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Surface Films Affecting Velocity Profiles of Slowly Moving Water in Open Channels

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Summary. Rates of movement of surface films and underlying water were measured using observable solid and liquid tracers. Water flow rate, surface width, water depth, and channel length were varied in flumes in which the water was allowed to flow over a broad weir crest at the tail end. In some runs the surface was blocked 5 cm in front of the weir. When this was done, velocity of the surface film immediately upstream from the block decreased to a small fraction of its previous value and this area of slow surface velocity built upstream with time, extending to as far as several meters under steady state conditions. In this reach, the film at the air-water interface of the water causes drag on the moving water similar to that at a solid-water interface.

Water surface in channels one cm wide and 100 cm long stopped moving when the shear force caused by water flowing beneath it dropped to less than 0.0013 dynes/cm^2. This indicates structure in the surface which does not deform or shear at rates proportional to the force applied. Average water flow velocities from 0.3 to 1 cm per second provided shear stresses in excess of 0.002 dynes/cm^2 and moved these surface films. However, the velocity distribution across the surface of the channel was not parabolic, and indicated that most of the shear in the film was taking place near the edges of the channel. Extrapolation of these observations to water film dimensions present in unsaturated soils indicates that air-water interfaces in unsaturated soils are usually static.

Introduction

Pollen, organic fibers, etc. on the surface of irrigation ditches or furrows often remain still while water below the surface moves at velocities of 0.1 to 1.0 cm/s. Downstream from that point, partial or complete blockage of the water surface often occurs by weeds or crop residues (i.e., a straw that has lodged across the channel). Measurements of velocity profiles in open channels also indicate that velocities are reduced near the air-water interface (Chow 1959).

If the assumption is made of zero flow resistance at the air-water interface, solution of the general equations for viscous laminar flow leads to the conclusion that the highest velocities occur at the surface and at the center of the channel midway between boundaries. In a wide, shallow channel, the midpoint surface velocity should be approximately 1.5 times the average water velocity. If the flow cross-section of the channel is semicircular, a particle on the surface at the midpoint should be moving with a velocity of twice the average water velocity. Measured surface velocity deviations from these theoretical values indicate forces at or near the air-water interface or on the elements in the body of the fluid which are not considered in the general laminar flow equations.

Surface tension of water is commonly measured by raising a ring of platinum wire, that is initially immersed in water, while measuring the force with which the water pulls the ring downward, until the film of water between the ring and water body breaks. Such measurements indicate that the surface tension of water is about 70 dynes per cm. In many treatments of fluid flow, forces of this magnitude can be neglected because hydraulic head or energy differences are sufficiently large to break or stretch the surface film. However, when water surface slopes are less than 0.001 in an open channel a few cm deep and a few meters long, the gravitationally induced force per unit width of the channel causing the water to move is of the same order of magnitude, or less, than the surface tension. Under such conditions, rate of movement of the surface will be affected by resistance of the film to shear forces, width of channel which it spans, and forces applied to the film at, and in the vicinity of, the point of measurement. The following study was conducted to define the effects of average flow velocities, channel depths, surface widths, and of blocking the surface or allowing the surface to flow over a weir crest on surface velocities and velocity profiles within the channel.

Equipment and Procedures

Flumes

Rectangular flumes were constructed 10 cm deep, 10.6 cm wide and 120 cm long as indicated in Fig. 1. The up stream end of each flume was closed while the top and

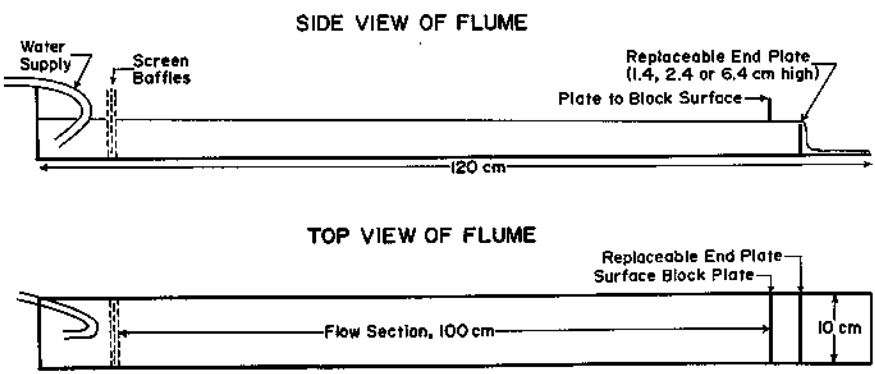

Fig. 1. Construction details of short flume

downstream end were left open. Weir plates 10.6 cm wide, 0.6 cm thick and 1.4, 2.4, and 6.4 cm high were made for inserting in the open end of the flumes to provide water depths about 1.7, 2.7, or 6.7 cm deep. Another flume with a semicircular cross section, 10.4 cm in diameter and 450 cm long, was made from a PVC pipe with the top 160° removed.

Procedure

Water introduced at various rates at the upstream end of the flume via a 1.3 cm dia. copper tube was stilled in a section about 10 cm square separated from the rest of the flume by a baffle made of three 20-mesh stainless steel screens (8 wires/cm) separated from each other by about 2 mm. Lack of dispersion of dye streams indicated no turbulence 10 cm downstream from these screens when average water velocities were less than one cm/s.

Water was supplied to the upstream ends of the flumes at constant rates for each run and in some runs at constant controlled temperatures from either a deep well, or from the distilled water system serving the laboratory. Average water velocities in the flume ranged from 0.1 to 1.0 cm/s.

Surface tension of the water was measured with a DuNouy type tensiometer. Rate of water surface movement midway between its boundaries was determined by marking the surface with small flakes (about $1 \times 1 \times 0.1$ mm) of modeling clay and recording their positions as a function of time. Water velocity profiles were observed by placing a column of dye (Toluidine-O) in the center of the flume with a hypodermic needle. The point of the needle was first placed on the bottom of the flume, midway between the sides, and then withdrawn vertically at a rate approximately equal to the rate at which dye was forces from the needle. This initially vertical column of dye was then displaced according to the velocity profile of the water. The surface velocity profile was observed by drawing the tip of the needle across the water surface. This also left a broad, faint but discernible line which could be followed visually.

To evaluate the effect of surface width on surface velocity, the water surface was partitioned into longitudinal strips of various widths by stringing parallel nylon or copper lines (0.2 mm dia.) between holders located slightly above the water surface and near the two ends of the flume flow section. These lines were laid on the surface of the water and tightened until they pulled slightly upward on the water surface.

Results and Discussion

Forces Acting on Slowly Moving Water Approaching a Weir

Velocity Profiles – With water running over an end plate in a rectangular flume and nylon lines fixed in the direction of flow and spaced at 1, 2, 4, 7, or 10.6 cm apart, water surface velocities midway between lines were measured. When the lines were $\geqq$ 4 cm apart, and the average water velocity, $\bar{V}$, was low (i.e., 0.18 cm/s), the surface velocity tended to increase as the outflow end of the flume was approached. Under these conditions, the dye plumes indicated vertical velocity profiles of the

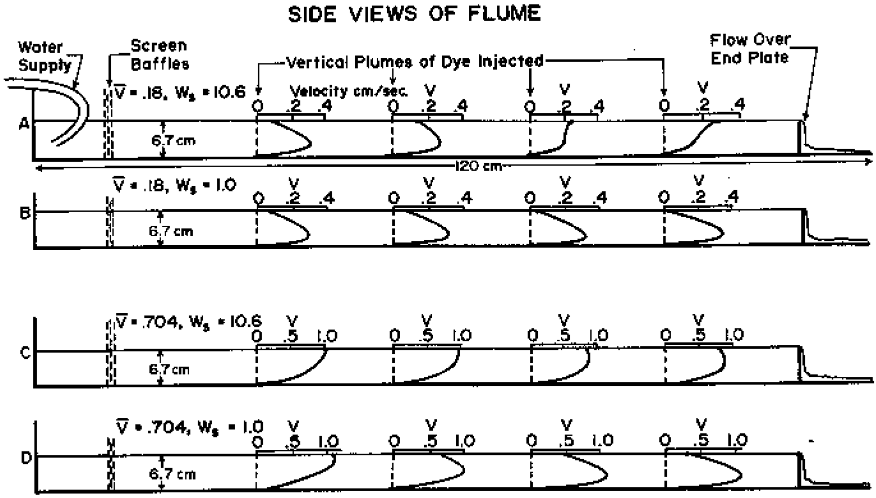

Fig. 2. Midplane velocity profiles in response to hydraulic gradients and forces on the surface film which flows over the end plate for two water surface widths and average flow velocities

type shown in Fig. 2A. The S-shaped velocity profile near the tail end of the flume and particularly the top portion thereof indicates a downstream force was acting on the surface flow in addition to the internal hydraulic forces normally considered. It is probably due to the forward drag on the surface film resulting from the more rapid movement of water as its effective flow path converges and it reaches high velocities as it passes over the crest of the end plate. This force is transmitted upstream by the tensile strength of the surface and creates a forward pull on the upstream surface. Newly supplied well water had a surface tension measured by a DuNuoy tensiometer, of about 72 dynes/cm and distilled water about 70 dynes/cm. When the water falls over the edge of the weir, gravity acting on the water mass can cause forces in excess of 72 dynes/cm which probably break the water surface. However, observations indicate that this surface has considerable elasticity, returning to cover its original area, even after being stretched and held in the deformed position for several minutes. This elasticity plays a major role in absorbing and transmitting forces from the body of the water to the film.

Hydraulic Forces – At the low flow rates imposed in the flume ($\bar{V} < 1$ cm/s), the hydraulic gradients, or slope of the water surface, in the main flow section of the flume were so small that they could not be measured. However, since the Reynolds number in the flow range with $V < 1.0$ cm/s is less than 2,000, and dye streams confirmed laminar flow, the Darcy-Weisbach equation, with its resistance coefficient equal to 64 divided by the Reynolds number, is applicable to this system (e.g., Rouse 1955). Using the Darcy-Weisbach equation and a Reynolds number calculated from the hydraulic radii of the channel when $\bar{V} = 0.18$ cm/s, the gravitational force component which is parallel to and which acts upon the prism (100 cm × 10.6 cm × 6.7 cm^3) of water in the flume was calculated to be 2.9 dynes. When the average velocity, $\bar{V}$, of the water is increased to 0.70 cm/s, this force on the prism of water in the flume increases to about 11.4 dynes.

Interaction of Surface and Subsurface Forces – From the basic equation defining viscosity, the drag or shear force F_s (dynes) exerted on a surface by water flowing beneath the surface is

$$F_s = \mu A \, [dV/dY]_s \tag{1}$$

where μ is the viscosity of the water, A is the area of the surface and $[dV/dY]_s$ is the water velocity gradient measured perpendicularly to, and evaluated at the surface. Thus, the force exerted on the surface film by the rapidly moving water as it passes over the broad (0.6 cm) weir blade is conservatively estimated as

$$F_s \doteq \mu \, (W) \, (L) \, (V_m - V_s)/(d_w/2) \tag{2}$$

where L and W are the length and width of the weir blade, V_m is the velocity of water at the mid plane of the depth through which it is flowing over the weir, d_w is the flow depth over the weir and V_s is the velocity of the water surface. The viscosity μ of water was 0.011 poise. The broad crested weir used had a crest width W of 0.6 cm and was 10.6 cm long. When the average velocities of water in the flume were 0.18 cm/s and 0.70 cm/s, values of d_w were 0.22 and 0.5 cm respectively. Average velocities over the weir, which are reasonably good estimates of $(V_m - V_s)$ were about 6 and 14 cm/s, respectively, which (from Eq. (2)) gave estimates of the forces on the surface film of $F \doteq 3.7$ and 4.0 dynes, respectively. Since the component of the gravitational force acting to move the body of water in the flume in the direction of flow was only about 2.9 dynes when $\bar{V} = 0.18$ cm/s, it is not surprising that the shear force exerted on the surface film at the weir ($\sim$ 3.7 dynes) was the primary factor governing surface movement and velocity profiles when the surface was wide (10.6 cm) and the end plate was approached (Fig. 2A). When $\bar{V}$ was 0.70 cm/s and the gravitational force acting, to move the body of water in the flume was about 11 dynes, the shear force on the surface film ($\sim$ 4 dynes) was relatively smaller, but still a significant factor in determining surface movement and velocity profiles when the surface was wide (10.6 cm) (Fig. 2C).

Changes in Surface Film Velocities and Their Implications

Unobstructed Surface Upstream from the Weir – As the water moved from left to right in the flume at $\bar{V} = 0.7$ cm/s (Fig. 2C), the surface velocity actually decreased slightly as the end plate was approached which, if considered alone, raises a question as to whether pull of the surface film from the weir is actually taking place. However, the progressive decrease in surface velocity from left to right when the surface is only one centimeter wide (Figs. 2B and 2D) indicates that drag from the surface boundaries increases in the direction of flow in these 100 cm long flumes. Surface movement stopped near the bottom end when $\bar{V} = 0.18$ cm/s and $W_s = 1$ cm (Fig. 2B). This indicates that retarding of the water surface involves water surface structure to which an appreciable force must be applied before it yields and begins to deform. Generally, steady state movement of the surface was not proportional to the force applied, and consequently the behavior of the water surface was non-Newtonian. Water in large channels at high flow rates can generally be considered as a Newtonian fluid. Textbooks (e.g. Albertson et al.,

p. 200) treat the definition and properties of Newtonian and non-Newtonian fluids in considerable detail.

The force causing movement of the water surface is at least staying constant and may be increasing as water approaches the outflow end. Consequently, decreasing surface velocities indicated in Fig. 2 B and D as water moves from left to right in the flume when $W_s = 1$ cm, indicate that this surface structure was becoming stronger and more resistant to deformation with distance travelled or with time. This apparent increase in structural strength of the surface with time may be associated with the newly formed nature of this air-water interface, which did not exist as the water came through the supply pipe and is formed or "stretched" into existence during the time (70 to 500 s) that the water moves through the flume.

Formation of "Stiff" Surface Film Structure with Blocked Surface – In the 100 cm long flumes there is an apparent overlapping of the surface strengthening phase and the region in which the surface is receiving significant pull from water going over the weir. This prevented independent evaluation of these two factors and prompted us to block the surface at the lower end, as shown in Fig. 3, to eliminate pull on the surface. Within seconds of inserting the surface block, a surface film structure which reduces surface velocity to about 25% of its upstream velocity developed in the area less than 20 cm upstream from the blocking plate. This "stiff" surface structure builds upstream as flow continues. Typical changes in surface velocity are shown in Fig. 3 A. Appreciable resistance of this "stiffer" surface to compression is indicated by the surface velocities near the surface blocking plate. Near the block, upstream movement of the water surface near the sides of the flume appeared to be almost equal to downstream surface movement in the center of the flume (Fig. 3 A). Effects of these surface velocity variations on midplane subsurface velocity profiles (as measured by dye plumes) are shown in Fig. 3 B. Along the sides of the flume, where surface movement was upstream, the velocity profile of the underlying water intercepts that of the surface. After a few hours this stiff surface structure had generally built back to the inlet end of the flume. When flow at low velocities or low flow rates (i.e., $\bar{V} = 0.18$ cm/s) was continued overnight

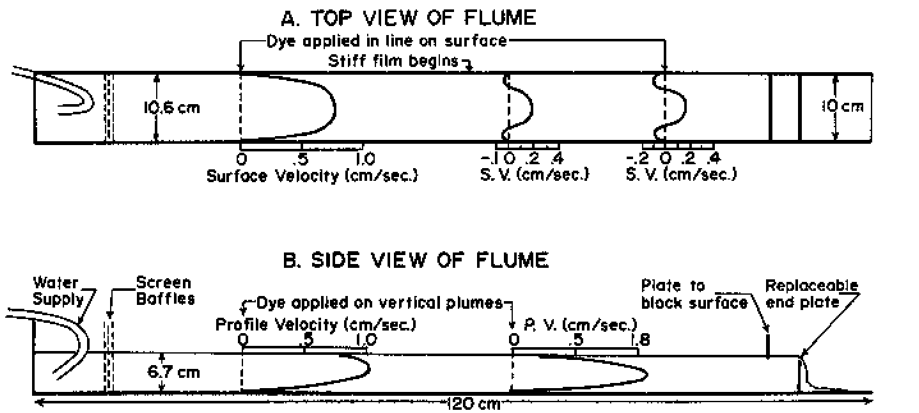

Fig. 3. Velocity profiles which develop when the surface film is blocked and a "stiff" film builds upstream from the block

with the surface blocked at the lower end, movement of the water surface had generally ceased by the following morning. Increasing the water velocity to higher flow rates (i.e., $\bar{V}=0.70$ cm/s) resulted in renewed movement of the surface.

The rates at which the extra stiff surface structure built back from the blocking plate were not always consistent. This raised the question as to whether random progressive contamination of the surface by molecules other than water was responsible for this apparent structure. In efforts to resolve this question the following steps were taken: (1) the flume was covered to prevent contamination from the air; (2) organic (polyvinyl chloride and polyethylene) supply pipes were replaced with copper lines; (3) the lucite flume was replaced by a glass flume and, (4) the well water supply was replaced by distilled water which was transmitted from the still to the flume through tin pipes. Even after these steps were taken, surface velocity measurements indicated substantial variation in the rate of buildup of the extra stiff surface film; but it always built up. In fact, the general tendency seemed to be for this stiff surface to build up faster when the potential sources of contamination were reduced to a minimum. Complete elimination of all surface contaminants is practically impossible. Thus we cannot say that surface contamination does not play a role. However, since the buildup of this extra stiff surface occurs in dirty irrigation water, "clean" well water, and carefully protected distilled water, it appears to be a general phenomenon.

Temperature Effects – One factor affecting surface velocities became apparent when the glass flume was moved into a "clean" chemical laboratory in a room closer to the distilled water supply in an effort to minimize potential sources of contamination. Thin nylon or copper lines (wires) were positioned along the surface to separate the open water surfaces into 1, 2, 4, 7, and 10.6 cm wide longitudinal strips. Average velocities of the mid channel surfaces when the average water velocity was 0.35 cm/s are shown in Fig. 4. In general, surface velocity tended to

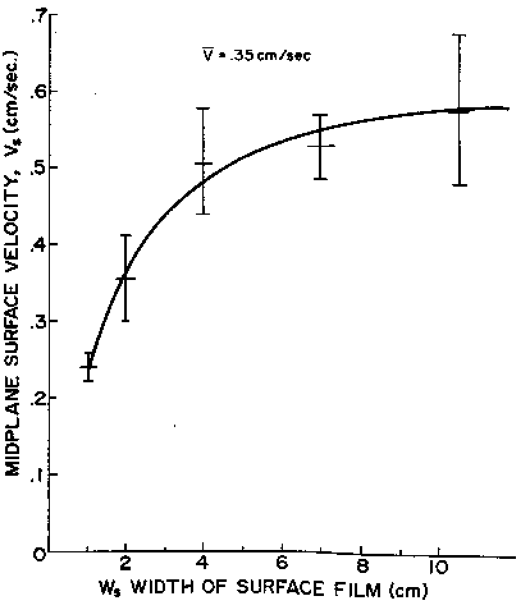

Fig. 4. Water surface velocities along the mid channel of various surface widths using distilled water 20 ± 2 °C

decrease as the surface became narrower. However, the variability of individual observations was much higher than in previous measurements. The midpoint of the vertical lines shown in the figure is the mean of four readings on separate runs and the upper and lower limits of the line represent plus and minus one standard deviation of the mean. Observation of vertically inserted dye plumes showed that when surface velocities were lower than average, the flow elements having the highest velocities were in the bottom portion of the flume and when surface velocities were higher than average, the flow elements having the highest velocities were near the top of the flume as indicated in Fig. 5. When the "nose" of the velocity profile was near the bottom of the flume, dV/dY at the surface was smaller than when the nose was near the surface. When some of the possible causes of the change in elevation, Y_n, of the velocity profile "nose" were investigated, it was found that the water temperature was fluctuating between 18 and 22 °C as the still cycled off and on. When the temperature was increasing, the nose of the velocity profile rose, as indicated in Fig. 5, as the warmer incoming water rose. The resulting velocity gradient dV/dY near the surface was increased which increased shear on the surface and caused the surface velocities to increase. When the temperature was decreasing the nose of the velocity profile lowered, the velocity gradient at the surface decreased, and thus the surface velocity was decreased.

Water was conveyed via underground lines over 40 m long to the laboratory where the initial studies were conducted. Consequently, temperature variations in the water supply were generally less than ± 1 °C. However, the supply water temperature during the initial runs was about 14 °C while the laboratory temperature was about 21 °C. The lucite and glass flumes were flat bottomed and initially rested on a wooden board which supported them. The tendency of the velocity profiles in Fig. 2B to have their noses near the bottom of the flume was probably due to the top of the water in the flume warming more rapidly than that in the bottom. The consequent tendency was for the incoming water to underride the warmer, lighter water which had longer residence time. For the remainder of the study a temperature controller was placed on the water supply which controlled supply water temperature to 18.0 ± 0.1 °C. Water supplied at this temperature (about 3 °C below ambient air temperature) substantially reduced the surface velocity variability. However, monitoring nose elevations of the velocity profiles in successive runs showed that there was still appreciable variation – perhaps as a result of air temperature fluctuations.

Scaled Surface Velocities – Using constant temperature well water "scaled surface velocities" at the center of water surface strips bounded on two sides by

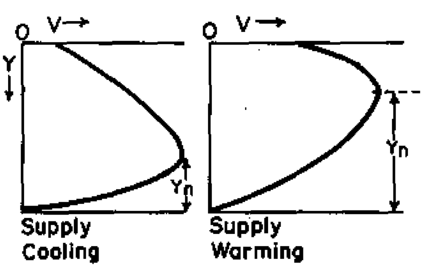

Fig. 5. Effect of water supply temperature cycling on velocity profiles

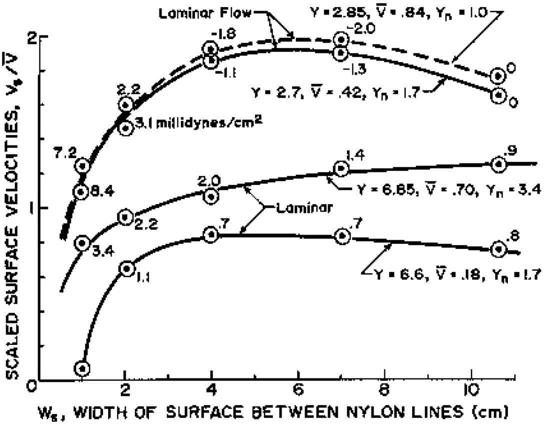

Fig. 6. Surface velocity ratios $V_s/\bar{V}$ midway between nylon lines of the indicated spacing for different flow depths and average velocities along with the corresponding shear forces, F_s for laminar flow in a rectangular flume

nylon lines were measured and are plotted against the widths of those strips in Fig. 6. These scaled velocity rates are measured midstrip surface velocities, V_s, divided by the average water velocity, $\bar{V}$, flowing in the flume. Velocities were measured in the middle reach (70 to 40 cm from the weir) of the glass flume, with the surface film free to flow over the weir (i.e., no surface blockage). Each point is the mean of two independent measurements and the radii of the circles represent the average standard deviations of the means.

Flow in a shallow flume where the width of the flow path is large compared to its depth approximates two dimensional flow and can be represented by the laminar flow equation for flow between parallel boundaries. For this condition, without considering the air-water surface effects, the maximum or surface velocity should be about 1.5 times the average water velocity.

When the flow depth, Y, was about 2.8 cm (two top curves of Fig. 6), and the surface width was greater than two cm, $V_s/\bar{V}$ varied from about 1.60 to 1.95 which might be considered close to 1.5. When the flow cross section is deeper, the viscous laminar flow equation for semi-circular channels indicates that the midplane surface velocity V_s should increase to be about $2\,\bar{V}$. When the depth Y in the rectangular flume was about 6.7 cm (bottom two lines of Fig. 6), $V_s/\bar{V}$ was actually in the range near 1.25 when $\bar{V}=0.70$ cm/s and was not greater than 0.8 when $\bar{V}$ was 0.18 cm/s. These discrepancies show that factors other than hydraulic gradients and viscous deformation play major roles in determining surface velocities.

Interactions Between Surface and Underlying Water Velocities – In general, when water in the flume was at a given depth and $\bar{V}$ was increased, V_s increased more than $\bar{V}$. This indicated that the stiff surface structure was weakened or partially disintegrated by the forces imposed by water moving more rapidly below the surface. The increase in $V_s/\bar{V}$ at higher $\bar{V}$ values was smaller in the top pair of curves in Fig. 6 than for the bottom pair. This was due at least in part to the nose of the velocity profile riding higher in the top set when $\bar{V}=0.42$ than when $\bar{V}=$ 0.84 cm/s. Calculations using (1) and estimates of dV/dY from dye plumes, gave estimates of the forward shear forces, F_s (dynes/cm²) exerted on the center plane surfaces by the underlying water. The numbers next to the plotted points in Fig. 6

represent those estimated forces in millidynes/cm². Negative numbers indicate that the surface is moving faster than the water and is helping pull the water in the midsection of the flume (70 to 40 cm from the weir) where these measurements were taken. Unfortunately, in these short flumes, the force of the underlying water on the surface does not represent the total force tending to disrupt that surface. As will be shown in the next section, the pull exerted on the surface film going over the weir is transmitted, in part, to the surface in the central section of these meter-long flumes where measurements were made. Measurements of V_s made from 20 to 10 cm upstream from the weir showed appreciable decreases in $V_s/\bar{V}$ at the outflow end of the flume compared to those in the flume midsection when $\bar{V}$ was 0.70 or 0.84 cm/s and less decrease when $\bar{V}$ was 0.18 or 0.42 cm/s. This is further evidence that the newly formed surfaces are in the process of becoming stiffer during the few minutes of their existence. It also points out that these flumes (100 cm long) were not long enough to allow the maximum development of stiff surface when average water velocities >0.5 cm/s.

It had been expected that values of $V_s/\bar{V}$ would be low when the surface width, W_s, was 1 cm wide and that $V_s/\bar{V}$ would increase as W_s increased. Measured $V_s/\bar{V}$ in many cases reached a maximum when W_s was 4 or 7 cm and was slightly, but significantly, lower when W_s was 10.6 cm. Observations of surface velocities using dye lines applied on the surface crosswise to the flow direction showed differences of the type shown in Fig. 7. When there were no nylon lines dividing the surface, the surface velocity was always >0. However, when the lines were in place as indicated, the water surface near the top end outside the lines actually moved upstream, then into the center channel and downstream. In the downstream reaches of the channel, the surface outside the lines moved downstream as expected. Apparently a surface film was being generated in the upper reaches outside of the lines, which joined the surface generated between the screen baffle and the upstream end of the lines and was pulled downstream between the lines. Forces pulling the surface downstream between the lines include drag by the maximum velocity water, probably aided to some extent by a pull on the surface from water passing over the weir (see next section). Consequently, one possible explanation of the higher $V_s/\bar{V}$ values when $W_s=4$ or 7 cm than when $W_s=10.6$ cm is that generation of the surface film outside the lines contributes to the needed surface, the tension is released to some extent, and the surface allowed to move

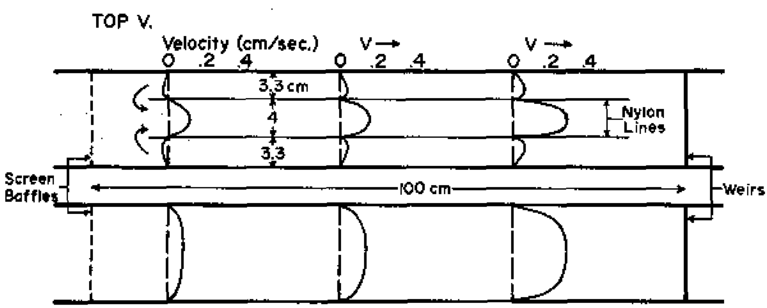

Fig. 7. Surface velocities observed with and without nylon lines dividing the surface. (Average water velocity, $\bar{V}=0.18$ cm/s, no surface blockage and water depth of 6.6 cm)

downstream slightly more rapidly in the middle section of the flume. However, this effect plus the stiffening of the surface as it travels downstream, and the pull on the surface due to water going over the flume, are all taking place at the same time in these 100 cm long flumes and their interpretation and evaluation are difficult and tentative.

Tests in a "Long" Semi-Circular PVC Flume

To separate the zone influenced by the surface pull of water going over the weir at the bottom end from the zone influenced by surface formation at the top end, a PVC flume 450 cm long was used. In this flume, with a semicircular cross section of radius 5.2 cm, the type of surface velocities measured as a function of distance from the bottom end weir are shown in Fig. 8. The top end baffle screen was 420 cm upstream from the weir.

Surface Velocities Without Blockage – The top curve in Fig. 8 was essentially a steady state surface velocity distribution with the channel surface 10.4 cm wide. Water flowed at an average velocity of $\bar{V}=0.87$ cm/s and exited over the bottom end weir with no surface blockage. The points are averages of two measurements and the vertical extents of the circles or crosses are two times the average standard deviation of the means for the points associated with that curve.

The mid channel surface velocity in a semicircular cross section of this type should be about twice the average water velocity if the surface film at the air-water interface were not offering resistance to flow due to its attachment to the walls and its own resistance to shear. Measured velocities, V_s, of the surface at the mid

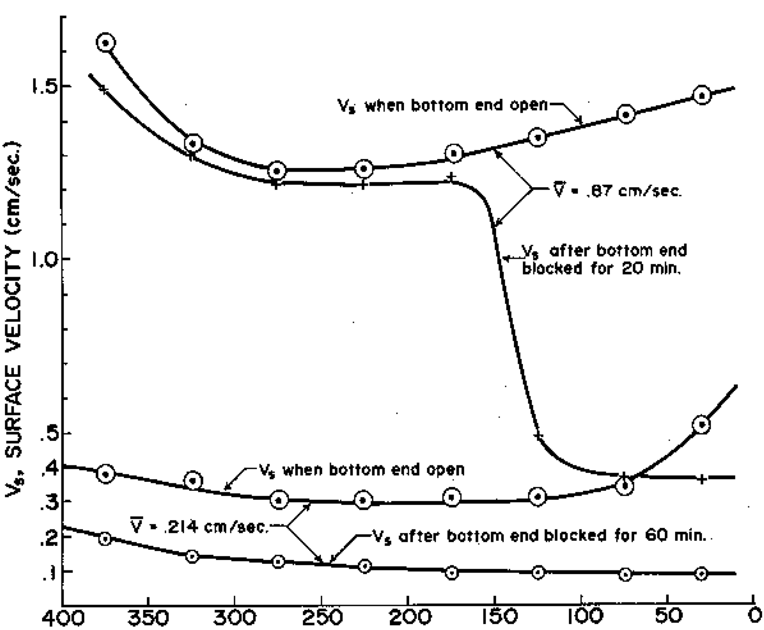

Fig. 8. Water surface velocities, V_s, in long PVC flume

channel were considerably less than 2 cm/s), indicating that the surface was stiff and offered considerable resistance. This resistance apparently increases considerably as water proceeds from the baffle screen (420 cm upstream from the weir), through the following 150 cm where the mid channel surface velocity decreases from more than 1.6 to less than 1.3 cm/s. Mid channel surface velocity begins increasing about 150 cm from the weir and was back up to 1.46 cm/s in the section from 50 to 10 cm from the weir, apparently as a result of the pull on the surface film by the water moving rapidly over the weir.

Surface Velocities with Blockage – After velocities without blockage were measured, the surface at the bottom end was blocked about 5 cm upstream from the weir and 20 min later the mid plane surface velocities indicated by the crosses (Fig. 8) were measured. The extra stiff surface had already developed upstream to a distance of over 125 cm from the weir as indicated by the low surface velocities. The velocities upstream from the extra stiff surface appeared to be decreased slightly, but in general followed the same pattern as before the surface was blocked. The relatively constant velocity in the range from 275 to 175 cm upstream from the weir indicates that in this reach the formation of "stiff surface" was being balanced by the breakdown of that surface by shear forces from the moving water underlying the surface.

The surface block was removed and the average velocity of the water, $\bar{V}$, was reduced to 0.214 cm/s. After imposing these conditions for about 30 min, the mid plane surface velocities were as indicated in the second curve from the bottom in Fig. 8. As in the 100 cm long flume, the increase in velocity resulting from pull on the film by water going over the weir causes a relatively large increase in the surface velocity near the weir. However, this effect does not appear to extend as far upstream as when the water velocity was faster. This may be due to less disruption along the edge of the surface in the slower moving case and consequent greater dissipation of a larger portion of the pull force, exerted on the surface film at the weir, on the sides of the flow channel rather than on upstream portions of the film.

Blocking the surface at the lower end of the channel for 60 min ($\bar{V}$ was 0.214 cm/s) resulted in the velocities indicated in the bottom line in Fig. 8, indicating a stiffening of the surface throughout the length of the flume, with surface at the inflow end being only about half as stiff as the outflow end.

Surface Film Strength – Water was left running overnight in the flume with the surface blocked and $\bar{V}=0.214$ cm/s. By morning there was no movement of the surface in any part of the flume. The film started moving again when $\bar{V}$ was increased to 0.47 cm/s. In general, data of the type shown in Fig. 8 indicate that at these average velocities ($\bar{V}<0.9$ cm/s) in the flat middle reach of these curves, sufficient time had elapsed for the surface to develop and the pull factor discussed above was not affecting the surface velocity. Consequently, this middle reach provided the best place to evaluate the effects of force on deformation of the surface film when it is fully developed. Mid plane surface velocities measured in the middle reach without surface blockage at the outflow end are plotted against the average water velocity in the top curve in Fig. 9. Extrapolation of the lower portion of this line indicates that a finite force must be exerted by the water on the 10.6 cm wide surface before the surface begins to move and therefore, the surface film on water does not behave as a Newtonian fluid.

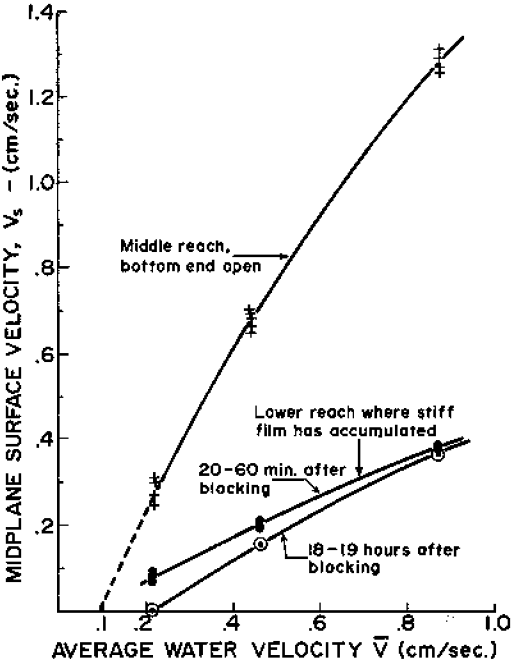

Fig. 9. Velocity of water surface along the center of a PVC flume with a semicircular flow path 5.2 cm in radius and 500 cm long

The second line down in Fig. 9 is drawn through points indicating velocities measured in the lower reaches 20 to 60 min after placing the surface block when the stiff surface had developed. The set of values obtained after the surface had been blocked for 18 to 19 h (bottom line) indicates that under this blocked condition the stiff surface continued to strengthen for at least several hours and its strength became great enough to resist the disruptive force of the underflow water when $\overline{V}$ was 0.214 cm/s so that it became still.

The curved opaque walls of the long flume prevented direct measurement of $[dV/dY]_s$, but from the values of $\overline{V}$, V_s and the depth of the water, $[dV/dY]_s$ was estimated to be 0.25 cm s^{-1} cm^{-1}. From this value and equation (1) it is estimated that the force of the moving water on the surface was 0.0028 dynes/cm^2 when that surface was still. This indicates that shear forces on the surface greater than 0.0028 dynes/cm^2 are required to break the surface loose and to start it moving in this channel where the surface width, W_s, was 10.4 cm and the blocked surface with its stiff film had become stationary.

Similar estimates for the intercepts of the data taken when the 10.6 cm wide surface was not blocked indicate that forces of the order of 0.0013 dynes/cm^2 would be necessary to break the normal strength surface film from the sides of the flume and start it moving. This compares with 0.0027 dynes/cm^2 exerted on the film by underlying water when the surface was disrupted in a one cm wide channel in the 100 cm long flume.

As previously discussed, and as is apparent from the curves representing open end flumes in Fig. 8, some of the pull on the surface film caused by water moving rapidly over the weir may be transmitted to the film upstream to a distance of over

100 cm. Consequently, the total force acting on the film to disrupt it in the short flumes with measurement sections 40 to 70 cm upstream from the weir was probably greater than 0.0014 dynes/cm².

If the surface behaved as a Newtonian fluid, with deformation proportional to force, the curves representing surface velocity would be parabolic. The blunt nosed curves observed (Fig. 3 A and Fig. 7) for surface velocities are further evidence of non Newtonian behavior of the surface. Most of the deformation and disruption of the surface appears to be taking place at the edges of the flow channel. This is compatible with the fact that forces exerted in the middle of the channel on the surface are generally transmitted to the edge of the channel and consequently, the shear force at the edges is the summation of forces across the channel, and is higher than in the mid sections. For a film that has structure and an appreciable yield point, the initial yield area, as force on a still film is increased should be near the film edges, as was observed. It also follows that in a long narrow strip of surface, the shear force per unit area, F_{sy} (dynes), on the surface required to cause initial yield of the surface should be inversely proportional to the width, W_s (cm) of the strip, i.e.,

$$F_{sy} = k / W_s. \tag{3}$$

Calculations of F_{sy} of 0.0028 dynes in a 10.6 cm wide flume from the data in Fig. 9 leads to a k value of 0.00026 dynes/cm when the surface is not blocked.

Practical Implications of Resistance to Deformation of the Surface Film

Water Movement in Unsaturated Soil – Using the k values of 0.00026 dynes/cm extrapolating via (3) to film widths expected during unsaturated flow in soils and estimating dV/dY values from ranges of water film velocities and thicknesses that normally occur therein, it is tentatively concluded that the air-water interface in unsaturated soils is generally stationary. If this is true, materials that tend to accumulate at air-water interfaces would not be convected through unsaturated soils by the moving water. Moreover the perimeter exerting drag on water moving through the soil will include the air-water interface in addition to the mineral-water interface.

Water Movement in Open Channels – When the velocity of water is low so the surface film structure remains intact, strong, and attached to the sides of the channel, the velocity of that surface is substantially lower than the most rapidly moving fluid. Where the width of the channel surface decreases, or the surface is blocked within a few meters downstream from the observation point, this reduction in the surface velocity can cause the surface film to exert a restraining drag on the moving body of water, similar to that exerted by the solid perimeter of the water body. Under these conditions, the hydraulic radius, commonly calculated as the cross sectional area divided by the perimeter exerting drag on the moving fluid body, should probably be reduced by an amount depending on the relative extent of the surface film and the degree of its mobility. In broad flat channels where the surface is stationary, the film at the air-water interface can exert almost as much drag on the water body as the solid boundary. Under these conditions the effective hydraulic radius would be only about half the value calculated without considering drag of the surface film.

Small amounts of straw, scattered over a furrow prior to irrigation have substantially increased water depth in the furrow and infiltration and reduced erosion (e.g., Berg 1983). Close observation of these furrows showed occasional straws lodged across the furrows which reduced the velocity of the surface film and may have been a significant factor in the deeper flow and consequent increased infiltration and decreased erosion.

Future Work Needed – To accurately quantify the strength of the normal and stiff surface films, verify (2) and to develop additional equations for behavior of the films will require a long covered flume, temperature control of the water and the facilities to vary water flow rate and to divide the surface precisely into long narrow strips oriented in the direction of flow.

Conclusions

When a slow moving ($V_s < 2$ cm/s) water surface is blocked, velocity of the surface film immediately upstream from the block decreases to a small fraction of its value when the surface is not blocked, even though the average water velocity remains constant. Relatively slow motion of this surface imposes a drag on the liquid moving below the surface, with the liquid immediately below the surface film having essentially the same velocity as the surface film.

When the flow cross section converged near the surface, i.e. as water went from a channel over a weir, the fast moving water passing over the broad weir blade developed a pull force on the surface film that affected surface movement as far as two meters upstream from the weir.

As water left a pipe and travelled downstream in a channel, the resistance to deformation of the new surface film, as indicated by the velocity of the midchannel surface, increased for several minutes until it reached a steady state.

Surface films on water in a channel 10.4 cm wide were sufficiently rigid to withstand a shear stress of 0.0014 dynes/cm^2 before the film yielded, when the bottom end of the surface was not blocked. When the bottom end of the surface was blocked, under the same conditions, the surfaces were sufficiently rigid to withstand a shear force of 0.0028 dynes/cm^2 before they yielded. This initial rigidity and subsequent surface movement as shear increases, show that water surface films do not behave as a Newtonian fluid (i.e., shear rate proportional to shear force).

The blunt nosed (non parabolic) nature of surface velocity distribution in the test channels were compatible with the non Newtonian behavior of the surfaces and indicate that most of the surface film shear takes place near the edges of the channel where the shear stress is an accumulation of all forces exerted on the surface from the center to the edge of the channel.

Surface films and their effects, as described above, were present in dirty irrigation water, clean well water, and distilled water that was delivered to a carefully cleaned and protected glass flume in a clean laboratory. While even the latter conditions did not completely eliminate the possibility of surface contamination playing a role in the surface film phenomena described above, the observations indicate that the phenomena are practically universally present in laminar open channel flow.

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