SURFACE SEAL INFLUENCE ON SURGE FLOW FURROW INFILTRATION

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ABSTRACT

The interactive influence of furrow surface seal formation and surge irrigation (intermittent flow) on furrow infiltration into a Portneuf silt loam soil was measured with a recirculating infiltrometer. When the formation of a surface seal was prevented by a layer of cheesecloth laid on the furrow perimeter, flow interruption increased furrow bed bulk density by 100 kg/m^3 and decreased infiltration by 25% compared to constant flow. However, on this highly erodible soil, the surface seal which formed on an unprotected perimeter during irrigation reduced infiltration rates by over 50% compared to furrows with a cheesecloth layer. Flow interruption did not increase soil consolidation or decrease infiltration when the normal seal was allowed to form. On the tested soil, surface sealing overshadows the effects of flow interruption on infiltration. **KEYWORDS.** Furrows, Surface irrigation, Infiltration, Surge irrigation, Surface Seal, Soils, Hydraulic conductivity, Crust, Bulk density.

INTRODUCTION

Surge irrigation is the intermittent application of surface irrigation water (Stringham, 1988; Stringham and Keller, 1979). Under some conditions, the technique reduces the application time and volume required to advance flows across the field surface and thus improves irrigation water distribution uniformity.

The reduced advance times are the result of reduced infiltration rates. The infiltration decrease, which results from interrupting the flow, is highly variable (Coolidge et al., 1982; Stringham, 1988; Kemper et al., 1988). Although much research has been carried out to determine the mechanisms involved, the process is still not fully understood and the results are difficult to predict. Past research has provided no explanation for the reduced infiltration other than a decrease in soil permeability (Lep, 1982; Samani, et al., 1985; Izadi and Heerman, 1988; Stringham, 1988). The most often cited mechanism for reduced permeability is the consolidation of the wetted soil during flow interruptions due to increased soil-water tension (Coolidge et al., 1982; Trout and Kemper, 1983; Samani et al., 1985, Kemper et al., 1988). However, this information alone does not explain the variable nature of the surge effect.

Article was submitted for publication in January 1990; reviewed and approved for publication by the Soil and Water Div. of ASAE in May 1990. Presented as ASAE Paper No. 89-2540.

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Kemper et al. (1988) proposed that intermittent flow can also increase the degree of soil aggregate breakdown and the amount of sediment erosion and deposition in furrows and thus the formation of depositional surface seals. They hypothesize that the surge effect will increase for a given soil as the amount of aggregate breakdown and sediment movement increases. However, this effect reverses if the erosiveness of the flow reaches a level such that the surface seal erodes away.

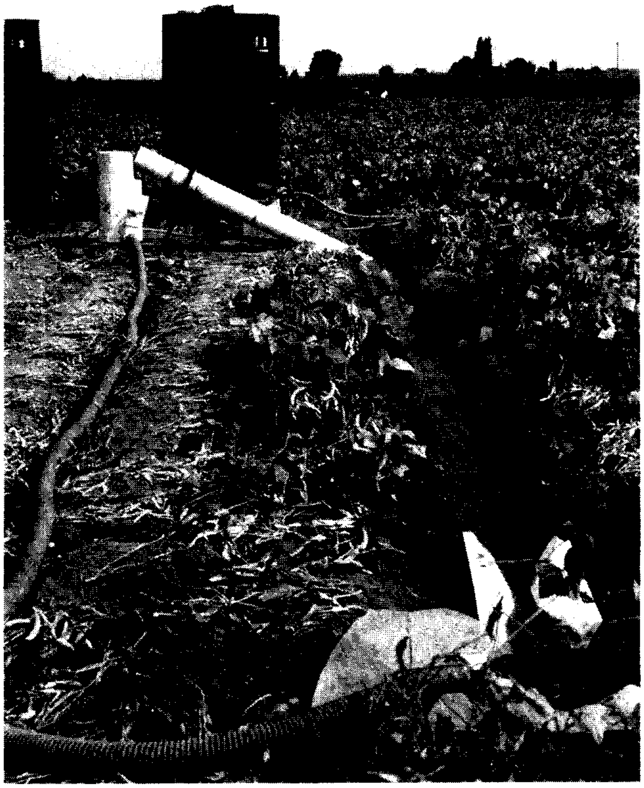
Samani (1983) also recognized the importance of surface sealing on surge effectiveness. He measured a larger impact of surface sealing than of flow interruption on furrow infiltration on two soils and found that the influence of flow interruption was much greater if sediment movement was reduced.

The objective of this study was to determine the influence of furrow surface sealing on the infiltration decrease created by flow interruption.

PROCEDURES

Furrows were formed in recently-tilled Portneuf silt loam soil at the USDA-ARS Research Center near Kimberly, Idaho. The Portneuf is a loess soil with low aggregate stability which readily erodes. Irrigation water was applied at 20 L/min to 6-m long furrow sections with a recirculating infiltrometer (Walker and Willardson, 1983). Furrow slope averaged 0.005. Treatments were constant and intermittent (surge) flow, with both bare ("conventional") furrows and the furrows with their surface covered with cheesecloth to reduce soil sediment movement and seal formation. The four treatments were randomly applied to adjacent furrows and replicated four times in 1987 and three times in 1989 on the same field. Infiltration, soil-water tension, and furrow bed bulk density were measured.

The recirculating furrow infiltrometer used in the study is shown in figure 1 and and is described in detail in Blair and Trout (1989). A low speed (about 50 RPM) Archimedes screw, constructed from a grain auger fixed in a PVC pipe, was used to lift the water from the downstream sump of the infiltrometer to a small return reservoir from which it flowed by gravity to the upstream end of the furrow section. This technique was devised to minimize the breakdown of sediment aggregates in the recirculation system and to insure that all sediment continuously recycles through the furrow section. Most moving sediment in furrows is in the form of small aggregates. Decreasing the size of these small aggregates changes sediment transport and deposition and the formation and structure of the furrow depositional layer (surface seal).



(a) General view of furrow, recirculating system, and supply tank.

(b) Archimedes screw lifter and return reservoir.

Figure 1–Recirculating furrow infiltrometer with screw lifter.

A constant-head Marriott syphon supply tank maintained a constant water volume in the infiltrometer. The water volume (depth) decrease in the supply tank, which is equal to the volume infiltrated, was measured every 5 minutes with a pressure transducer and recorded with a data logger. At the beginning of each test, low flow rates were used to wet the furrow sections at a rate of about three meters per minute to duplicate average field stream advance and thus aggregate wetting conditions.

Soil-water tension was measured with a 10-mm diameter by 90-mm long porous ceramic cup connected, via a 1.5-mm nylon tube, to a Microswitch 160 pressure transducer* (fig. 2). Either a

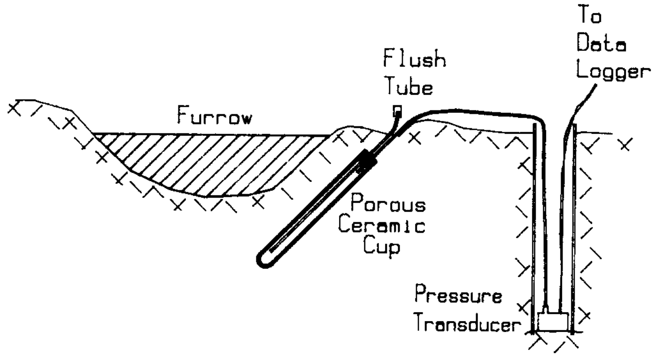


Figure 2–Furrow cross-section showing placement of tensiometer porous cup and pressure transducer.

2.5 or 7 kPa full scale transducer was used, depending on the expected pressure range. The transducer was placed in an access tube below the soil surface at a depth greater than the maximum expected soil-water tension head below the elevation of the furrow water surface. It thus measured increasing positive pressures as the soil-water tension decreased and vice versa. Pressure was recorded every 5 minutes by the data logger. The ceramic cup was laid in the flowing water in the furrow adjacent to the tension measurement point at the beginning and end of each test to establish the pressure datum at the water surface. Approximately 5 minutes after the beginning of the test, the cup was inserted into the wet soil about 10 mm from the furrow edge at approximately a 45-degree angle. Thus the upper end of the tensiometer was located about 10 mm horizontally from the edge of the flow and the lower end was about 30 mm below the bed of the furrow as depicted in figure 2.

Bulk density was measured gravimetrically at the beginning of each flow interruption and at the end of all tests. Measurements were made as soon as possible after water drained from the furrow and thus before soil-water tension (and consolidation) increased. Thus, soil conditions at the end of the previous flow period were measured. The bulk density sample was collected in a 36-mm diameter by 30-mm long thin-walled aluminum ring which was wetted and manually inserted into the furrow bed. The sample was extracted with the help of a bent spatula inserted below the ring. The ends were trimmed before the sample was washed into a container for oven drying and weighing. The bulk density samples thus represented the surface 30 mm of the furrow bed soil. Two replicate samples were collected. The sampling procedure was tedious, especially at low soil-water tension, and results were sensitive to the particular technique used. Consequently, one person (the author) collected all bulk density data to improve reproducibility.

In the "no seal" furrows, the soil was protected from the shear of the flowing water with a double layer of cheesecloth laid on the furrow perimeter. The cloth was anchored with nails and a 6-mm diameter steel rod laid longitudinally along the furrow bed. The effectiveness of the cheesecloth was evident from the low sediment concentrations in the flowing water and the visibly rough condition of the furrow perimeter at the end of the tests. The resistance to flow of the cheesecloth increased the effective furrow roughness coefficient and thus increased

*Names of equipment manufacturers and suppliers are provided for the benefit of the reader and do not imply endorsement by the U.S. Department of Agriculture.

the flow depth and wetted perimeter an average of 20% compared to the bare furrows.

The surge treatment flows were interrupted three times for 20 minutes following 25-minute flow periods. Thus, the cycle time and cycle ratio for the three surges were 45 minutes and 0.55, respectively. During the interruptions, water (and sediment) which ran off from the furrow was collected and reapplied to the furrow at the beginning of the following flow period. After the three interruptions, the irrigation was continued with constant flow for a total infiltration opportunity time of 6 to 8 hours. Surge flow cumulative infiltration time was based on application (infiltration opportunity) time and not elapsed time.

RESULTS

INFILTRATION

Table 1 and figure 3 show measured infiltration for the 4 treatments. In the conventional (bare) furrows, flow interruption had little effect on 6-hr cumulative infiltration. Although the results are mixed and differences not statistically significant, surging tended to increase steady-state infiltration rate. Although the slightly higher cumulative infiltration can be explained by hydraulic principles (increased soil-water tension following flow interruptions due to water redistribution), a reason for the higher steady-state rate is not known.

Reducing sediment movement and, thus, surface seal formation with the cheesecloth layer dramatically increased infiltration into this soil. Cumulative infiltration more than doubled and steady-state infiltration rate more than tripled compared to the conventional constant-flow furrows. If infiltration is assumed proportional to wetted perimeter (the maximum possible response), approximately one-quarter of this increase could be attributed to the wetted perimeter increase resulting from the cheesecloth.

When surface sealing was prevented, surging consistently reduced steady-state and cumulative infiltration by about 25%. However, infiltration was still much higher in these surged, no-seal furrows than in the conventional furrows.

TABLE 1. Cumulative and steady-state infiltration

		6-hr Cumulative infiltration (L/m)				Steady-state infiltration rate (L/m/hr)			
		Conventional		No seal		Conventional		No seal	
Year	Rep	Constant	Surge	Constant	Surge	Constant	Surge	Constant	Surge
1987	1	38	47	92	75	3.6	5.7	12.2	10.0
	2	40	43	96	70	4.1	3.8	12.5	8.5
	3	41	42	105	72	3.6	3.2	14.8	7.8
	4	57	44	95	90	3.4	4.2	10.0	9.3
	Average	44	44	97	77	3.7	4.2	12.4	8.9
1989	1	36	50	92	63	3.0	5.0	12.0	8.0
	2	38	40	91	69	3.4	3.0	12.0	9.0
	3	50	55	84	68	5.0	7.0	12.0	9.0
	Average	41	48	89	67	3.8	5.0	12.0	8.7
AVERAGE		43	46	94	72	3.7	4.6	12.2	8.8
RELATIVE TO CONVENT. CONSTANT		1.00	1.07	2.18	1.69	1.00	1.22	3.28	2.36
CORRECTED FOR WETTED PERIMETER		1.00	1.07	1.82	1.40	1.00	1.22	2.73	1.97

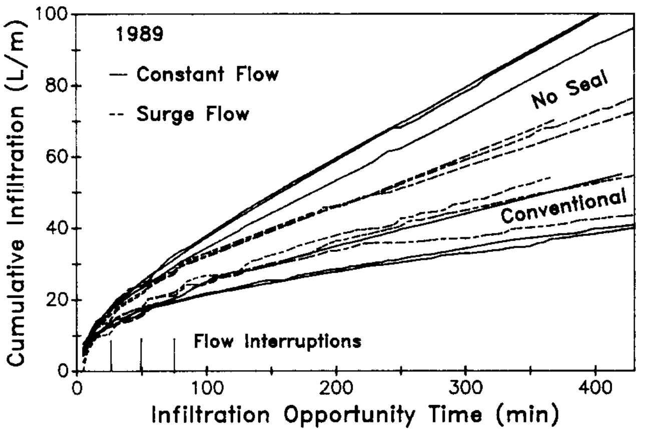


Figure 3–Cumulative infiltration for the 1989 tests.

SOIL-WATER TENSION

Figure 4 shows how the soil-water tension varied with time during a set of tests. When flow was interrupted, tension increased quickly beneath both types of furrows as the water redistributed downward. Tension was still increasing at the end of the 20-minute interruptions. When flow was resumed, the tension rapidly decreased toward a steady-state value as the soil rewetted. In the conventional furrows, tension asymptotically approached the steady-state value over the initial 200 minutes indicating increasing seal resistance over that period of time (Segeren, 1990). In the no-seal furrows, the lower steady-state value was reached as the soil wet up within the first 60 minutes. The tensiometers appear to respond quickly to the rapid tension changes during flow interruption. The short-term random tension fluctuations are likely instrument related.

Table 2 summarizes the peak and steady-state soil-water tension data. In the conventional furrows, flow interruptions had a small and inconsistent affect on steady-state soil-water tension. The trend for lower steady-state tension with surge flow implies less infiltration resistance near the surface and supports the trend of increased infiltration, but a cause is not known.

The cheesecloth treatment reduced the average constant-flow steady-state tension by 80%. This result reflects the large infiltration resistance of the furrow seal in the conventional furrows and the success of the cheesecloth in

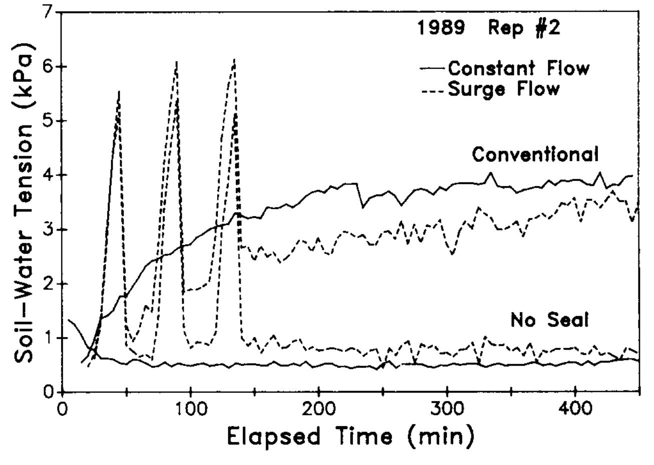


Figure 4–Soil-water tension variation with elapsed time.

TABLE 2. Steady-state and peak soil-water tension 20 mm from the furrow perimeter

		Steady-state tension (kPa)*				Peak tension (kPa)	
		Conventional		No seal		Surge	
Year	Rep	Constant	Surge	Constant	Surge	Conven.	No seal
1987	1	2.7	2.0		1.5		4.7
	2		2.5	0.5	1.5	5.4	
	3	1.9	2.1		1.2	5.1	4.5
	4		1.2	0.5	0.8	3.5	3.7
	Average	2.3	2.0	0.5	1.3	4.7	4.3
1989	1	2.8	3.1	0.4	0.4	6.0	6.6
	2	3.9	3.5	0.5	0.8	8.0	5.3
	3	2.7	1.6	0.6	1.0	7.5	7.5
	Average	3.1	2.7	0.5	0.7	7.2	6.5
AVERAGE		2.7	2.3	0.5	1.0	5.7	5.2
RELATIVE TO CONVENT. CONSTANT		1.00	0.86	0.19	0.39	1.00	0.91

* 1 kPa ≈ 0.01 bar ≈ 100 mm H_2O head.

eliminating seal formation. Flow interruption in the cheesecloth-treated furrows doubled the steady-state tension at the tensiometer. This is primarily the result of decreased permeability due to soil consolidation which occurs during the flow interruptions but would also be affected by changes in the water release characteristics of the soil.

Soil-water tensions exceeded 4 kPa (400-mm H_2O head) on all furrows at the end of flow interruptions (Table 2). The peak tensions produced averaged only about 10% higher with the surface seal than with the cheesecloth treatment. This difference might increase with longer flow interruptions and thus higher tensions if the less porous seal effectively resists air entry (Kemper et al., 1988).

Bulk Density

Table 3 summarizes the bulk density data. The 1989 data are more consistent than the 1987 data due to more consistent measurement technique, but both years show similar trends. Furrow bed bulk density at the end of the approximately 8-hr irrigations tended to be slightly higher in the conventional furrows after surging. In the cheesecloth-covered furrows with constant flow, bulk density was significantly lower than in the conventional constant-flow furrows. Flow interruptions in these no-seal furrows increased the bulk-density to near the level in the conventional furrows. These bulk density differences were evident from the resistance of the furrow bed soil to insertion of the sampling ring and the slumping of the samples after removal.

Figure 5 shows the trends in the 1989 bulk density data collected at the beginning of each flow interruption period. The bulk density of the conventional furrow beds averaged 30 kg/m^3 (0.03 g/cm^3) higher than the no-seal furrow beds after only 25 minutes of flow. This supports the tension data shown in figure 4 showing rapid seal formation. Most of the remaining density increase in the conventional furrows occurred during the first flow interruption (between surges 1 and 2). The rate of density increase in the constant flow furrows could not be measured but the final density was similar with both flow regimes.

In the no-seal furrows, the density increased during both of the first two interruptions, and appears to have decreased slightly by the end of the irrigation. The bulk density in the no-seal furrows is lower at the end of the constant-flow irrigation than after the first 25 minutes of flow (surge 1 data). This apparently reflects some swelling of the soil with time in the absence of a surface seal or flow interruptions. Data from 1987 (not presented) show that the bulk density increases from the beginning to the end of each flow interruption period and then tends to partially rebound during the following flow period. Bulk density increases during the first interruption period averaged 90 kg/m^3, and during later interruptions averaged 40 kg/m^3.

Discussion

These field data exhibit the expected interrelationship between soil-water tension and soil consolidation and the expected relationship between soil consolidation and infiltration. Tension increases soil bulk density and thus reduces the soil porosity and permeability. Lower permeability reduces infiltration and results in higher tension. The process is, to an extent, self perpetuating. Flow interruption temporarily increases soil-water tension and consolidates the soil, thus decreasing its permeability. The surface seal which forms when water flows over the soil surface reduces the permeability of the furrow perimeter which also increases tension and soil consolidation below the seal. Since the least permeable layer exerts the greatest influence on infiltration, the net effects of these two processes, surface sealing and soil consolidation, are not additive. Thus the benefits of a practice such as surge irrigation depends on the infiltration resistance created by other processes, such as surface sealing.

Dry aggregates in the furrow disintegrate as they are wetted (Kemper et al., 1985). The shear of the flowing water in furrows further disintegrates weakened aggregates and transports the sediment particles. In the Portneuf soil, sediment concentrations in the furrow flow early in the irrigation are high - often exceeding 1000 mg/L. Many of the larger sediment particles and aggregates quickly deposit on the furrow bed, especially in the initially low flows near the wetting front, filling cracks and other macropores and resulting in a wide, shallow furrow shape. In the Portneuf soil, this smoothing process is visually evident within one meter behind the advancing stream front. As the moving sediment microaggregates roll and saltate with the flow, they abrade and become smaller. Although this increases their transportability, given enough opportunities, most sediment particles eventually are deposited on the furrow surface. Once particles settle, soil-water tension tends to hold them in place (Brown et al., 1988). This process was evident from decreasing sediment concentrations with time observed in the recirculating flow. As flow continues and finer particles deposit, the seal appears slick and smooth. The result is surface seal or crust layer with much smaller

TABLE 3. Bulk density of the furrow bed

			BULK DENSITY ($kg/m^3 \times 10^{-3}$)*									
			Conventional					No seal				
Year	Rep	Sample	Constant Final	Surge 1	Surge 2	Surge 3	Surge final	Constant final	Surge 1	Surge 2	Surge 3	Surge final
1987	1	1	1.13					1.15				1.20
		2	1.16					1.15				1.18
	2	1	1.13				1.15	1.07				
		2	1.11				1.19	1.17				
	3	1	1.12				1.19	1.04				1.17
		2	1.12				1.18	1.13				1.15
	4	1	1.12				1.19	1.09				1.17
		2	1.23				1.13	1.00				1.15
Average			1.14				1.17	1.10				1.17
1989	1	1	1.26	1.17	1.23	1.25	1.24	1.12	1.10	1.19	1.19	1.23
		2	1.20	1.16	1.18	1.24	1.29	1.08	1.14	1.19	1.18	1.17
	2	1	1.21	1.17	1.21	1.21	1.15	1.07	1.14	1.18	1.20	1.23
		2	1.19	1.10	1.19	1.21	1.21	1.10	1.20	1.19	1.19	1.18
	3	1	1.19	1.18	1.20	1.19	1.19	1.11	1.08	1.17	1.22	1.20
		2	1.25	1.23				1.09	1.15	1.16	1.26	1.20
Average			1.21	1.17	1.21	1.22	1.22	1.10	1.14	1.18	1.21	1.20
AVERAGE			1.18				1.19	1.10				1.19

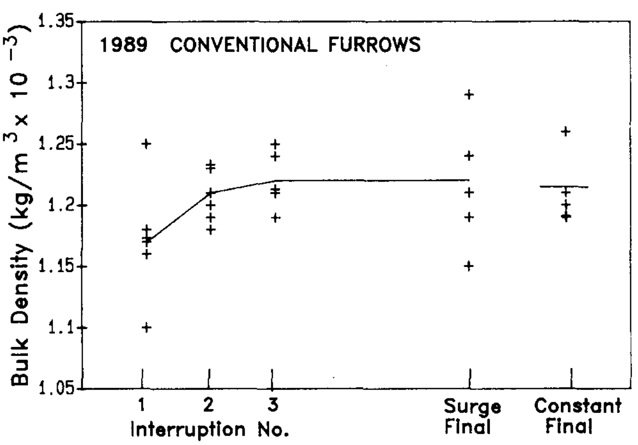
* $1\ kg/m^3 \times 10^{-3} = 1\ gm/cm^3$

pores and thus lower permeability than the original soil structure.

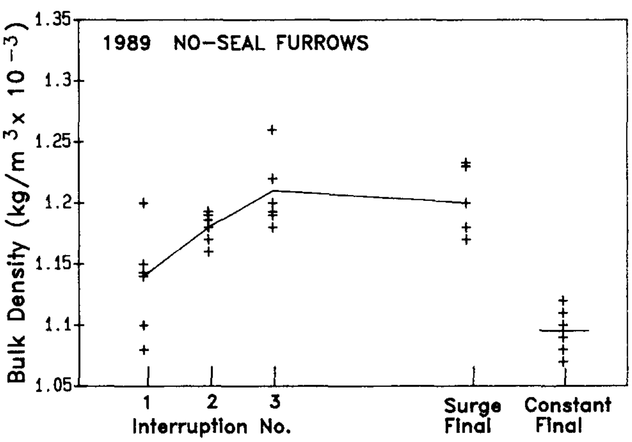
Segeren and Trout (1991) estimate the saturated hydraulic conductivity of a 0.3-mm thick furrow surface seal formed in a Portneuf soil as 2 mm/hr compared to 48 mm/hr for the perimeter soil without a seal. The flow resistance of this seal layer reduces infiltration rates by 50%. The seal resistance was also sufficient to create steady-state soil-water tensions averaging 2.7 kPa at the tensiometer located approximately 20 mm from the perimeter. Although this soil-water tension doubled during flow interruption in these conventional furrows, this increase did not cause significant additional consolidation or further decrease infiltration. In the Portneuf soil, the effect of the surface seal overshadows the influence of surge irrigation.

When sediment movement and surface seal formation was prevented with the cheesecloth, soil-water tension at the tensiometer averaged only 0.5 kPa and bed soil bulk density averaged 1100 kg/m^3. Water redistribution during flow interruptions created average soil-water tensions of 5 kPa. These short-term tension peaks were sufficient to consolidate the surface 30-mm soil layer of the bed to an average bulk density of 1190 kg/m^3.

Samani et al. (1985) measured somewhat larger density increases with similar tensions in laboratory columns of the



a. Conventional furrows.



b. No-seal furrows.

Figure 5–1989 Furrow bulk density data and mean trends.

Portneuf soil in ponded water, but their initial soil was less dense and their density measurements were made before water was reintroduced (before any swelling could occur). Their 150 kg/m^3 density increase with a tension increase from 0.5 to 5.0 kPa resulted in a 70% reduction in saturated hydraulic conductivity (from 90 to 30 mm/hr). A 90 kg/m^3 density increase (from 1040 to 1130 kg/m^3) resulted in a 55% reduction in saturated conductivity. Using these soil column tension:conductivity relationships, Samani (1983) projects a 20 to 25% reduction in furrow infiltration with a 15-min flow interruption. A two-dimensional finite difference porous media flow model originally developed by Samani (1983) and adapted by Segeren (1990) predicts that the saturated hydraulic conductivity of the soil in these tests must decrease by 40% (from 48 to 29 mm/hr) to create the measured 25% decrease in infiltration rate after 300 minutes.

Kemper et al. (1988) related the surge effectiveness of field trials on the Portneuf soil to the shear exerted by the flow on the furrow wetted perimeter. They defined the relative shear as furrow slope to the 13/16^{ths} power times flow rate (L/min) to the 3/8^{ths} power. The relative shear in the present tests was 0.04 (0.005 m/m slope and 20 L/min flow rate). Assuming that the furrows used in these tests were similar in terms of roughness, shape and erodibility to the non-wheel, late season furrows cited in that study, the surge effect with this relative shear should be sufficient to reduce the inflow time to complete advance time by 30%. Such a reduction requires about a 40% reduction in the infiltration rate for the studied field conditions (estimated from kinematic wave furrow advance simulations). These data do not support the surge effectiveness vs. relative shear relationship proposed by Kemper et al.

Two conditions which may influence surge effectiveness under normal field operations were not duplicated in these recirculating infiltrometer tests. Under field conditions, if flow interruption reduces infiltration rates, surged flows advance more rapidly across the field which results in more rapid wetting of the aggregates and thus more aggregate disintegration (Kemper et al., 1988). In these tests, wetting rates were equal for both surge and constant-flow furrows. Under field conditions, much of the sediment eroded from the upstream ends of furrows is translocated further downstream and deposits as furrow flow rates decrease (Trout and Neibling, 1991). This would probably leave head sections of furrows with less surface seal. With the recirculating infiltrometer, all sediment is recycled through the short furrow section and thus erosion and deposition must balance in the section. It is also possible that the infiltrometer flow-recirculation system decreases the sediment particle (aggregate) sizes resulting in a less porous seal. These differences may influence the surge effectiveness, but they will not change the basic conclusion of this study.

Soil consolidation during flow interruptions caused the soil to begin cracking about 10 minutes after water drained from the soil surface. With the cheesecloth layer, sediment movement during the following flow periods was insufficient to fill the cracks. Although the cracks partially filled with sloughed soil, they remained visually evident throughout the irrigation. Kemper et al. (1988) proposed that crack filling with sediment reduces swelling during rewetting and thus increases consolidation. If sediment movement had been sufficient to fill cracks, the consolidation and infiltration reduction may have been greater in the no-seal surged furrows.

The surge effect is highly variable on the Portneuf soil as indicated by the results presented by Kemper et al. (1988) and other data by the author. The infiltration reduction during first irrigations following tillage varies from 0 to 40%. This study indicates that the infiltration reduction created by flow interruption is dependent on the infiltration rate which occurs with normal constant-flow conditions. Although the sediment-related factors described by Kemper et al. (1988) should enhance the surge effect, many of these factors will also influence infiltration with constant flow. Quantifying the relative effects of these factors under the two flow regimes requires quantification of the soil aggregate stability/erodibility at the time of irrigation and the erosiveness of the two flow regimes. In soils less erosive than the Portneuf, surface seals may be less restrictive to infiltration, but the same principles will apply.

Conclusions

On the highly-erodible Portneuf silt loam soil, surface seal formation reduces infiltration by about 50%. This was sufficient to overshadow benefits derived from the soil consolidation and sediment deposition which occurs during flow interruption. When surface seal formation was prevented, flow interruption reduced infiltration rates by about 25%. Although sediment movement and deposition should reduce infiltration with surge irrigation, these processes can also reduce infiltration with constant flow. Thus, predicting the benefits of surge irrigation depends on projecting the influence of erosion and sediment movement under both flow regimes as well as the effects of soil consolidation which occurs during flow interruptions.

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