FIFTH AUSTRALASIAN CONFERENCE
on
HYDRAULICS AND FLUID MECHANICS
at
University of Canterbury, Christchurch, New Zealand
1974 December 9 to December 13

THE INTERACTION BETWEEN A RAINDROP AND A SHALLOW BODY OF WATER

by

T. P. Tuong and D. J. Painter

SUMMARY

A raindrop striking a body of water gives rise to an upward splash and a cavity impressed in the water surface. The collapsing cavity gives rise to an upward jet, which, when it recedes, causes fluctuations in ambient water velocity whose nature and magnitude depend on previous events in the sequence. These velocity fluctuations travel as a submerged pulse to cause stress fluctuations at the bed of the receiving water.

Motivated by the importance of the process to rainfall-induced, accelerated soil erosion, a study has been carried out which included detailed observation and measurement of events in the sequence just outlined, for single raindrops and both stationary and moving receiving water of depths from several to many drop diameters. In each case (stationary or moving water), mechanisms are suggested and measurements reported for splash and cavity geometry, upward jet behaviour, the probability of splash closure, the effects on the receiving water and the fixed bed.

Multidrop rainfall introduces further complexity, but an appreciation of the sequence as outlined in this paper is basic to an understanding of the multidrop case.

T. P. Tuong, National Agricultural Centre, Saigon, South Vietnam.
D J. Painter, N. Z. A E. I., Lincoln College, Canterbury.

GLOSSARY

d	diameter of a sphere whose volume = that of a drop
D	flow depth
g	gravitational acceleration
p	probability
t	time
T	surface tension
u	mean flow velocity (of channel flow)
v	drop fall velocity at impact
ρ	density of water
ν	kinematic viscosity of water

drop Reynolds number: $5500 < vd/\nu < 53\,300$

drop Weber number: $760 < \rho v^2 d/T < 4070$

drop Froude number: $390 < v^2/gd < 1800$

flow Reynolds number: $2000 < uD/\nu < 10\,000$

INTRODUCTION

A raindrop striking a body of water whose depth is greater than the depth to which the drop would penetrate in a very deep receiving pool, gives rise to an upward splash and a cavity impressed in the water surface. Upon collapse, the splash will form a bubble floating on the water surface in some circumstances, but not others. The collapsing cavity gives rise to an upward jet, which, when it recedes, causes fluctuations in ambient water velocity whose nature and magnitude depend on previous events in the sequence. These velocity fluctuations travel as a submerged pulse to cause stress fluctuations at the bed of the receiving water. The terminology used in this paper is best made clear by referring to certain of the figures: Fig 1d shows an upward splash and a cavity in the receiving water; Fig 1e shows an upward jet; a dome (which in this photograph has within it an upward and a downward jet) is illustrated in Fig 2a; and Fig 2b shows a downward pulse in the receiving water.

Rainfall interaction with shallow overland flows is important in many forms of accelerated soil erosion. With this motivation, detailed observation and measurement of events in the sequence outlined above have been carried out as part of a study of shallow channel flows modified by rainfall (1). Cine- and stroboscopic photography were used to supplement visual observation and aid measurement.

It is convenient to consider first the case of stationary receiving water, and subsequently to describe (in less detail) the changes which occur when the receiving water is flowing in a direction nearly perpendicular to that of the falling drop.

STATIONARY RECEIVING WATER

A water drop approaching its terminal velocity in still air has a shape intermediate between an ellipsoid with its major axis horizontal and a hemisphere (with the flattest part of the surface downwards) (Fig 1b). A water drop released in still air from a stationary drop former is an ellipsoid whose oscillations in shape (Fig 1a) decrease until terminal shape is reached.

Simulated raindrops of equivalent spherical diameter 3.2 to 4.8 mm, falling from heights up to 6 m, were used in these experiments; their velocities after falling from various heights were indistinguishable from those predicted using the data of Laws (2).

The impacting drop is deformed as it begins to form the cavity in the water surface. The motion of the receiving water at this stage is equivalent to that of a steady upward flow about an imaginary body comprising the portion of the drop below the original water surface together with its mirror image in that surface. (Strictly, this has only been shown, in (3), to be true for a rigid body). The streamlines of this equivalent flow indicate the direction in which the

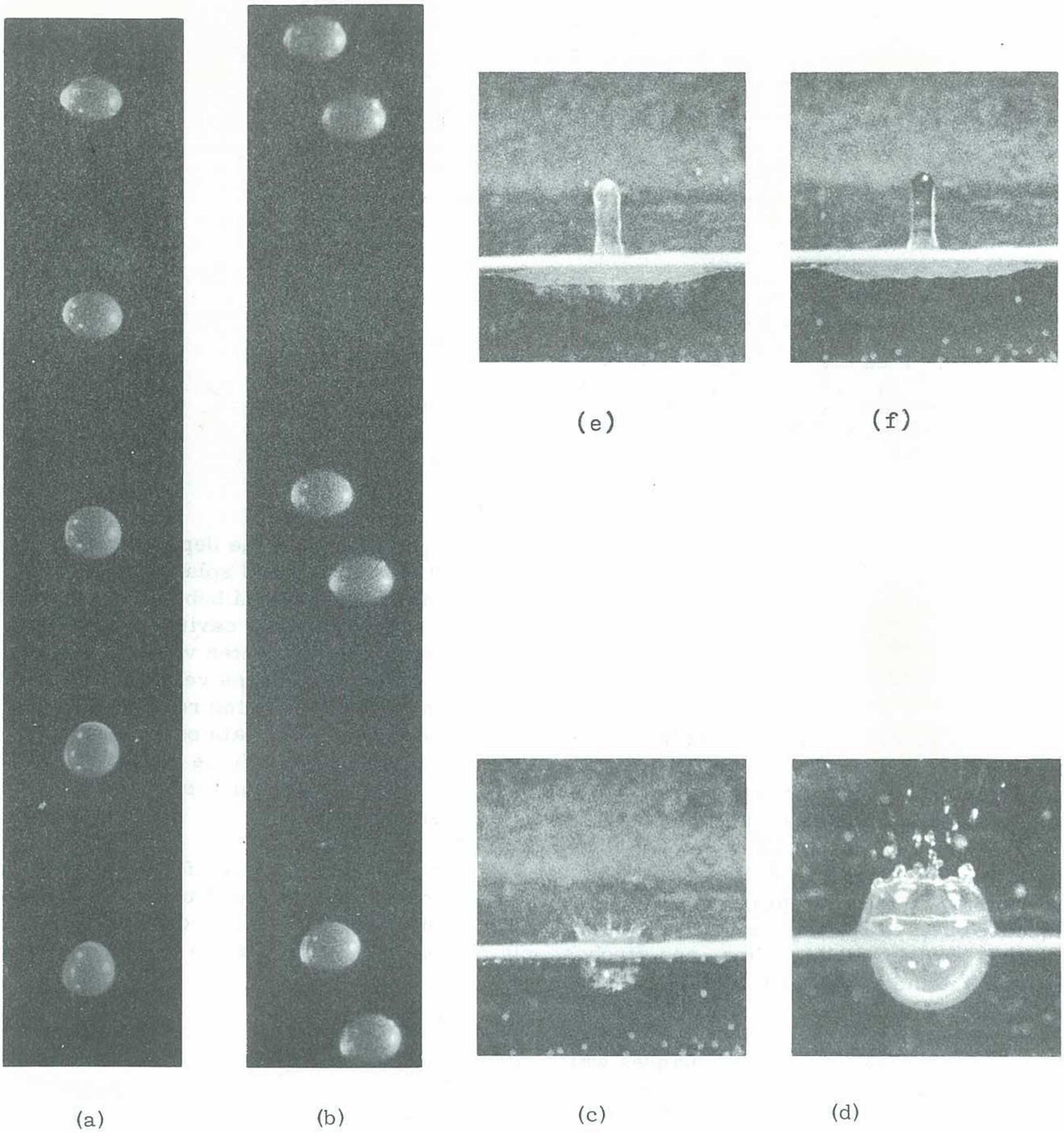


Fig 1. The falling drop; splash, cavity and upward jet formation

(a) A single drop, stroboscope flash rate 200/sec, d = 4.8 mm, height of fall 0.8 m
(b) Two drops, 200 flashes/sec, d = 4.8 mm, height of fall 4.5 m (near-terminal shape)
(c) 0.01 sec after drop impact, d = 4.0 mm, v = 6.5 m/sec
(d) 0.06 sec after drop impact, as (c)
(e) 0.12 sec after drop impact, as (c), drop contained fluorescein dye
(f) 0.12 sec after drop impact, as (c), drop contained black dye

upward splash moves. The splash is convex outwards with an upper edge of varying height above the water surface, the uppermost parts separating to form droplets and giving the well-known 'crown' shape (Fig 1c). A number of recent studies (e.g. (4)) have examined this part of the sequence in detail.

The upward splash continues to rise as the cavity grows (Fig 1d). Both surface tension and reduced pressure in the wake of the falling drop tend to close the upper surface of the splash to form a nearly hemispherical dome. Whether or not the splash actually closes to form a dome depends on the drop size, shape and velocity (as well as the water density and viscosity). As shape could not be measured for every drop used in studying dome formation (many were still oscillating in shape at impact), the probability that a dome would form was estimated from numerous observations with the drop size and velocity controlled (about 100 replicates of each case). For a given size of drop, and with the particular density and viscosity of the water used, the probability that a dome would form remained less than 5% as impact velocity increased, until a limiting value of impact velocity was reached. Thereafter, the probability of a dome forming rose rapidly to over 80%. Although the experiments did not define the role of density or viscosity, the effects of the other variables were summarised by a single dimensionless group comprising drop Weber and Froude numbers:

$$p < 5\% \quad \text{for} \quad 25 < \rho v d^{1.5} g^{0.5} / T < 60;$$

$$p < 80\% \quad \text{for} \quad 75 < \rho v d^{1.5} g^{0.5} / T < 100.$$

The kinetic energy of the drop is imparted to the receiving water, which moves away to form a cavity (Fig 1d). The cavity attains its maximum depth as the receiving water comes momentarily to rest at the deepest point. Before attaining maximum depth, all the observed cavities were closely hemispherical, with maximum diameters from 2.5 d at low drop Froude numbers ($v^2/gd \approx 400$), increasing to a constant value about 3.5 d for drop Froude numbers which corresponded to nearly terminal drop velocities ($1600 < v^2/gd < 1800$). A plot of cavity diameter: drop diameter ratio against drop Froude number grouped the results about a single curve, no variation with drop Reynolds or Weber numbers being apparent.

After the cavity attains maximum depth, its diameter at the water surface continues to increase while an upward jet is formed at the deepest part of the cavity. The jet rises above the original water surface (Fig 1e). (This event resembles the formation of a 'Monroe' jet, when a plane shock wave travels through water to a concave cavity at its surface (5)). The water which originally formed the drop is nearly all contained in this upward jet (Fig 1e and 1f).

If no dome was formed by the initial splash, the upward jet rises as shown in Fig 1e and 1f. A dome, however, markedly limits the maximum height reached by the jet. Two reasons for this are suggested: air movement within the dome influencing the jet and, more importantly, the formation of a downward jet from the highest part of the dome. The pressure reduction behind the falling drop, and the impact of splash closure, combine to form this downward jet which subsequently collides with the upward jet (Fig 2a).

The collapse of the upward jet into the receiving water gives rise to a pulse of liquid which moves towards the bed, and spreads out as it approaches the bed (Fig 2b). The pulse is well-defined in the case where no dome interfered with the upward jet, and resembles the pulsed, submerged jet studied by Sutherland (6) in connection with his sediment entrainment hypothesis. An upward jet which has had to break through a dome gives a weaker and less well-defined downward pulse when it collapses into the receiving water. In some cases the dome is not destroyed by the upward jet and a bubble is left floating on the water surface; then the downward pulse is very weak and confined to near the water surface (Fig 2c).

The velocity fluctuations in the receiving water were studied using a hot-film turbulence probe placed at various horizontal and vertical displacements from the drop impact point. The output from the probe, displayed on an oscilloscope, was recorded simultaneously with, and on the same cine-film as, the photographic record of the drop impact and following events. Drops of 4.0 and 4.8 mm equivalent spherical diameter fell from 2.40 m into stationary water 46 mm deep, conditions which allowed the upward jets to rise free from interference from domes. As would be expected, the magnitude of the fluctuations decreases with either

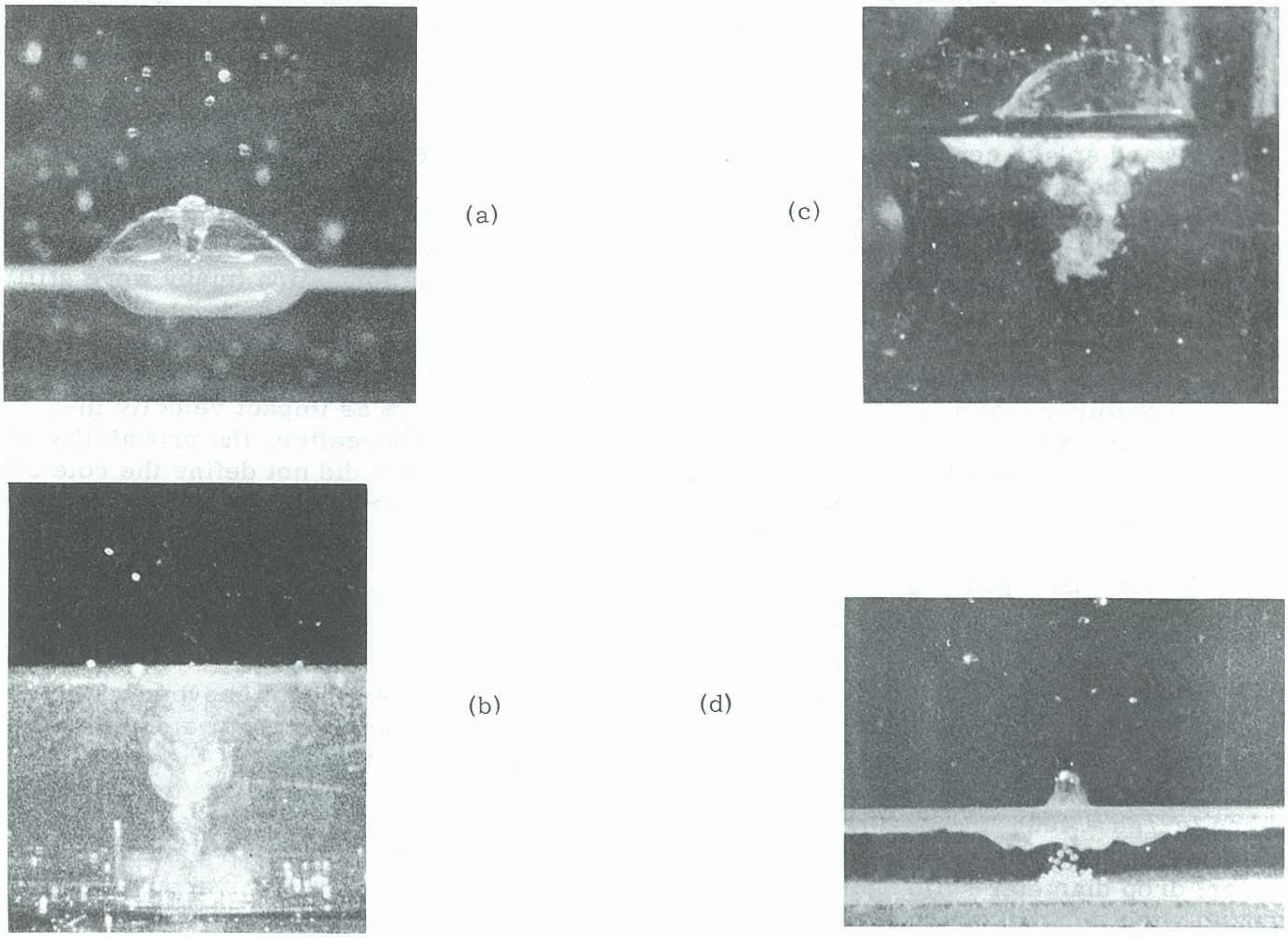
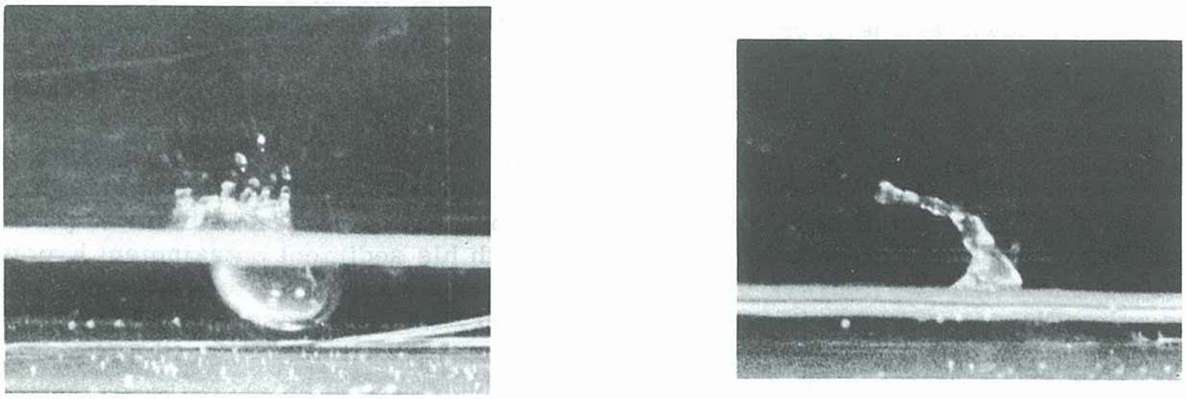


Fig 2. The upward jet, the dome, and the downward pulse

(a) downward jet arising from a dome, $d = 4.8$ mm, $v = 7.7$ m/sec, $t = 0.10$ sec
(b) a well-defined downward pulse, $d = 4.0$ mm, $v = 6.5$ m/sec, $t = 0.75$ sec
(c) a weak downward pulse following dome formation, $d = 4.8$ mm, $v = 7.7$ m/sec, $t = 0.33$ sec
(d) effect of the upward jet on bed material, $d = 4.0$ mm, $v = 6.5$ m/sec, $t = 0.10$ sec



(a) (b)

Fig 3. The splash, cavity and upward jet in moving water (right to left)

(a) splash and cavity, $d = 4.0$ mm, $v = 6.5$ m/sec, $u = 0.3$ m/sec, $t = 0.06$ sec
(b) the upward jet, as (a) but $t = 0.10$ sec

increased horizontal or vertical displacement from the impact point. The delay between the time of impact and the start of fluctuations on the oscilloscope trace is equal to the time taken for the first circular surface wave to reach a position vertically above the probe, independently of the probe depth, and these first fluctuations are thus due to the elliptical motion of water particles beneath the wave. Less obviously, the fluctuations near the bed, vertically beneath the impact point, remain small during the first events of the sequence, and rise when the downward pulse from the collapsing upward jet arrives, to a level similar to that of the near-surface fluctuations close to the impact point.

The observations so far described were made with a fixed bed beneath the receiving water, but it is possible to infer from them the nature of effects on bed material susceptible to being moved by the stresses associated with velocity fluctuations. Partly-hollow polystyrene particles of nearly neutral buoyancy were used as marker particles on the bed to reinforce such inferences. Following impact and while the cavity is forming, the particles remain on the floor although they may move horizontally outwards if the water depth is but little greater than the maximum depth attained by the cavity. The rise of the upward jet in this case will draw particles inward and upward (Fig 2d). But most disturbance to bed material occurs with the arrival of the downward pulse formed by the upward jet collapse. Depending on the nature of the upward jet (as previously described), the polystyrene particles may: move horizontally outward; lift above the bed and move outward; or lift above the bed and move in vertical circular motion (resembling flow in the cross-section of a vortex ring). The last alternative occurs when a well-defined pulse is formed from an uninterrupted upward jet and may be observed at depths up to 25 drop diameters in suitable conditions.

MOVING RECEIVING WATER

The case now considered is when a drop falling vertically meets a shallow, nearly horizontal channel flow.

The upward splash and the cavity form much as they do when the receiving water is stationary, but are convected downstream by the flow (Fig 3a). The probability that a dome will form from the initial splash is much lower now that the receiving water is moving and has a slightly disturbed surface. For two mean flow velocities tested (0.18 and 0.35 m/s), the same dimensionless group as used in the stationary case again summarised the probability of dome formation, which did not rise above 60% in these experiments.

$p < 5\%$ for $40 < \rho v d^{1.5} g^{0.5}/T < 70$;
$5\% < p < 30\%$ for $70 < \rho v d^{1.5} g^{0.5}/T < 90$;
$25\% < p < 60\%$ for $90 < \rho v d^{1.5} g^{0.5}/T < 100$.

Although the cavity is deformed (Fig 3a), the flowing water does not measurably change the cavity depth: drop diameter ratio, at the same drop Froude number, from that appropriate for stationary receiving water (for v/u between 10 and 30 approximately).

The upward jet moves with the flow as it forms and collapses (Fig 3b). The tip of the jet moves in a parablola, with a flow-direction velocity component up to 10% greater than the surface velocity of the main flow, so that it collapses into the receiving water just downstream of the moving cavity's centre.

Not only is the probability of a dome forming less than when the receiving water is stationary, but there is less likelihood of a direct collision between the upward jet and a downward jet arising from dome closure because the upward jet is not moving vertically. So it is less often prevented from reaching maximum height than in the stationary water case.

As in the stationary water case, the collapse of the upward jet forms a pulse of water moving towards the bed, but now it is entrained by the main flow. For the limited range of flows studied, the pulse was able to retain its identity and reach the bed provided the flow Reynolds number was about 3000 or less. Observations of a thin dye layer flowing along the bed did not detect any influence at the bed from events in the drop interaction sequence until the downward pulse disturbed the dye, bringing it up into the main flow to be transported downstream and mixed by the turbulence.

DISCUSSION

The observation that water which originally formed the drop is nearly all contained in the upward jet (Fig 1e and 1f) is different from the result obtained by Harlow and Shannon (7). Their numerical solution of Navier-Stokes equations showed the drop material to be trapped by the collapsing sides of the cavity, which formed the upward jet. Although their drop Froude numbers were much lower ($0.5 < v^2/gd < 8$) than those in this study ($390 < v^2/gd < 1800$), they expected the result to remain true as the Froude number increased. However, Harlow and Shannon neglected surface tension and viscosity in their computations; surface tension in the physical experiments would both aid the drop in retaining its identity and affect the shape of the collapsing cavity.

This study emphasises the importance of the downward pulse formed when the upward jet collapses. That this is the part of the sequence most likely to have the biggest effect at the bed of the receiving water does not seem to have been emphasised previously. One interesting result of these observations is that large drops falling at high velocity might well have less effect on the bed than smaller drops falling at lower velocities, if conditions are such that splash domes interfere with upward jet progress. This has been confirmed by hot-film measurements of root-mean-square fluctuation values under repetitive drop application (1).

When the receiving water is less deep than the maximum potential depth of cavity penetration, the sequence is the same as reported here, but with most of the individual events modified. Likewise, multidrop rainfall introduces further complexity, but an appreciation of the sequence as outlined in this paper is basic to an understanding of the multidrop case.

REFERENCES

1. Tuong T. P. 'An experimental investigation of rainfall-modified open channel flows'. Ph. D. thesis, University of Canterbury, New Zealand, 1972.
2. Laws J. O. 'Measurements of fall velocities of water drops and raindrops.' Trans. Amer. Geophys. Union 22:709, 1941.
3. Birkhoff G. and Zarantonello E. H. 'Jets, wakes and cavities'. Academic Press, 1957.
4. Mutchler C. K. 'Splash droplet production by water drop impact'. Water Resources Research 7(4):1024, 1971.
5. Bowden F. P. 'Formation of microjets'. Phil. Trans. Roy. Soc. Lond. A260:94, 1966.
6. Sutherland A. J. 'Entrainment of fine sediments by turbulent flows'. Report KH-R-13, W. M. Keck Lab. of Hydraulics and Water Resources, Calif. Inst. Technology, California, 1966.
7. Harlow F. H. and Shannon J. P. 'The splash of a liquid drop'. J. App. Phys. 38(10): 3855 - 3866, 1967.

ACKNOWLEDGEMENTS

A. J. Sutherland and F. M. Henderson contributed much to the study on which this paper is based. Both A. J. Sutherland and T. D. Heiler made useful comments on the manuscript.