Fingered Flow in Laboratory Golf Putting Greens

P. A. Nektarios
T. S. Steenhuis
A. M. Petrovic
J. -Y. Parlange

ABSTRACT. Golf course putting greens are intensively maintained and often contain a sand based root zone and, therefore, need to be managed to prevent nitrate and pesticide contamination and ground and surface water pollution. In this laboratory study, we investigated the water and solute movement through a typical tri-layer United States Golf Association (USGA) putting green profile. Results indicate that even though the soil layers were homogeneous, preferential flow paths were formed, causing a major portion of the soil profile to be bypassed and, thus, increasing the likelihood of groundwater contamination. *[Article copies available for a fee from The Haworth Document Delivery Service: 1-800-342-9678. E-mail address: getinfo@haworthpressinc.com <Website: http://www.haworthpressinc.com>]*

KEYWORDS. Irrigation, nonpoint source pollution, preferential flow, infiltration, percolation, golf course, sandy soils, layered soils

INTRODUCTION

Soil compaction is a major limiting factor of turfgrass growth on golf courses (Carrow and Petrovic, 1992). In response, to avoid soil compaction and improve turfgrass growth, the United States Golf

---

P. A. Nektarios is Consultant, 14 Adersen Street, N. Psychiko, 115 25 Athens, Greece.

T. S. Steenhuis and J. -Y. Parlange are Professors, Department of Agricultural and Biological Engineering, Riley-Robb Hall, Cornell University, Ithaca, NY 14853 (E-mail: tss1@cornell.edu).

A. M. Petrovic is Professor, Department of Floriculture and Ornamental Horticulture, Cornell University, Ithaca, NY 14853.

Addres correspondence to T. S. Steenhuis.

Journal of Turfgrass Management, Vol. 3(1) 1999

Association (USGA) developed recommendations for putting green profiles that consist of 30 cm of sand with 1 to 5% organic matter at the surface, an optional 5 cm coarse sand as a middle layer, and a 10 cm gravel layer at the bottom including drainage tiles (USGA, 1993).

Research has shown that water flow through layered coarse textured soil profiles (similar to putting greens) is at a rate much less than the saturated conductivity of finger-like preferential flow patterns caused by an instability in the wetting front (Hill and Parlange, 1972; Raats, 1973; Diment and Watson, 1985; Glass et al., 1988; Hillel and Baker, 1988; Selker et al., 1992). Once a finger is formed, water and solutes will follow the same path during all infiltration events until its 'memory,' based on hysteresis of the soil moisture characteristic curve, is lost by saturation or drying (Liu et al., 1995). The sharp interface between wet finger and dry soil can also be explained by hysteresis (Glass et al., 1989b; Liu et al., 1995).

Fingered flow is not restricted to coarse grained soils but also occurs in water repellent soils (Dekker and Ritsema, 1994; Bauters et al., 1998). Water repellent soils are widespread and occur in Florida, Arizona, and California (DeBano, 1969), as well as abroad in New Zealand, England, and Australia (Bond, 1969; McGhie and Posner, 1980) and the Netherlands (Hendrickx et al., 1988; Dekker and Ritsema, 1994). Some researchers even suggest that repellency is the norm rather than the exception (Dekker and Jungerius, 1990; Wallis et al., 1990). Wetting agents are specifically used by golf courses to reduce water repellency in soils.

Because of the intensive maintenance requirements and high irrigation and chemical use, putting greens are likely candidates for leaching of nitrates and pesticides (Abrams, 1991). Moreover, fingered flow can cause fast transport of water and chemicals (as well as reduce the efficacy of the applied nutrients and pesticides) and invalidates the predictions of many of the current pesticide fate models that are based on the convective-dispersive equation in which the water and solutes statistically sample all pore spaces. The objective of this study was to characterize the extent of preferential fingered flow through a putting green layered soil profile.

MATERIALS AND METHODS

A golf putting green was recreated within a glass sided slab chamber 50 cm wide, 46 cm high, and 1.2 cm thick. The profile had three

layers of silica sand: the top layer consisted of 30 cm of medium sand with particle sizes between 0.3 to 0.43 mm; the middle layer was 5 cm deep with particle sizes between either 0.45 to 0.85 mm or 0.85 and 1.4 mm; and, finally, the bottom layer, with a height of 10 cm, consisted of very coarse sand with grain diameters between 1.4 and 2 mm. Silica sand, which is transparent, was used to aid in the visualization. The chamber was filled with oven dried sand through a hopper and an extension having three randomizing screens. The sand was gravity packed by adding an extra 15 cm of sand above the desired height. The excess sand was removed with a glass tubing attached onto a vacuum pump (Selker et al., 1992).

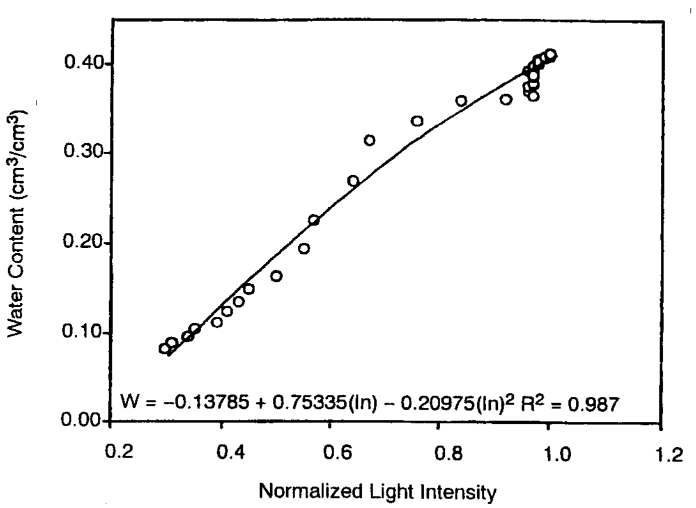
Water applications were made with a pesticide nozzle tip (TeeJet XR8001, Spraying System Co., North Avenue and Schmale Road, Wheaton, IL 60178) attached to a chain driven shuttle that distributed water and dye uniformly as described by Selker et al. (1992). Two flow rates were used: 2.8 cm h^{-1} and 5.8 cm h^{-1} (when the middle layer of the coarse sand was substituted with sand having a particle size range of 0.85 to 0.45 mm). The flow rate was manipulated using a delay switch. All experiments were performed in a constant temperature room at 22.5°C.

The visualization technique of Glass et al. (1989a) was used to observe the evolution of the moisture content field in the entire chamber. The technique consists of supplying one side of the slab chamber with a diffuse light source composed of a bank high output fluorescent light bulbs run by high frequency ballasts (40,000 Hz). Moisture contents are visualized differences in light intensity at the other site. The brighter the location the higher the moisture content for the same sand. The light intensities were recorded with a black and white video camera (Panasonic, TV Camera WV 1850) and a lap recorder (Panasonic, AG 6720) on videotapes with a time resolution of 1/30 sec. The videotape was processed with IRIS Video Image Software (Data Translation Inc., 100 Locke Drive, Marlboro, MA) and used to determine the finger velocity, size, and structure determination for artificial coloring of light intensity differences.

Eight experimental runs with two different irrigation rates were performed with similar results, therefore, only one run of each different irrigation rate is reported. The experiments started with a water application on dry sand. This is similar to a situation just after construction. After the fingered flow field was fully developed and steady state was reached, the irrigation was stopped. After a 24 hour period, water was applied again at the same rate. To aid in the visualization, the water was colored with FD&C Blue Dye #1 at a concentration of 1.0 g/l. After steady state was reached, a switch from dyed to pure water was made. The experiment was continued until all blue dye was removed from the chamber. The light intensities of the dry sand and subsequent infiltration cycles were recorded on tape. At the end of the experiment, the chamber was saturated from the bottom and a final image was recorded.

In a separate experiment, the light intensity and moisture content were correlated (Figure 1) using the method of Bell et al. (1990) and Liu et al. (1993). Moisture content determination with light intensity in the two bottom layers was not possible because of the high amount of light transmitted by the capillary fringe in the top layer that distorted the rest of the picture.

FIGURE 1. Correlation between normalized light intensity and volumetric water content for the fine sand. The moisture content and intensity were related as: $\theta = -0.138 + 0.753I_n - 0.298I^2_n$ for $I_n \geq 0.2$; $R^2 = 0.9$ where θ is the volumetric moisture content and I_n is the normalized moisture content and can be expressed as: $I_n = \frac{I - I_d}{I_s - I_d}$ where I is the light intensity of transmitted light, I_s is the light intensity of the saturated slab chamber, and I_d is the light intensity through the dry chamber.



The velocity of each finger was calculated from the location of finger taken from a video frame approximately every 5 min with IRIS software.

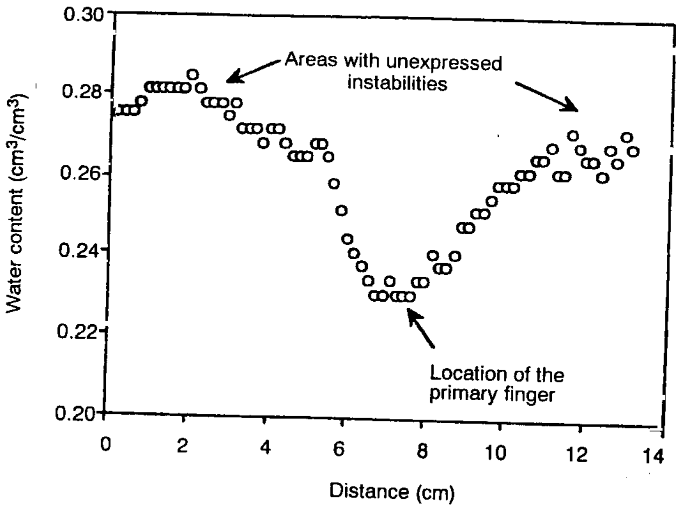
RESULTS AND DISCUSSION

Water Infiltrating into Dry Sand at 2.8 cm/hr: The distribution water in the dry golf putting green is shown in Figure 2 (see Appen for Figure 2). (This situation is similar to the moisture condition j after construction of the putting green.) For easy visualization of moisture contents in the top layer, light intensities were translated to colors of red for saturated and dark blue for dry sand. In the top 2 cm the profile, water moved as a wavy front (Figure 2a). An induction distribution) zone within the top 2 cm was formed, then the wett front became unstable and a single (primary) finger developed (Fig 2b). Previous studies have shown when higher flow rates were appl (60 cm h^{-1}) to sand, several fingers were formed (Selker et al., 19 Scanning the light intensity in the induction zone (Figures 2b anc revealed that the water content in the induction zone was the lowes the starting point of the finger. As expected, we found lower mois contents are related to higher suctions in the induction zone, a pote gradient funnels or directs all the applied water towards the finger.

When the primary finger reached the first interface between sand layers, the downward movement was halted, and water starte move sideways forming a capillary fringe (Figure 2c). At the s time, two new fingers (secondary) began to form in the induction z (Figure 2d). Light intensity observations along the axis of the prin finger just before (44 min) and after the primary finger had reachec interface (50 min), showed that the moisture content was the s except from the induction zone where the moisture content was hi (Figure 4). This increase in the water content and the associated m potential in the induction zone of the primary finger, allowed secondary fingers to develop (Figure 2d).

Because there was more than one path for the water, the flux (w flow rate) through the secondary fingers was smaller than for primary finger. As a result, the secondary fingers moved slower, smaller, and had a lower moisture content than the primary fin (Table 1, Figure 5). However, for all three fingers the tip was wettest part of the finger (Figure 5). The velocity of the wetting of the primary finger was, on the average, 0.75 cm/min and relati

FIGURE 3. Water content in the induction zone shows a lower moisture content where the primary finger begins. The white dotted line in Figure 2b indicates the area that was scanned.



constant after the first 5 min when the water content of the induction zone did not change anymore. The velocity of secondary fingers became faster as they become longer where the highest velocity was 0.6 cm/min (Figure 6).

The moisture content of fingers 2 and 3 at the tip was 2.5 and 2 times smaller, respectively, than the moisture content in the tip of the primary finger. Differences were also observed between the two secondary fingers (Table 1) suggesting that the flux through each secondary finger is not the same and depends on the distance from the primary finger.

After both secondary fingers had reached the capillary fringe, two more (tertiary) fingers developed which moved even slower, and were smaller and dryer than the secondary fingers. Precise data could not be taken because of the small amount of light that was transmitted, compared with the capillary fringe.

Water flowed into the second layer as a marginally unstable front (Figure 2e). Once it reached the interface of the bottom layer water flowed immediately across as a single finger (Figure 2e). The finger in the third layer was 2 cm wide which was much smaller than the 8 cm

FIGURE 4. Normalized light intensity along the axis of the primary finger 44 min before the secondary fingers were formed and at 50 min after t secondary fingers were initiated. Notice the differences in the transmitted li intensity in the finger near the induction zone (circled area).

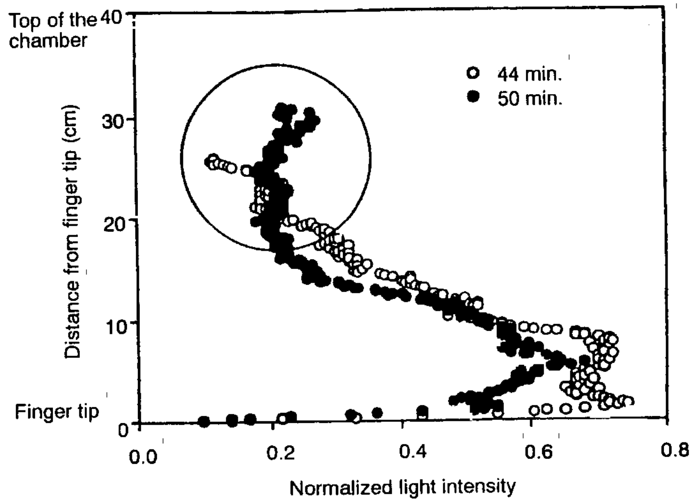


TABLE 1. Comparison of finger characteristics between the primary and two secondary fingers.

Finger Number	Type	Maximum Velocity cm/min	Average Velocity cm/min	Maximum Finger Width cm	Maximum Water Content cm³/cm³
1	Primary	0.79	0.76	8.1	0.31
2	Secondary	0.59	0.39	5.9	0.12
3	Secondary	0.50	0.24	5.7	0.16

wide finger in the top layer. This is consistent with previous fin in which the finger size is inversely proportional to the grain (Diment and Watson, 1985; Glass et al., 1989a).

Dye Movement in the Wetted Profile (2.8 cm/hr): In order t amine the solute path after the profile was wetted, blue dye wa

FIGURE 5. Moisture content along the axis of the dominant finger (Finger 1) and a secondary one (Finger 2) in th fine sand top layer.

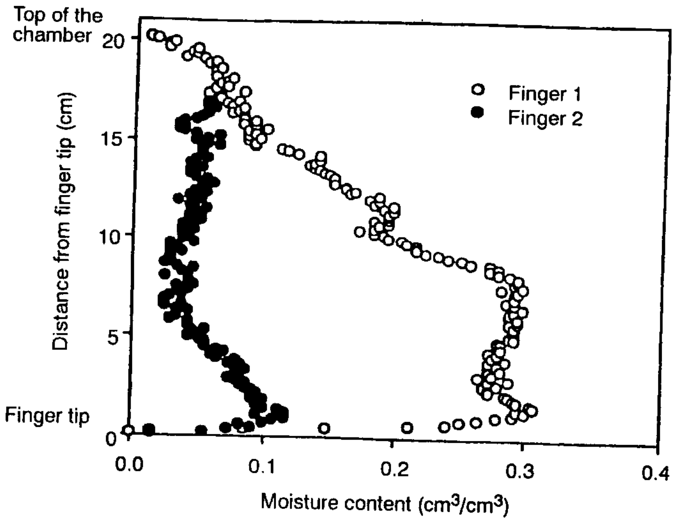
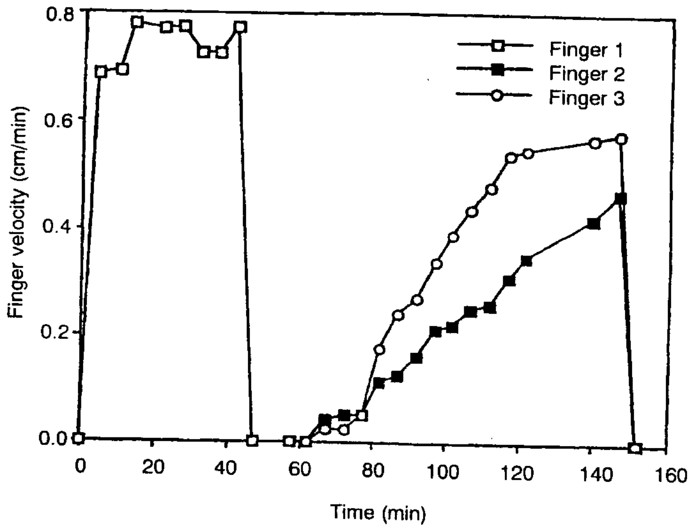


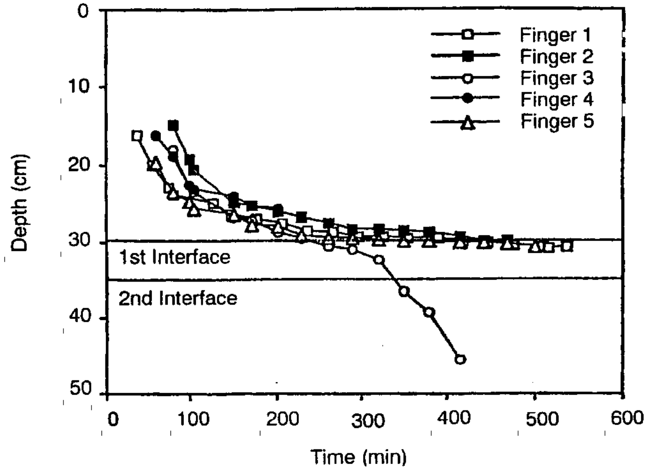
FIGURE 6. Averaged velocity for the dominant finger (Finger 1) and the two secondary fingers (Fingers 2 and 3).



plied after a 24 hr drainage period when the outflow from t chamber was negligible. Only qualitative observations could b because the rapid-moisture visualization technique was unabl tect differences in moisture in the dyed water. Dye followed th pathways created during the first infiltration cycle. In this c water moved through the five fingers that were formed earli velocity through each finger was the same, although the am water carried by the primary finger might have been more t remaining fingers because it was brighter. After the dye trav first 20 cm in the top layer, the fingers converged towards the m the chamber (Figure 2f), creating a single finger just over the c fringe which concentrated and conducted all the flux from the The point at which the fingers converged and passed into the layer was the same location where the first finger broke throu the second layer in the initial infiltration cycle (Figure 2g). Dy immediately through the interface, without spreading laterally.

The downward velocity of the five fingers was approxima same and decreased as they reached the capillary fringe above interface (Figure 7). This decrease was caused by the elevate ture content and the sideways movement of the fingers (Fig

FIGURE 7. Finger location as a function of time for the re-infiltration ments. At the interface, all water was funneled into Finger 3 and then at a fast rate while the other fingers became stationary.



The velocity increased again after the five fingers merged into one (Figure 2h), since the flux from five fingers was concentrated into one.

Water Movement Using a Flow Rate of 5.8 cm h^{-1}: A similar, but not identical, infiltration pattern developed at the higher flow rate (5.8 cm h^{-1}). After the 2 cm induction zone was developed, a single (primary) finger was initiated. When the primary finger reached the interface, a secondary finger formed (Figure 2i). Because the middle layer was finer sand (0.85-0.48 mm) than for the lower flow rate, the capillary fringe in the fine sand above the first interface was much smaller. When the secondary finger reached the interface, water broke through to the underlying layer at points where each finger contacted the interface (Figure 2i). New finger formations in the top layer stopped after breakthrough in the second and third layer had occurred. Once the flow pattern was established, the paths became wider but, otherwise, remained the same for the entire duration of the study (one week). Figure 2j shows the water flow pattern after blue dye was added to the water.

CONCLUSIONS

Experiments with a layered profile similar to artificial golf putting greens were conducted in slab chambers to visualize water and solute flow. The results show that thin soil slabs are a useful technique to visualize water and solute movement in golf putting greens. We showed that bypass flow may occur in golf putting greens as a result of instabilities at textural interfaces of homogeneous sands. Once a flow pattern was established, it reoccurred again after water application.

Since the solutes were bypassing most of the soil matrix, the time for pollutants (pesticides or fertilizers) to reach the outlet of the greens is less than when a convective-dispersive flow is assumed. This reduced time could lead to less biodegradation and higher concentration of turfgrass chemicals lower in the profile.

In these experiments, we did not have any plants or thatch layer present which could modify the pattern in the upper layer. The instabilities at the textural interface will not be affected by the absence or presence of plants or thatch because the instabilities are caused by the properties of the lower layer. Further research is needed to confirm the presence of finger and funnel flow under field conditions, as well as procedures that will limit the formation of fingers to reduce the potential for enhanced groundwater contamination due to solute leaching.

REFERENCES

Abrams, R. 1991. Toxic Fairways: Risking Groundwater Contamination from I cides in Long Island Golf Courses. New York State Attorney General Re Albany, NY.

Bauters, T.W.J., D.A. DiCarlo, T.S. Steenhuis, and J.-Y. Parlange. 1998. Prefer Flow in Water Repellent Sands. Soil Science Society of America Journal press.)

Bell, J.L., J.S. Selker, T.S. Steenhuis, and R.J. Glass. 1990. Rapid Moisture Mea ments of Thin Sand Slabs. Paper 90-2635. ASAE, St. Joseph, MI. 20 pp.

Bond, R.D. 1969. The Occurrence of Water-Repellent Soils in Australia. *In:* Repellent Soils, L.F. DeBano and J. Letey (Eds). Univ. Calif., Riverside, CA. p

Carrow, R.N. and A.M. Petrovic. 1992. Effects of Traffic on Turfgrasses. *In:* grass Agronomy Monograph No. 32, D.V. Waddington, R.N. Carrow, and Shearman (Eds.). American Society of Agronomy, Madison, WI. pp. 285-33

DeBano, L.F. 1969. Water Repellent Soils: Worldwide Concern in Managem Soils and Vegetation. Agr. Sci. Rev. 17:11-18.

Dekker, L.W. and P.D. Jungerius. 1990. Water Repellency in the Dunes with S Reference to the Netherlands. Catena Suppl. 18:173-183.

Dekker, L.W. and C.J. Ritsema. 1994. How Water Moves in a Water Repellent Soil. I. Potential and Actual Water Repellency. Water Resources Res. 30:2507-

Diment, G.A. and K.K. Watson. 1985. Stability Analysis of Water Movement in U rated Porous Materials. 3. Experimental Studies. Water Resources Res. 21:979-

Glass, R.J., T.S. Steenhuis, and J.-Y. Parlange. 1988. Wetting Front Instabilit Rapid and Far-Reaching Hydrologic Process in the Vadose Zone. J. Co Hydrol. 3:207-226.

Glass, R.J., T.S. Steenhuis, and J.-Y. Parlange. 1989a. Wetting Front Instabil Experimental Determination of Relationships Between System Parameter Two-Dimensional Unstable Flow Field Behavior in Initially Dry Porous Water Resources Res. 25:1195-1207.

Glass, R.J., T.S. Steenhuis, and J.-Y. Parlange. 1989b. Mechanism for Finger tence in Homogeneous, Unsaturated, Porous Media: Theory and Verificatio Sci. 148:60-70.

Hendrickx, J.M.H., L.W. Dekker, E.J van Zuilen, and O.H. Boersma. 1988. and Solute Movement Through a Water Repellent Sand Soil with Grass Proc. Int. Conf. and Workshop on Validation of Flow and Transport Mod the Unsaturated Zone. May 23-26. Ruidoso, NM. pp. 131-146.

Hill, D.E. and J.-Y. Parlange. 1972. Wetting Front Instability in Layered Soil Sc. Soc. Am. Proc. 36:697-702.

Hillel, D. and R.S. Baker. 1988. A Descriptive Theory of Fingering During I tion into Layered Soils. Soil Sci. 146:51-56.

Liu, Y., B.R. Bierck, J.S. Selker, T.S. Steenhuis, and J.-Y. Parlange. 1993. Intensity X-Ray and Tensiometer Measurements in Rapidly Changing Prefe Flow Fields. Soil Sci. Soc. Am. J. 57:1188-1192.

Liu, Y., J.-Y. Parlange, and T.S. Steenhuis. 1995. A Soil Water Hysteresis Mo Fingered Flow Data. Water Resources Res. 31(9):2263-2266.

McGhie, D.A. and A.M. Posner. 1980. Water Repellence of a Heavy Textured Western Australian Soil. Austr. J. Soil Res. 18:309-323.

Raats, P.A.C. 1973. Unstable Wetting Front in Uniform and Nonuniform Soils. Soil Sci. Soc. Am. Proc. 37:681-685.

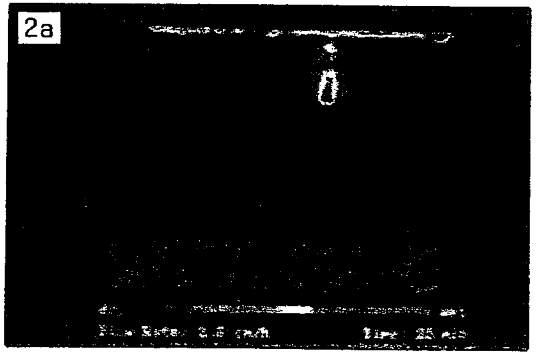
Selker, J.S., T.S. Steenhuis, and J.-Y. Parlange. 1992. Wetting Front Instability in Homogeneous Sandy Soils under Continuous Infiltration. Soil Sci. Soc. Am. J. 56:1346-1350.

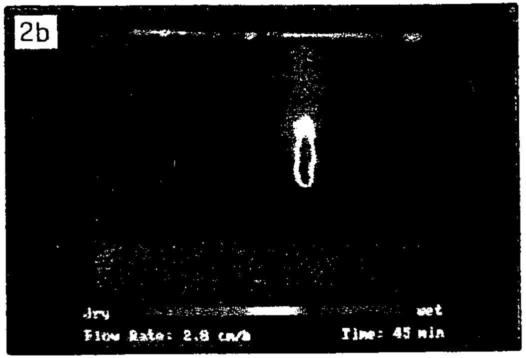
United States Golf Association, Greens Section Staff. 1993. USGA Recommendations for a Method of Putting Green Construction. USGA Green Section Record (March/April):1-3.

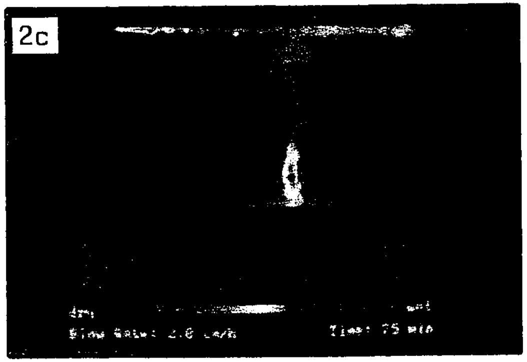
Wallis, M.G., D.G. Horne, and K.W. McAuliffe. 1990. A Study of Water Repellency and Its Amelioration in a Yellow Brown Sand. 2. The Use of Wetting Agents and Their Interaction with Some Aspects of Irrigation. New Zealand J. Agr. Res. 33:145-150.

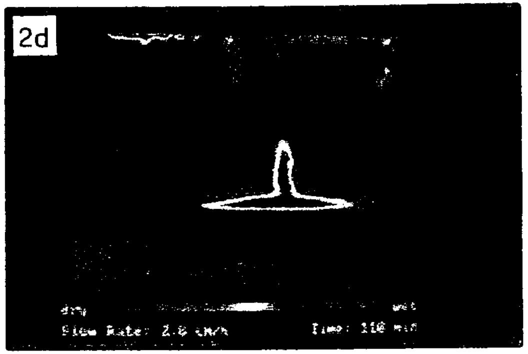
APPENDIX

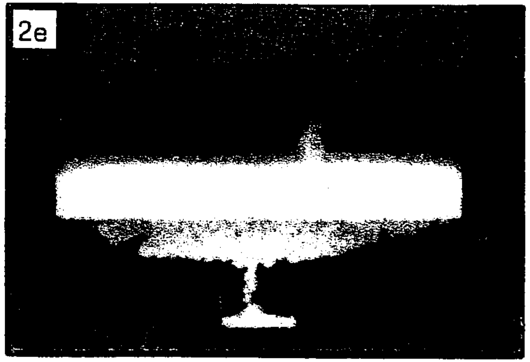
FIGURE 2. Finger development in a slab chamber with an artificial golf putting green for irrigation rates of 2.8 cm/hr and 5.8 cm.hr^{-1}. (a) Single primary finger develops for flow rate of 2.8 cm/hr; (b) The induction zone remains stationary while the finger moves downward; (c) The primary finger water moves sideways when finger reaches textural interface; (d) Two more fingers are formed; (e) Flow pattern in next two layers; (f) Flow paths are shown with FD&C Blue Dye #1 after irrigation water applied again after 24 hr drainage; (g) Water flows in the fingers through the capillary fringe to the previously established flow path in the coarse sand and bottom layers; (h) Flow path in coarse and bottom layers; (i) Flow pattern established for a flow rate of 5.8 cm h^{-1}; (j) Blue dye in irrigation water applied after a period of 24 hr drainage follows the same pathways created earlier.

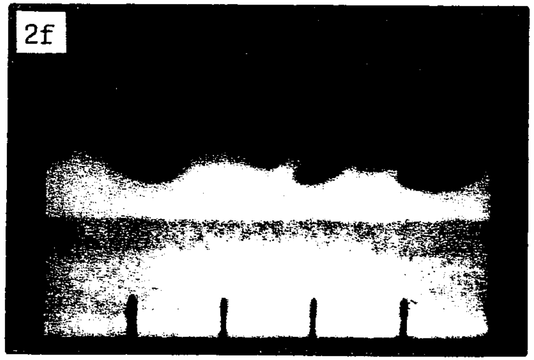


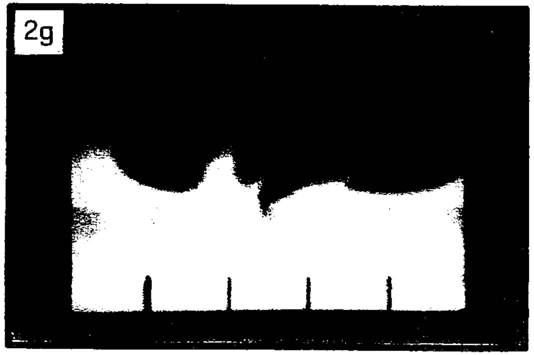


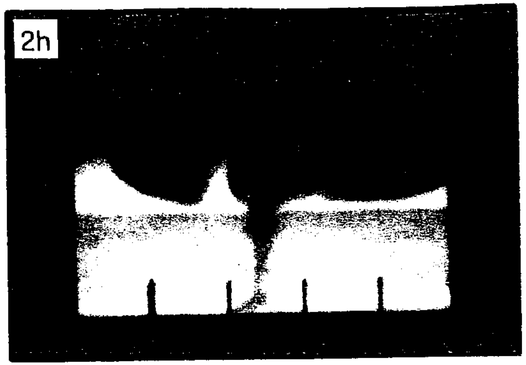


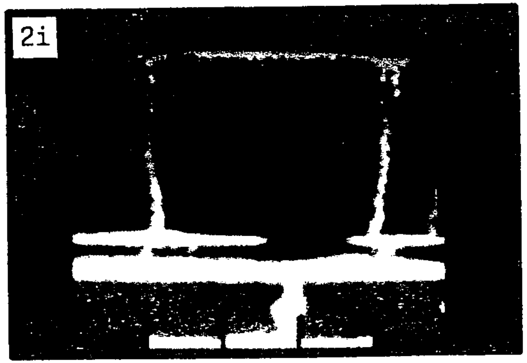


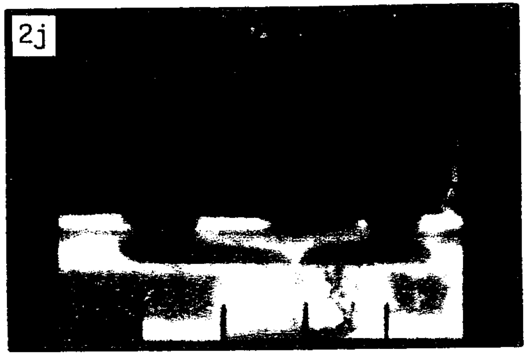

2e


2f


2g


2h


2i


2j