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WATER INFILTRATION IN LAYERED SOILS WHERE A FINE TEXTURED LAYER OVERLAYS A COARSE SAND

Robert J. Glass, Jean-Yves Parlange and Tammo S. Steenhuis*

ABSTRACT

Wetting front movement in two-layered porous media in which the top layer has a lower permeability than the underlying layer was studied in the laboratory. The effects of initial moisture content on flow behavior were determined through systematic laboratory experimentation. The wetting front tends to lose its one-dimensionality as it moves into the coarse layer, the more so when the initial moisture content is lower. When the one-dimensional wetting front breaks down, fingers form creating preferred paths for the movement of water. The width of the fingers is small for initially dry soils while for initially wet soils the fingers are wider. The fingers are also slower moving and drier when the soil is initially wetter, suggesting that air entrapment in wet soils is an important factor. Fingers widen in time due to lateral diffusion until a steady state configuration is obtained. Vertical transport, however, remains largely confined to the original finger or "core" area.

INTRODUCTION

Infiltration into layered soils has intrigued soil scientists and hydrologists for many years. A large number of papers dealing with one dimensional wetting fronts have been written (e.g. Takagi, 1960, Childs and Byborji, 1961, Hillel and Gardner, 1970, Fok, 1970, Aylor and Parlange, 1973, Ahuja, 1974, Bouwer, 1976). However, when infiltration takes place in a layered soil system with a fine layer overlying a coarse layer, the one dimensional wetting front may become unstable. Wetting front instability is still not fully understood, but it can have a great importance in groundwater contamination. When instability occurs, the travel time through the unsaturated zone is greatly diminished and the amount of soil with which the pollutant can react is decreased.

Wetting front instability was first noted in experiments by Tabuchi (1961), and later by Miller and Gardner (1962), Peck (1965), and Smith (1967). The first laboratory experiments to explicitly demonstrate the phenomenon in dry layered soils were conducted by Hill and Parlange (1972). The stability of wetting fronts was analyzed by Raats (1973) and Philip (1975). Experiments conducted by White, Colombera and Philip (1976, 1977) demonstrated that Philip's analysis characterized the width and spacing of fingers in Hele-Shaw cells but not in soils. Parlange and Hill (1976) derived a relation for the diameter of a finger using integral properties of the soil. They reasoned finger diameter to be on the order of the ratio of the sorptivity squared to the saturated conductivity.

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*Graduate Research Assistant, Professor and Associate Professor respectively, Dept. of Agricultural Engineering, Cornell University, Ithaca, NY 14853 USA.

Since it is rare that field soils are uniformly dry, it is important to understand the effect of initial moisture content and its distribution on wetting front instability. The effect of initial moisture content on the width of fingers can be seen in the photos of Smith (1967) showing a narrow finger moving down through dry sand to widen several fold when it entered a wetted region at the bottom of the experimental chamber. Initial moisture content also may effect the stability of the one dimensional wetting front as suggested by Diment, Watson and Blennerhassett (1982) and Diment and Watson (1983, 1985). However, Starr et al (1978) found fingering to occur in a field soil with non zero initial moisture content.

This paper presents the results of laboratory experiments that determine the effects of initial moisture content distribution on wetting front instability in two-layered sand systems in which the top layer has a lower permeability than the underlying layer. Both uniform initial moisture content and nonuniform initial moisture content generated by previous unstable infiltration cycles are explored. Single fingers are also simulated under uniform initial moisture conditions and a simple model for a steady state finger in uniformly wet soil is proposed.

EXPERIMENTAL DESIGN

Two types of laboratory experiments were conducted. Two-layer infiltration experiments with a fine sand layer overlying a coarse sand layer were designed to determine the effect of the initial moisture distribution on flow field behavior. Point source infiltration experiments were also designed to simulate an isolated finger in the coarse layer under both initially dry and initially wet moisture conditions so that finger structure and lateral movement of water could be more easily explored.

The need of visual observation and documentation required the exploration of a two dimensional infiltration flow field. Since the widths of all fingers were greater than 1 cm, the space between the walls of the slab infiltration chamber was made to be 1 cm to force the two dimensional flow field. The width of the chamber was 30 cm, the height of the coarse bottom layer was 81 cm and that of the top layer in the two layer experiments was 8 cm. The slab chamber was composed of 10 cm high plastic sections stacked in a steel frame. A small gap between sections allowed air to escape. The gaps were small enough that the coarse sand could not escape and large enough that water never entered them during an experiment.

White silica sand used commercially for sand blasting was dry sieved through a nesting sequence of 8-inch wire mesh sieves (US sieve series numbers 14, 20, 30, 40, 50, 60, 80, 100, 140, 200) by a mechanical shaker. The 14-20 sand fraction was used for the coarse textured bottom layer while several of the others were used for the fine textured top layers (see Table 1). The sands obtained from dry sieving were cleaned to assure a uniform contact angle. Each sand was boiled in a .5% solution of Pex laboratory glass cleanser used for analytical and research laboratory glassware for 1/2 - 3/4 hours. The sand was then rinsed with warm tap water 15 times, the soap disappearing by the 5th to 8th rinse. Next, the sand was boiled in tap water for 15 minutes and rinsed an additional three times to assure the removal of all soap. The sand was then rinsed five times with distilled water and allowed to dry in aluminum trays in a drying oven at 60°C for a week.

The chamber was filled with sand through a slotted two-dimensional funnel attached to the top of a 68 cm extension that fitted above the slab chamber. The extension contained a wide wire mesh grate 10 cm from its bottom that acted as a falling sand randomizer. Sand was poured into the funnel and the level in the chamber rose evenly across its width eliminating heterogeneities. For the two layered experiments, the textural interface was made as flat as possible and a thin piece of cotton cloth was placed between the layers to keep fine particles from filtering down into the bottom layer. The sand slab was packed by raising the slab chamber and frame up 1.5 cm and dropping it back onto the platform 200 times. After packing the bottom layer, at least the top 10 cm of sand overburden was removed as this had a higher porosity than below where a constant porosity of 42% was found for the 14-20 sand fraction.

Distilled water with a constant low nonadsorbing dye concentration (.025% solution of USDA Red #3) was used in all experiments. The two layer experiments were started by ponding the fluid to 1.5 cm quickly and evenly across the top of the fine textured layer through a plastic pipe containing many small holes. A pump applied fluid to the plastic pipe and the depth of ponding was maintained constant throughout the twenty-four hour duration of each experiment by a take-off tube that was connected back to the pump. In the point source experiments, the fluid was applied to the midpoint at the top of the coarse layer from a 50 ml burette. A constant flux was achieved by maintaining the fluid level in the burette with a constant head mariott device. In both types of experiments, the velocity field at a point in time was visualized by injecting pulses of blue dye (1% solution of USDA blue #2) into the water supply.

Flow field data were recorded with a Bolex movie camera set to take a frame every 2.5 seconds. Data was pulled from the film by projecting it onto a screen and then tracing the wetting front position with time on acetate sheets. The flux out the bottom of the chamber was measured through 10 drip sections each having a width of 3 cm. The drip sections restricted the lateral movement of water at the bottom of the chamber and thus enabled the monitoring of the flux through individual fingers and its change in time.

The initial moisture distribution in the two layer experiments was varied systematically by running three consecutive infiltration experiments in each experimental porous media packing. In the first experiment, denoted by a lower case "a" following the experiment number, the sand was initially dry. This experiment was conducted for twenty-four hours and then the chamber was sealed to inhibit evaporation and allowed to drain for twenty-four hours. The moisture content field at the end of the drainage cycle formed the initial moisture field for the second experiment. The second experiment, denoted by a lower case "b" following the experiment number, was then conducted for twenty-four hours. In preparation for the third experiment, the bottom layer was saturated, sealed and drained for another twenty-four hours. A homogeneous moisture field (6%) in the bottom layer resulted and formed the initial moisture field for the third experiment also conducted for twenty-four hours and further denoted by a lower case "c" following the experiment number. In this way the first ("a") and third ("c") experiments represented the extreme initial moisture content conditions (i.e. uniform) often used in analytical and numerical studies of infiltration flows. The second ("b") experiment may be mimicking more realistically a field situation where initial moisture content varies from point to point. All in all, nine two-layer experiments were conducted (see Table 1). Three different fine textured layers were used on top of the coarse 14-20 sand with the three consecutive infiltration cycles ("a", "b" and "c" experiments) performed on each layered system.

The effect of initial moisture content in the point source experiments was also examined by performing experiments at two uniform initial moisture contents: initially dry and after saturation and drainage for 24 hours (6% moisture content). These initial moisture content fields compare to the "a" and "c" two layer experiments respectively described above. Six experiments were conducted with fluxes of 10, 20 and 30 ml/min supplied to the top of the coarse sand at the two uniform initial moisture contents (see Table 2).

PRESENTATION AND DISCUSSION OF RESULTS

Two-Layered Experiments

Table 1 gives the results of the two layer experiments. Figure 1a is a drawing of the wetting front position at time increments of one minute in experiment A6a. As designated in Table 1, A6a was a two-layer experiment with a top layer of 100-140 sieve fraction sand and a bottom layer of 14-20 sand conducted under uniform dry initial moisture content conditions. As shown in figure 1a, at the end of the first minute, the wetting front has moved across the textural interface and fingers have begun to form in the bottom layer. The two-layer infiltration experiments yield a clear qualitative description of the unstable flow field instigated by the increase in pore size across a textural interface, its development in time and the effect of the initial moisture.

For infiltration into initially dry two-layer sand systems ("a" experiments), the unstable flow field may be divided into three zones: the top layer, the interface between the two layers, and the fully developed finger zone. Flow in the finer top layer is characterized by an initially flat wetting front and vertical streamlines. The interface between the two layers allows water to pass into the bottom layer at discrete, fairly regularly placed locations or "point sources." Small fingers form under these sources and then many merge within the next 10 cm to form wider fingers. These fingers then pass into the fully developed finger zone which is characterized by fairly constant finger velocity, width and spacing. Occasionally in this zone, a merger of fingers will occur to produce a faster moving wider finger.

Three stages in the development of the flow field in the initially dry experiments may be delineated: a) an initial "rapid" period, b) a transitional "slow" period and c) a final period of almost no change. The initial "rapid" period is characterized by rapid change in wetting front position with time. This period is shown in figure 1a for experiment A6a. It continues until the descending fingers arrive at the water table or, in the case of the laboratory experiments, when they arrive at the bottom of the chamber.

TABLE 1. SUMMARY TABLE TWO LAYER EXPERIMENTS

Experiment #	Top Layer Sand Fraction	Initial Moisture Conditions	Flux through System (cm/min)	Stable or Unstable
A6a	100-140	Dry	1.95	Unstable
A6b		1 day drainage of A6a	1.66	Unstable
A6c		Saturation then 1 day drainage	1.27	Marginally Unstable
A9a	60-80	Dry	4.15	Unstable
A9b		1 day drainage of A9a	3.45	Unstable
A9c		Saturation then 1 day drainage	4.88	Marginally Unstable
A8a	40-50	Dry	11.97	Unstable
A8b		1 day drainage of A8a	7.10	Unstable
A8c		Saturation then 1 day drainage	2.26	Marginally Unstable

The transitional "slow" period is characterized by very slow changes in wetting front position as wetting fronts diffuse laterally into the dry areas between fingers. This period is shown in figures 1b and 1c for experiment A6a. The diffusing water creates a less saturated "fringe" area around the more saturated "core" areas defined by the initial location of the fingers in the dry porous medium. Dye pulses demonstrate that most of the flux in the system continues to occur downward in these core areas. Occasionally during this period a finger itself will become unstable and a small split-off finger or "dendrite" may form and move slowly downward to the water table. This period ends when the lateral wetting fronts have moved through all the porous media and some moisture is present at all locations.

The final period is characterized by no perceptible change in the flux direction or magnitude within the flow field. Moisture content differences are visible between the core areas and the fringe areas and the addition of blue dye verifies that most of the flow in the system continues to occur downward through the core areas. This period has been documented to last for at least 10 days of continuous infiltration (the duration of our longest experiment).

In the "b" experiments performed with an heterogeneous initial moisture content left after drainage of the "a" experiments, fingers form in the same locations as in the "a" experiments. This identity of finger path can be seen in figure 1d, the composite drawing of experiment A6b. An increased movement of water across the textural interface in between the initial point sources, however, was evidenced by dye tracer pulses. Movement in the former fringe areas is enhanced but the size and configuration of the core areas match almost exactly with those of the previous initially dry experiment. Basically, the heterogeneous, initial moisture content field formed by a previous unstable wetting cycle allows a rapid transition into the third and final flow period, seen in the "a" experiments, by enhancing movement in the fringe areas. As evidenced by dye tracer pulses, the majority of the flow continues to be conducted by the core areas with no change in flow field during the duration of the 24 hr infiltration cycle.

In the final "c" experiments, the initial moisture content in the bottom layer is at a uniform 6%. As exemplified in figure 1e, the composite drawing of experiment A6a, the wetting front becomes wavy as it moves into the bottom coarse layer and the amplitude of the wave increases as the wetting front proceeds downward. Thus, the wetting front is indeed unstable, but since the wavelength of the disturbance is on the order of the width of the chamber, separate fingers cannot form. The dramatic finger structure found in the dry and heterogeneous initial moisture content distribution experiments is not observed. However, after the wetting front has reached the bottom of the chamber, blue dye pulses show an exaggeration of the initial wave form of the wetting front thus indicating faster movement of moisture in wide "core" areas associated with the location of the initial bulges in the wetting front. The flow field shown by the blue dye pulse was constant throughout the duration of this final 24 hr infiltration cycle. Thus, even though the flow field looked completely uniform once the wetting front had reached the bottom of the chamber, flow indeed deviated from the uniform.

The flux distribution of the "a", "b" and "c" experiments at the bottom of the chamber through the ten drip sections and its standard deviation can be used as an additional measure of the uniformity of the flow field: the more uniform, the lower the standard deviation. In all experiments the standard deviation of the percent total flux across all ten drip sections decreases from dry ("a") to heterogeneously wet ("b") to uniformly wet at field capacity ("c") initial moisture content conditions. For example, in A6a, five fingers flow into the set of drip sections causing flow out of all but two of them. Over time, as lateral wetting fronts move into the dry sand between finger core areas, the fringe areas begin to contribute to the flux distribution by smearing out the effect of the core areas. Flow from the sections with the lowest fluxes has increased while flow from those with the highest fluxes has tended to decrease, thus decreasing the standard deviation from 9.21 to 7.82 in 24 hours. In A6b, the standard deviation decreased to 5.28 and did not change during the 24 hr infiltration cycle. As has been described above, the core areas present in A6a are also core areas in A6b; however, the fringe areas were seen by dye pulses to be more active in conducting water than in A6a at 24 hours. The decrease in the standard deviation shows this increased fringe area conduction as well. Experiment A6c shows a further reduction in the standard deviation of the flux distribution to a constant 1.45 throughout this final 24 hr infiltration cycle. The influence of high, uniform initial moisture content is to further uniformize the flow field for the width of our chamber. However, the fact that the standard deviation is not lower supports the result of dye pulses that the flow is still not entirely uniform.

In summary, from the two-layer experiments, five major points can be remarked. First, the textural interface provides a very strong perturbation, discritizing the uniform flow at a number of discrete point sources. Second, under dry initial conditions, fingers that form have a dramatic moisture content structure - very wet inside the finger and very dry outside the finger. Third, over time, slow sideways diffusion of moisture from finger core areas takes place resulting in a steady flow field with finger core areas persisting and continuing to conduct most of the flow. Fourth, on subsequent infiltration cycles, flow remains concentrated in the same core areas as first delineated fingers thus emphasizing the importance of slight variation of initial moisture content between past fringe and core areas on the heterogeneous moisture movement and the persistence of fingers. Fifth, when the initial moisture content is uniform and high, fingers widen and can coalesce giving the appearance of an almost uniform flow field but with horizontal variation in flux still apparent.

Point Source Experiments

In order to study in detail the effect of uniform initial moisture on individual fingers, isolated fingers were simulated by applying a known flux of water directly to the top of the coarse layer from a burett as a point source. This procedure both yielded the same structure as a finger and mimicked the nature of the textural interface as a distribution of point sources. An analogous technique was used by Saffman and Taylor (1958) to generate one finger in a Hele-Shaw cell in their exploration of viscous instability in saturated porous media. Table 2 gives the point source experiments conducted. Composite drawings of experiments D6 and D3, in which the initial moisture content was dry and at 6% respectively and the supplied flux was 20 ml/min, are shown in figures 2a and 2b.

TABLE 2. SUMMARY OF POINT SOURCE EXPERIMENTS

Experiment #	Sand Fraction	Porosity (%)	Initial Moisture Content θ_i	Flux Through Finger, (ml/min)
D7	14-20	42	Dry	10
D6	14-20	42	Dry	20
D8	14-20	42	Dry	30
D4	14-20	42	6%	10
D3	14-20	42	6%	20
D2	14-20	42	6%	30

In the initially dry experiments D6, D7 and D8, single fingers generated by the point source at the top of the coarse layer have the same velocity and width for the flux supplied as fingers from initially dry two-layer experiments. The core area is well defined and the widening of the fringe area can be seen to be due to both lateral and downward movement within the fringe areas. As in the initially dry two-layer experiments, downward moving bulges that occasionally develop into dendrites are present in all runs indicating the importance of gravity on movement within the fringe areas. These dendrites also point to the marginal stability of the flow within the fringe region where the downward flux is much less than the saturated conductivity.

In experiments D2, D3 and D4, where the initial moisture content is uniform and at field capacity (6%), the flow pattern for point source discharge is qualitatively similar to the two layer uniform initial moisture content "c" experiments. Moisture content variations appear to be much more subdued, showing no dramatic core area and fringe area as seen in the dry experiments. Dye pulses, however, show a wide area in the middle of the fingers where most of the flow occurs. The fingers are much wider, have a much lower velocity than in the initially dry cases and lateral movement is much enhanced.

The moisture content of a finger averaged over the wetted region as it grows to the bottom of the chamber may be determined by dividing the volume of water infiltrated plus the initial moisture content by the wetted region's volume. This average moisture content as a function of time is plotted for all the simulated fingers in figure 3. It is clear that the fingers in the initially dry experiments have a much higher moisture content than those in the initially wet experiments.

In order to quantify lateral moisture movement, the width of the finger is measured in time. In initially dry experiments, fingers widen uniformly with depth once the finger tip has passed but the width was affected by the erratic downward moving bulges at the sides of the finger (see figure 2a). Thus, the region of the finger that was not affected by the bulges for the longest time was used to determine finger widening with time. As edge bulges were not present in the initially wet experiments, finger width was measured at each depth corresponding to the position of the finger tip at each minute after the onset of infiltration. The lateral diffusion time was zeroed at each of these depth positions by subtracting the infiltration time to the particular finger tip position. For example, in Figure 2b, position 5 corresponds to the horizontal line drawn at the finger tip position at the fifth minute after the start of infiltration. Lateral diffusion time for this depth position is then set to zero at the fifth minute. Finger widths at subsequent times are then measured along the horizontal line at that position.

One half the finger width is plotted against the square root of time for the initially dry experiments in figure 4. Figure 5 shows this plot for each depth position in the initially wet experiment D4. The other initially wet experiments give similar results. Rapid finger widening as the finger tip passes followed by a linear growth with $\sqrt{t}$ is seen in the dry experiments in figure 4. The initial rapid widening as the finger tip passes followed by a linear growth with $\sqrt{t}$ is also seen in figure 5 at each depth position, but as time increases, the linear behavior deviates with the slope decreasing steadily. Figure 5 shows that when the slope approaches zero asymptotically at large time, the finger width increases with depth for the initially wet soil. In initially dry soil, however, figure 4 shows no consistent change in width of the fringe area with depth.

The widening process may be broken into three stages. The first stage occurs almost instantaneously for the dry experiments and within the first 10 - 20 seconds for the initially wet experiments as the center core area of the finger falls like a plug through the coarse sand. The second phase shows the linear growth as a function of $\sqrt{t}$ in the figures. The final stage is when the steady state is approached resulting from the depletion of the core by lateral diffusion. Since water not only moves laterally but is pulled downward by gravity, a steady state envelope will slowly be approached with a width which increases with depth.

This approach toward the steady state envelope is clearly seen for the fingers in the initially wet sand as the growth in one half the width vs $\sqrt{t}$ deviates more and more from its linear dependence at large time. The final stage is not seen in the initially dry experiments even after times an order of magnitude greater than in the initially wet experiments. It is hypothesized that the time scale of the widening process is stretched relative to the wet experiments. That is, if we were to let the experiment continue for a very long time, the third stage would eventually become apparent.

To begin to explain the differences between fingers that form in initially dry or wet soils, we hypothesize that air entrapment plays a crucial role. When the sand is initially wet, air entrapment changes the relative time scales for horizontal and vertical diffusion processes. When air is entrapped, the largest pores are cut from participation in conducting water, the effective porosity is lowered and the tortuosity is increased thus effectively changing the properties of the porous medium. This change is thought to affect the conductivity, and thus the downward movement driven by gravity, much more than the capillary properties of the medium and so the ratio of capillary to gravity forces increases with air entrapment resulting in a wider more diffusive finger.

In summary, from the point source experiments, three main observations can be made. First, compared to fingers in initially dry soil, fingers in initially wet soil move more slowly, are wider and dryer and exhibit an enhanced lateral diffusion. Second, fingers in initially wet soil widen in time to approach a steady state envelope which widens with depth with most of the flow continuing to be conducted within a wide core region. Third, fingers in initially dry soil widen very slowly in time and the width of the fringe area varies little with depth, the initial core region continuing to conduct almost all of the flow.

Simple steady state model of a two dimensional finger

To increase our understanding of fingers, a simple steady state model is proposed from which several of the observed features of simulated fingers may be reproduced. A simple model is preferred as the fingering phenomenon is complicated and insight is desired rather than theoretical rigor. Since we do not know the top boundry condition for a finger, at $z = 0$, the finger is simply taken to have a uniform flux per unit area, Q, across the strip $-h < x < h$ where x is the horizontal coordinate and z is the vertical coordinate taken position downward. If we assume that α is constant with

$$\alpha = D^{-1}\frac{dK}{d\theta} \approx \frac{2\,K_s(\theta_s - \theta_i)}{S^2} \quad \ldots \quad (1)$$

where K is the hydraulic conductivity, θ the moisture content, D the moisture diffusivity and S the sorptivity with the subscripts i and s denoting initial and saturated values respectively. Continuity of mass becomes

$$\frac{\partial^2 K}{\partial z^2} + \frac{\partial^2 K}{\partial x^2} = \alpha \frac{\partial K}{\partial z} \quad \ldots \ldots \ldots \ldots \quad (2)$$

The solution of (2) with Q given at z = 0 has been found by Batu (1978) and is rather complicated. In order to obtain a simple solution that will give better insight, we will ignore diffusion in the z direction (slender plume assumption) thus reducing equation (2) to

$$\frac{\partial^2 K}{\partial x^2} = \alpha \frac{\partial K}{\partial z} \quad \ldots \ldots \ldots \ldots \quad (3)$$

The flux per unit area, u, in the vertical direction given by

$$u = K - \frac{1}{\alpha}\frac{\partial K}{\partial z} \quad \ldots \ldots \ldots \ldots \quad (4)$$

also obeys equation (3) since both equations (3) and (4) are linear. With the boundary conditions that u = 0 for x > h and x < -h at z = 0 and u = Q for -h < x < h at z = 0, equation (3) admits the solution for u:

$$u = \frac{Q}{2}\left\{ \operatorname{erf}\left[\frac{h - x}{\sqrt{4\alpha^{-1}z}}\right] + \operatorname{erf}\left[\frac{h + x}{\sqrt{4\alpha^{-1}z}}\right] \right\} \quad \ldots \ldots \ldots \ldots \quad (5)$$

Away from the surface, u ≈ K and equation (3) gives the K distribution. But α and h are not independent. Parlange and Hill (1976) suggest that

$$\frac{2\, K_s(\theta_s - \theta_i)}{S^2} = \frac{\pi}{h} \quad \ldots \ldots \ldots \ldots \quad (6)$$

or $\alpha h \simeq \pi$. For x = 0, equation (5) expressed for z = nh becomes

$$u = Q \operatorname{erf}\left[\sqrt{\frac{\pi}{4n}}\right] \quad \ldots \ldots \ldots \ldots \quad (7)$$

Taking this midline value for u to be representative of the average flux across the finger, one half the finger width is given as a function of n by

$$\text{half width} \approx \frac{h}{\operatorname{erf}\left[\sqrt{\frac{\pi}{4n}}\right]} \quad \ldots \ldots \ldots \ldots \quad (8)$$

Equation (8) is not expected to apply very near z = 0 due to our simple assumption for Q there, but sufficiently far from the fingers origin we expect equation (8) to give a reasonable approximation of the order of the finger's width. For example, due to the decrease in the midline flux with n, the finger will widen by a factor of 10 at a depth 50 times the finger width at the surface. Thus even when steady state is reached the finger will remain slender.

A comparison of equation (8) with experiment D4 is shown in figure 6. The width of the finger was measured at 80 min when infiltration was stopped. Only the top 45 cm of the finger is plotted in the figure as below, the sides of the chamber had been encountered. The half width of the finger at $z = 0$ (h) was difficult to determine exactly so equation (8) is plotted for $h = 3$, 4 and 5. The width of the steady state finger should be underpredicted due to our taking the flux at $x = 0$ to be the average value. The order of magnitude of the width, however is quite well estimated as is its change with depth. The finger in experiment D4 had not yet reached its steady state configuration but since it will take longer to reach the steady state width at greater depth, equation (8) is expected to correspond best to the experiment near the surface. For $h = 5$ the measured values are seen to be remarkably well predicted by equation (8) for the first 15 cm.

To obtain this estimate of the finger width with depth, we assumed α is constant. This assumption is reasonable only for small changes in moisture content within the middle of its range (Parlange and Hogarth, 1985). Thus α constant is a poor assumption for the initially dry sand experiments but when the soil is initially wet, the predicted finger shape should be reasonable. Since α becomes small where the moisture is low, away from the finger core in the initially dry sand, the pull of gravity is much less important than lateral diffusion and so the fingers in the initially dry sand will tend to widen fairly uniformly with depth as can be seen in figure 2a. Also in the initially dry soil, lateral diffusion will bring the steady state only after a long time.

CONCLUSION

Hill and Parlange (1972), Raats (1973) and Philip (1975) predicted that the two-layer experiments, including those at high initial moisture contents, to be unstable and indeed they are. Increasing the initial moisture content was also predicted by Parlange and Hill (1976) to increase finger width and this also is demonstrated here.

The present study finds, as did Diment and Watson (1985) for a uniform initial moisture content of 2%, that for a uniform initial moisture content of 6%, the wetting front becomes wavy with the wave amplitude increasing in time. Since this behavior satisfies the criterion for front instability, the wetting front may be technically considered to be unstable even for initial moisture contents at field capacity. The fact that separate fingers do not form under uniformly high moisture contents is due to the widening of fingers as shown in the initially wet point source experiments and their merger in a laterally constrained infiltration chamber. This widening and merger seems to be found only if the initial moisture content is uniform - a condition not often found in nature.

The most striking result of the present study, is the effect of an heterogeneous distribution of moisture content as formed by a previous unstable flow field (the "b" experiments) on wetting front instability. In additional infiltration cycles, fingers form in the same locations as they did initially and have the same core areas which conduct almost all of the flow. This work thus emphasizes the need to look more closely at the initial condition of uniform initial moisture content commonly used in both laboratory experiments and theoretical discussions of infiltration phenomena.

The point source experiments demonstrate that individual fingers may be generated from a nonuniform horizontal water supply without the necessity of an abrupt conductivity change within the soil profile. In fact, the two layer experiments demonstrate the nature of the textural interface to be a discritizer of the flow field allowing flow at discrete locations. The generalization of this to field soils is important. In the field, disturbances in the form of heterogeneities are abundant. While at first glance it may seem that the heterogeneities might swamp any instability that may occur, a closer look indicates heterogeneities and instability could combine to dictate a flow field much more heterogeneous than with either operating alone. Numerous structures within the soil profile can cause the flux to converge during infiltration and once this has occurred, either within or at the top of a coarse textured layer, the flow can take place through fingers. Examples of such structures are clay hardpans with filled cracks, macropores in the topsoil when water is ponded on the surface and layers in subsoils where rocks are abundant. Recent field experiments conducted by us indicate the importance of these convergence mechanisms. For example, in one field experiment a large dead root from a mature raspberry bush which had been removed the preceding year provided a preferred path for water flow through the top soil and initiated the growth of a finger that reached to a depth of 190 cm in 8 hours.

It is obvious from the present study that the effect of initial moisture content on wetting front instability is quite complicated. Further experimental research, both in the laboratory and the field, and theoretical research is needed in order to fully understand its affect.

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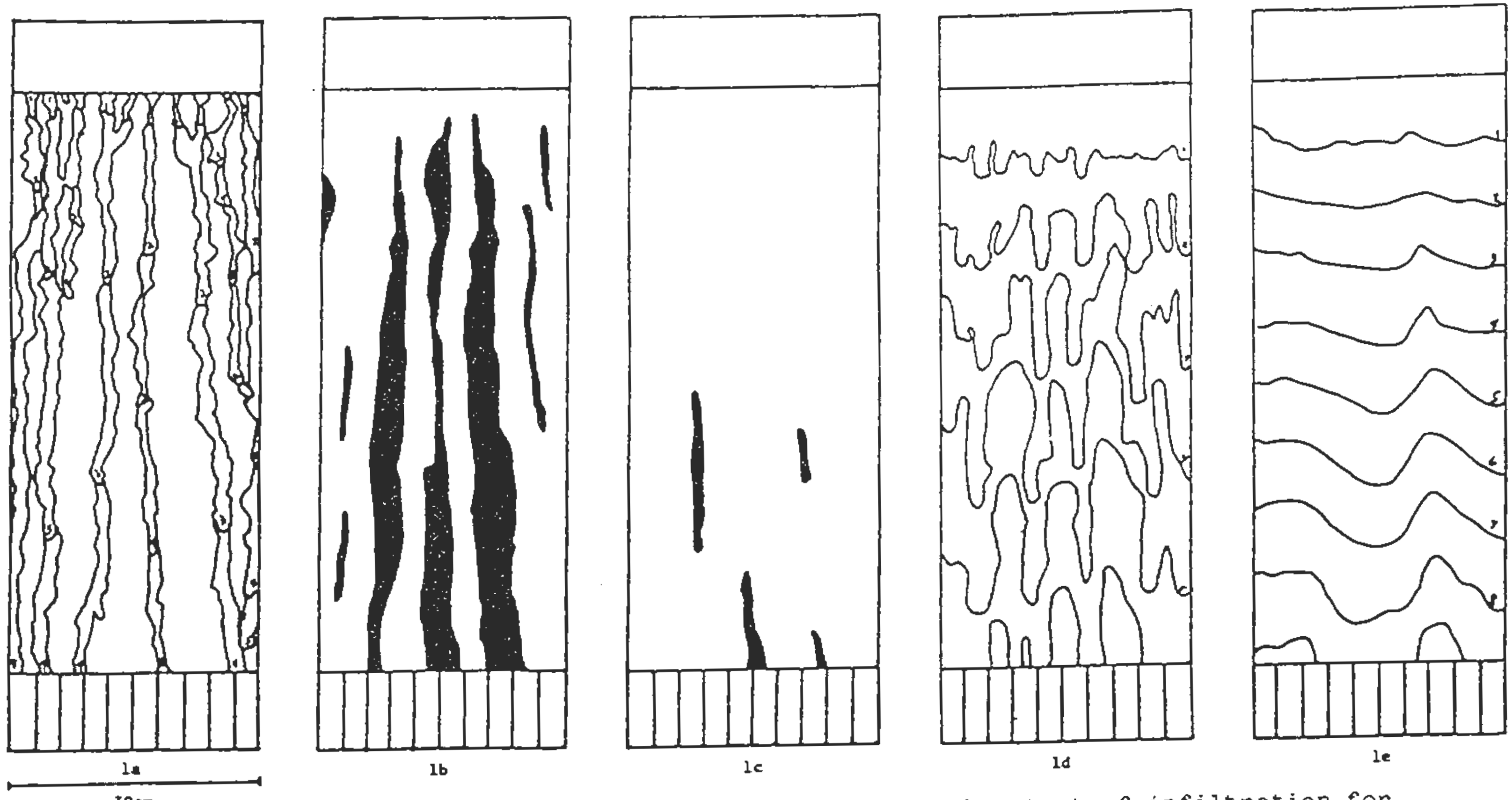

Figure 1. Composite drawings of wetting front position in time after the start of infiltration for experiment A6. 1a) Experiment A6a in an initially dry two-layer sand system. Wetting front position is drawn in minutes. These initial finger areas constitute the "core" areas that continue to conduct most of the flow in "a" and "b" experiments. The transitional "slow" period where wetting fronts move from initial core areas laterally creating a less saturated "fringe" area around the fingers is shown after 1b) one hour and 1c) five hours (dark areas denote dry sand). The majority of the flow continues to take place through the core areas within the wetted region. 1d) Experiment A6b, wetting front position is drawn in minutes. Initial moisture content was heterogeneously distributed by A6a. Most of the flow continues to take place through the same core areas as in A6a created by the initial instability. 1e) Experiment A6c, wetting front position is drawn in minutes. Initial moisture content of 6% (field capacity) was distributed evenly through the two-layer sand system by saturation and drainage after A6b. The exact core areas present in A6a and A6b have been removed by raising the initial moisture content uniformly to field capacity. The wetting front, however, is still unstable.

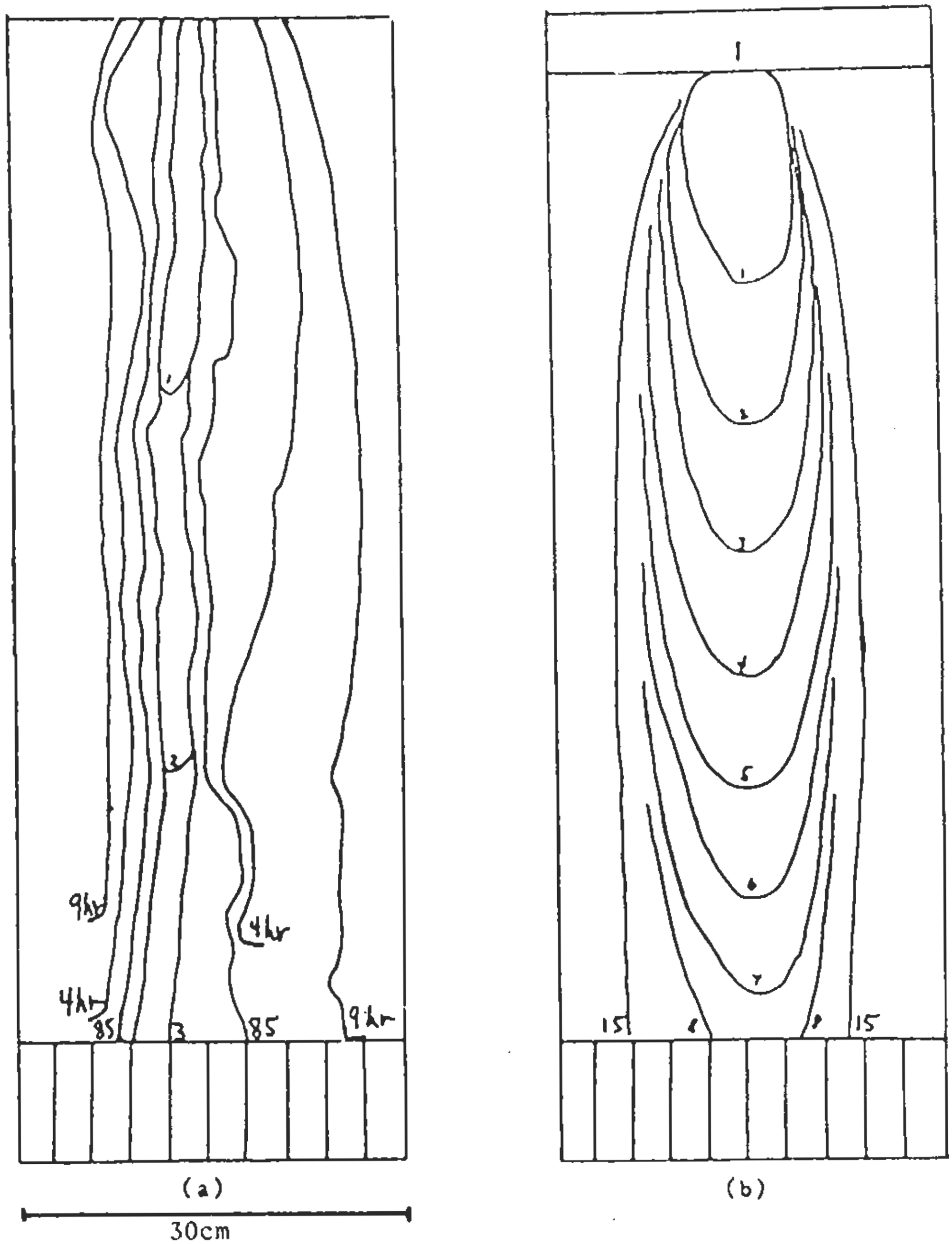

Figure 2a. Wetting front position for various times (minutes and hours where designated), from a point source (Q = 20 ml/min) located at the top of an initially dry, single coarse layer (14-20 fraction).

2b. Wetting front position for various times (minutes), from a point source (Q = 20 ml/min) located at the top of a single coarse layer (14-20 fraction) with a uniformly distributed initial moisture content of 6% (field capacity).

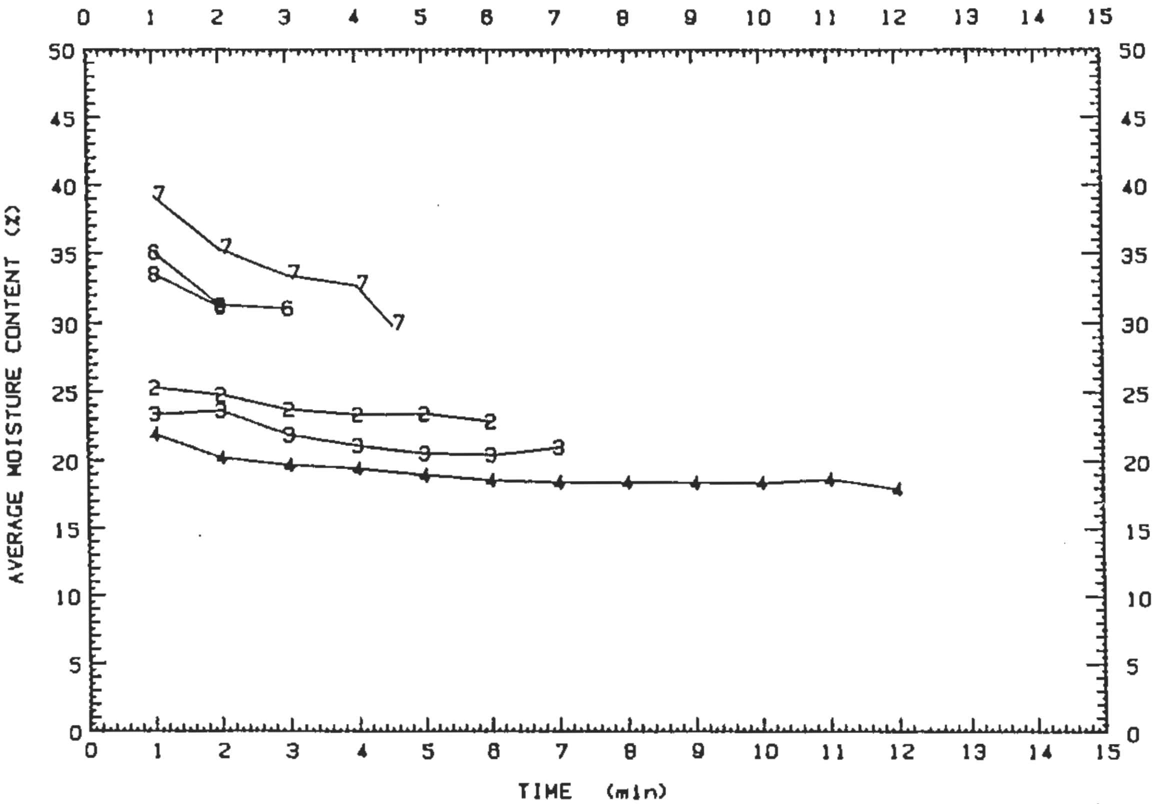

Figure 3. Finger initial moisture content as a function of time. Numbers 2, 3, 4, 6, 7, and 8 represent experiments D2, D3, D4, D6, D7 and D8.

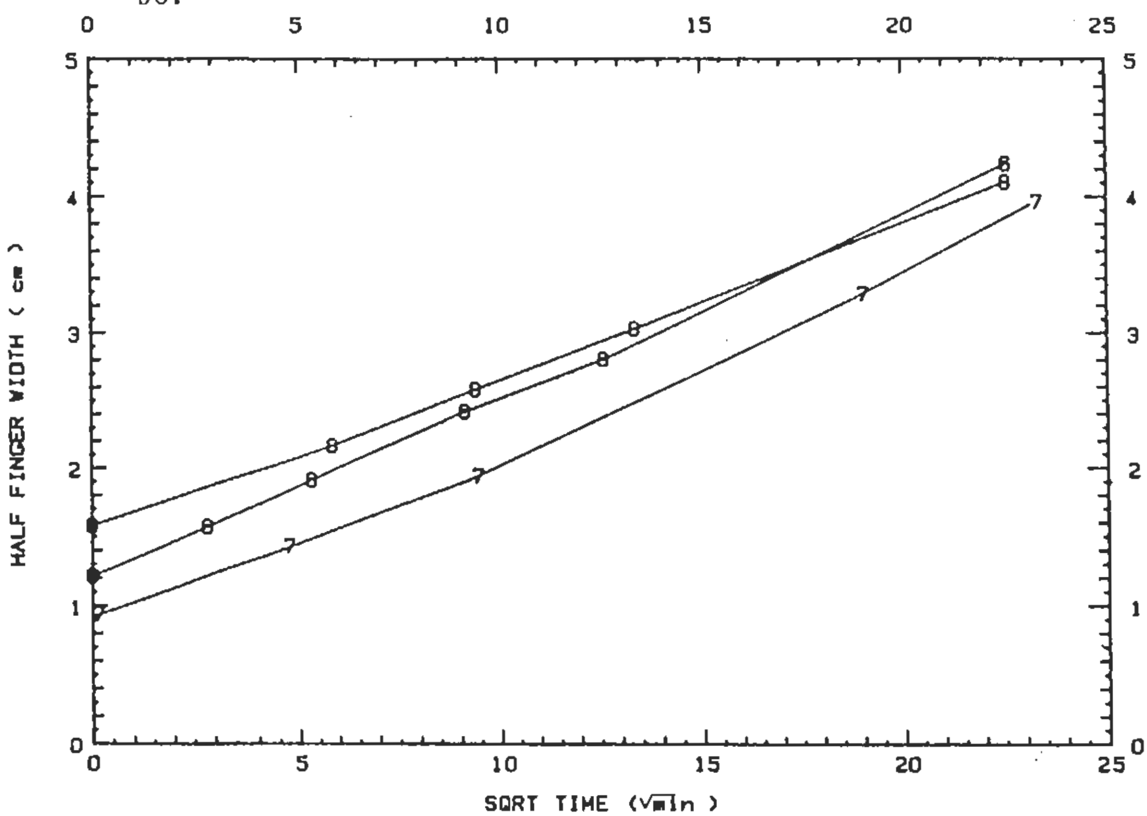

Figure 4. Lateral diffusion for fingers in initially dry coarse sand. Numbers 7, 8 and 9 represent experiments D7, D8 and D9.

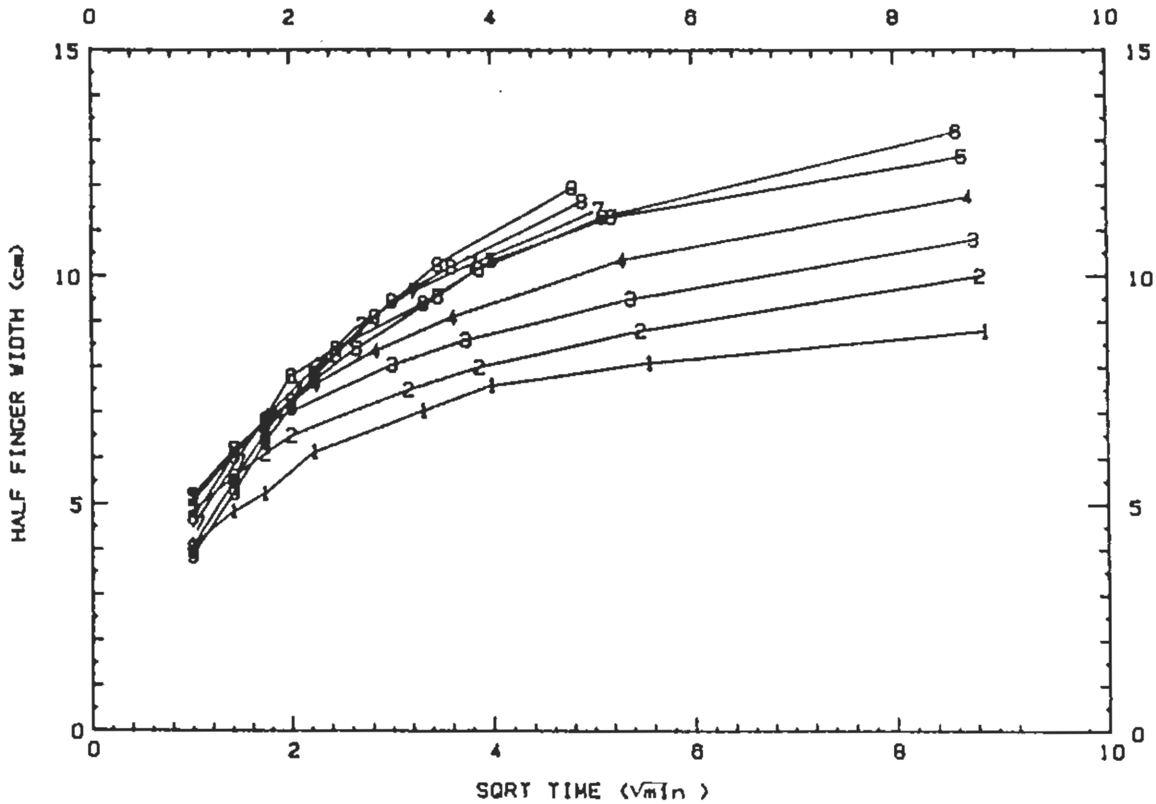

Figure 5. Lateral diffusion for finger D4 in initially wet coarse sand. Numbers represent depth positions 1 through 9.

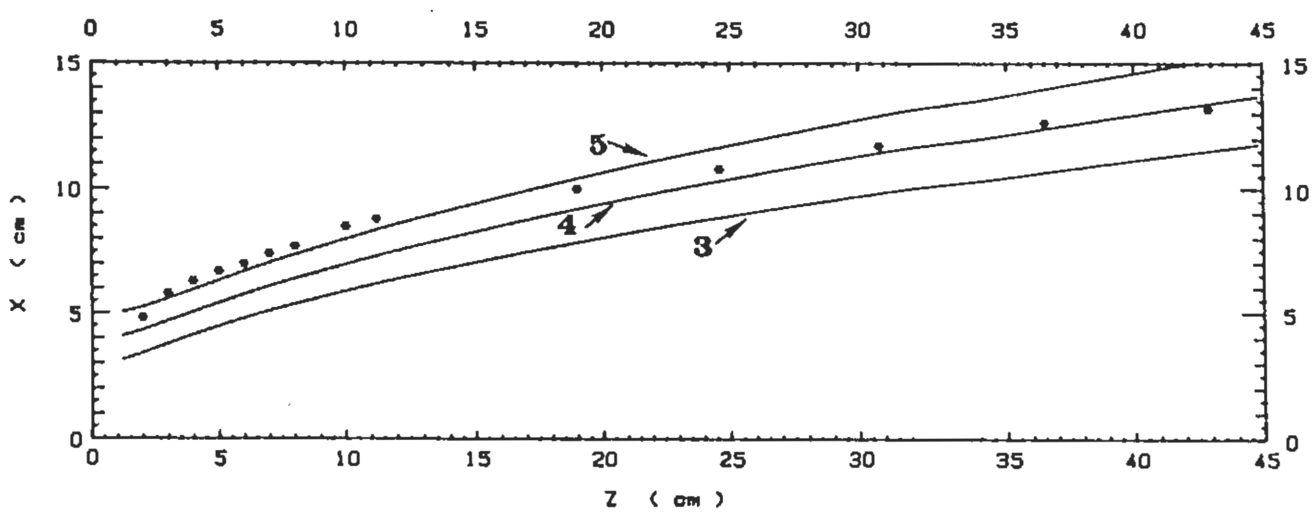

Figure 6. Comparison of equation (8) for h = 3, 4 and 5 with experiment D4. The distance from the middle of the finger to its edge is x, while z is the vertical distance positive downward. Solid lines are calculated values. *'s are measured from experiment D4.