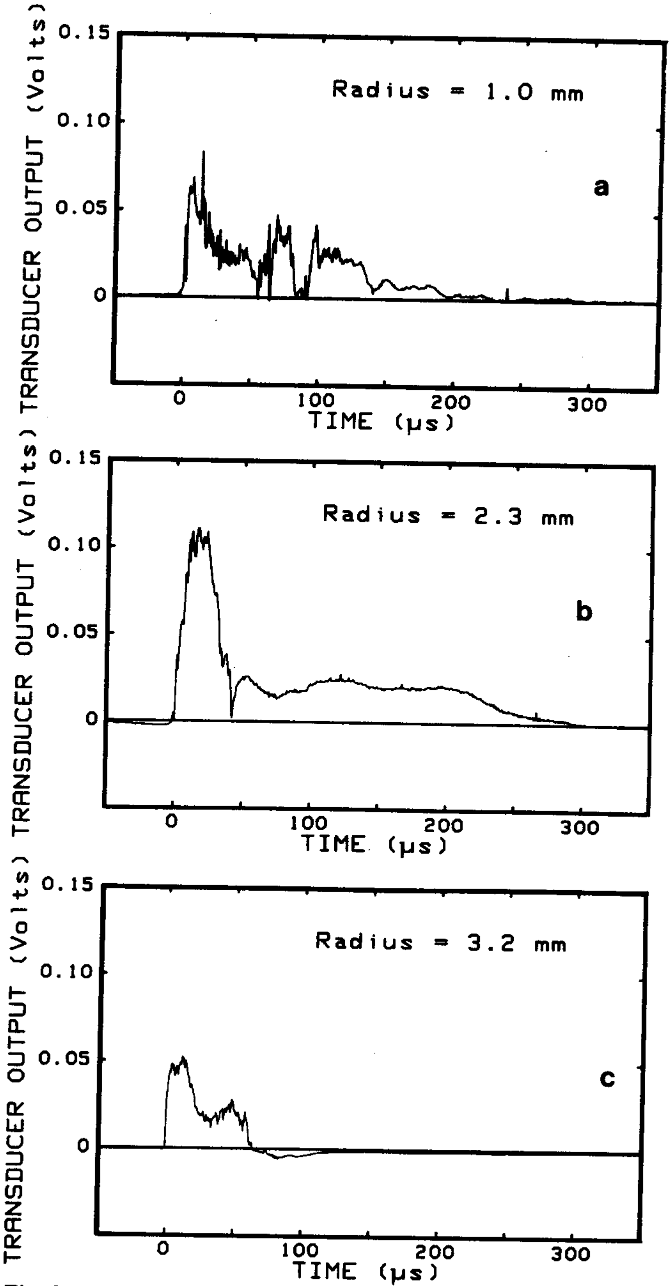

Fig. 3. Voltage output at a distance from the impact center of (a) 1.0 mm, (b) 2.2 mm, and (c) 3.2 mm.

The remainder of difference between rigid and soil impact pressures may be due to several factors. One is the granular nature of soil. Individual particles had potential to move into air-filled voids upon drop impact, which effectively reduced rigidity of the material on a local scale and, hence, reduced pressures of impact. Because the scale of motion of the soil particles (i.e., strain induced) during impact was much larger than that due to the passing of a compressional wave, it was reasonable to expect that the effective rigidity was less in case of the drop impact. Lower rigidity would cause lower pressures. Another possible reason for lower observed pressures may be that a portion of energy of the waterdrop may have been expended by shear and surface waves in the soil. Shear and surface waves were not considered in the one-dimensional theory of Nearing (1987).

The granular nature of soil material was thought to be the probable reason for variability of peak pressures observed in this experiment. First, the area of impact was not great enough compared with the size of soil particles to represent the material as a continuum (Holtz and Kovacs, 1981). Hence, large stress discontinuities and high variability from point to point were inherent to the impact process. Second, the soil structure produced variable rigidity for the grains as a statistical function of the geometry surrounding the particles.

Experimental error was another contribution to the observed variability in peak pressures. Although care was taken to align the transducer as horizontal as possible for each measurement, some misalignment was inevitable. Movement of the transducer on impact, as discussed previously, was another probable source of error. A third possible source of experimental error may have been with regard to the measurement of the distance of the transducer from the drop center. An attempt was made to measure that distance to the nearest 0.1 mm, but location of the center of the impact was done visually and was therefore somewhat arbitrary. The estimated experimental error in measurement of peak pressure (Nearing, 1986) was between 7 and 12% compared with a coefficient of variation of between 28 and 100%. It may therefore be estimated that 10 to 40% of the variation in peak pressures was due to experimental error, whereas between 60 and 90% of the variation was inherent.

The fact that impact pressure changed with soil density and matric potential is qualitatively in agreement with the theory of Nearing (1987), which predicts that increased density and suction results in increased impact pressures. These data show that soil parameters can have an effect on waterdrop impact pressures as predicted by Nearing (1987). The experimental data also indicate that extension of existing theory is required to quantitatively predict impact pressures on soils.

SUMMARY

The primary information obtained from this study may be summarized as follows:

1. Peak vertical pressures of waterdrop impact on the soil surfaces were nearly two orders of magnitude less than those observed for impact of waterdrops on rigid surfaces. Maximum stresses generated by the 5.6-mm diam drop were located in an annular ring approximately 1.8 to 2.3 mm from the center of the impact area and ranged from about 190 to 290 kPa. Average pressures outside of that region were of the order of 40 to 130 kPa.
2. Variability in the values of peak pressures was large and due mainly to the granular nature of the soil.
3. Soil bulk density and matric potential influenced the measured impact pressures on the soil as predicted qualitatively by the theory of Nearing (1987), i.e., impact pressure increased with both density and water suction. The experimental values were lower than those predicted from the theory and indicate a need to improve existing impact theory for soils.

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