Mechanisms by which Surge Irrigation Reduces Furrow Infiltration Rates in a Silty Loam Soil

W. D. Kemper, T. J. Trout, A. S. Humpherys, M. S. Bullock
MEMBER ASAE MEMBER ASAE MEMBER ASAE

ABSTRACT

SURGE irrigation, the intermittent supply of water to furrows or borders, generally reduces infiltration rates. However, the degree of infiltration reduction is variable and difficult to predict. Mechanisms by which surge irrigation reduces infiltration rates include (a) consolidation of the furrow perimeter due to increased soil water tension during flow interruptions, (b) filling of cracks which develop during flow interruptions with bed load during the following surge, (c) forced settlement of suspended sediment on the furrow perimeter when the water supply is interrupted, and (d) greater sediment detachment and movement caused by more rapid advance of the surged stream front.

INTRODUCTION

Surge irrigation (Bishop et al., 1981), the cyclically interrupted supply of water to furrows and borders, has been found to decrease infiltration rates (Malano, 1983; Izuno et al., 1985) and thus increase water advance rates (Walker et al., 1981). Surge irrigation has the potential to increase the uniformity of surface irrigation application both by increasing advance rates and thus decrease infiltration opportunity time differences across a field; and by decreasing the infiltration rate at the upstream ends of furrows or borders to compensate for their longer infiltration opportunity times. Supply interruption while water is initially wetting the upper end of a field followed by continuous supply during and following wetting of the lower ends often achieves the desired relative decrease in infiltration rate at the upper ends.

Surge irrigation is becoming a commonly used method for improving irrigation. However, it does not always achieve this objective. A better understanding of the basic mechanisms which enable supply interruption to reduce intake is needed to help predict the conditions under which significant intake rate reduction and subsequent improved uniformity will occur.

Several studies have been conducted to determine mechanisms which cause flow interruption to decrease infiltration rates. Moisture redistribution in the profile during water application interruptions increases soil water tensions near the soil surface. These higher water tensions also increase the forces which pull water into the soil when it reenters the furrow (Lep, 1982; Samani et al., 1985). Consequently, the permeability of the soil must decrease significantly to reduce the subsequent infiltration rates (Samani et al., 1985). Trout and Kemper (1983) and Samani et al. (1985) attribute a major part of the permeability decrease to consolidation of the soil near the furrow perimeter by increased water tension during flow interruptions.

This paper describes concepts and observations which provide some understanding of the infiltration rate reduction mechanisms associated with water supply interruption. Soils in the fields used in these studies were Portneuf silt loams which are wind deposited, have clay, silt, and sand contents of about 20, 60, and 20%, respectively, and organic carbon contents of about 0.5%. They are highly erodible and commonly have sustained furrow infiltration rates of 3 to 5 L/m/h.

MECHANISMS FOR REDUCING INFILTRATION RATES

Consolidation Due to Temporary Soil Water Tension

When recently tilled furrows are wetted quickly, clods and large aggregates which make up the perimeter and lie loose in the furrow quickly disintegrate into small aggregates by forces associated with entrapped air (Kemper et al., 1985b and 1985c). Flowing water commonly exerts sufficient force on the exposed portion of these small aggregates to roll them down the furrow as bed load to new protected positions where forces exerted by the water are no longer sufficient to keep them rolling (Brown et al., 1987; Trout and Neibling, 1987). As the bed load rolls and bounces on the furrow bed, primary particles are abraded both from the moving aggregates and from those on the surface of the bed. These tiny silt and clay particles continue to move as suspended sediment because their settling velocities are smaller than the upward velocities of turbulent eddies in the flowing water.

During the first irrigation following tillage, the bottoms of flat-to-moderately-sloped furrows are commonly covered quickly with the small aggregates which become bed load and subsequently find a resting place. The flow cross section of the furrows normally changes from V-shaped to relatively flat bottomed and becomes broader, and shallower. The major portion of the interior of this reformed channel bed, composed largely of small aggregates deposited by the water, has a low density and relatively high permeability.

If the water supply stops before water reaches the end of the field, the water remaining in the furrow is absorbed and its fine suspended sediment is deposited in the larger pores and as a thin layer on the surface of the furrow bed. Deeper, drier soil continues to pull water

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The authors are: W. D. KEMPER, Soil Scientist; T. J. TROUT, Agricultural Engineer; A. S. HUMPHERYS, Agricultural Engineer; and M. S. BULLOCK, Graduate Research Assistant, USDA-Agricultural Research Service, Kimberly, ID.

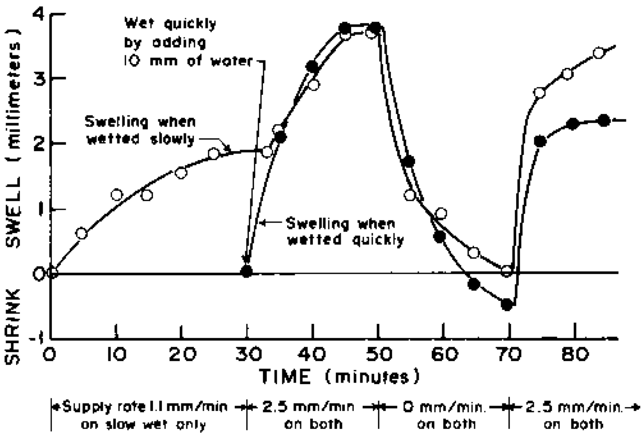


Fig. 1—Swelling and shrinkage of Portneuf silt loam soil columns on which the indicated supply rates were maintained following slow and quick wetting (adapted from Figs. 7 and 8 of Bullock et al., 1988).

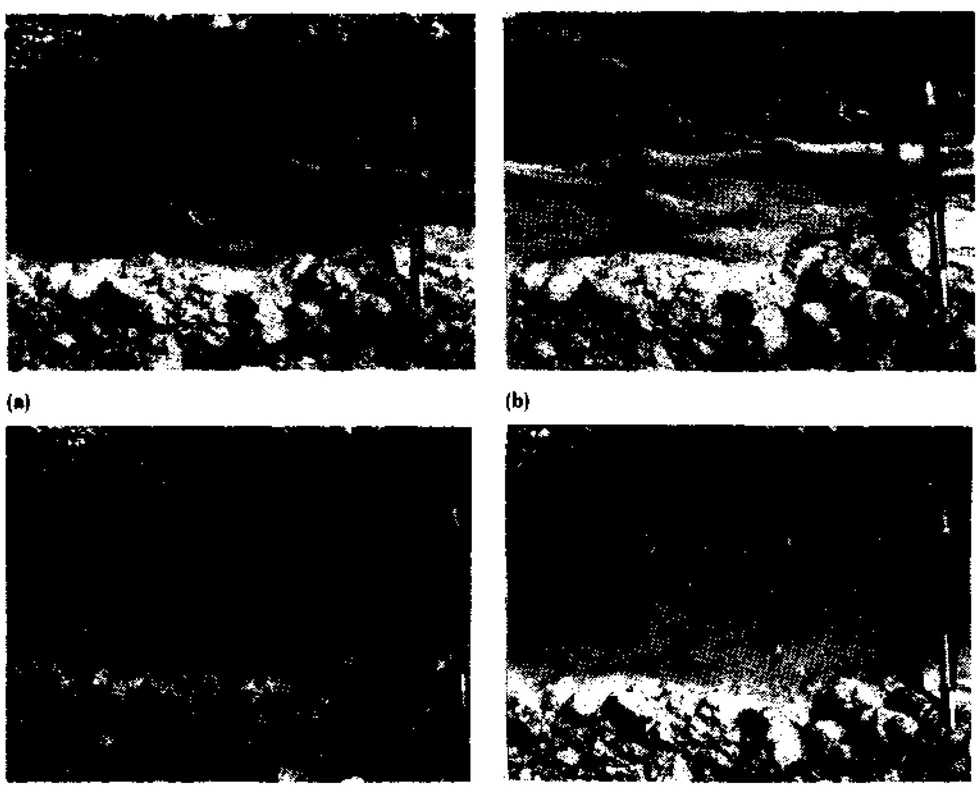
from the soil near the furrow perimeter creating tension in the soil water. Filling of the large pores in the thin layer of soil on the wetted perimeter of the furrow by fine sediment increases the maximum soil water tension that can be reached before air enters that layer of soil. Measured tensions 10 mm below furrow perimeters reached 500 mm during 20 min flow interruptions. Decreasing the seal formation by eliminating sediment movement resulted in 150 mm lower peak tensions. This maximum tension in the water phase prior to air entry is numerically equal to the maximum effective compacting pressure on the surface layer. Samani et al. (1985) also found that the degree of compaction is a function of the soil-water tension.

If bonds between soil particles are weakened or broken during the previous quick wetting process, this compacting pressure reduces the volume of the surface layer below that of its pre-wet state, as illustrated by the shrinking and swelling curve of quickly wetted soil in Fig. 1. When soils are wetted slowly, the entrampment and subsequent explosion of air is less (Kemper et al., 1985b) and shrinkage of the layer is also less when the water supply is subsequently interrupted as shown for the slowly wetted soil in Fig. 1. Greater shrinkage or densification decreases the infiltration rate.

After air enters the pore space of the soil layer on the furrow's wetted perimeter, the tension no longer exerts a compacting force on the whole layer, but pulls groups of soil particles together that lie between the air-filled pore spaces. Continued or increased tension generally results in shrinkage and consolidation of aggregated units within the layer and larger voids between those aggregates. Where these larger voids happen to be adjacent to each other, they form planes of minimum cohesion, some of which are the precursors of shrinkage cracks.

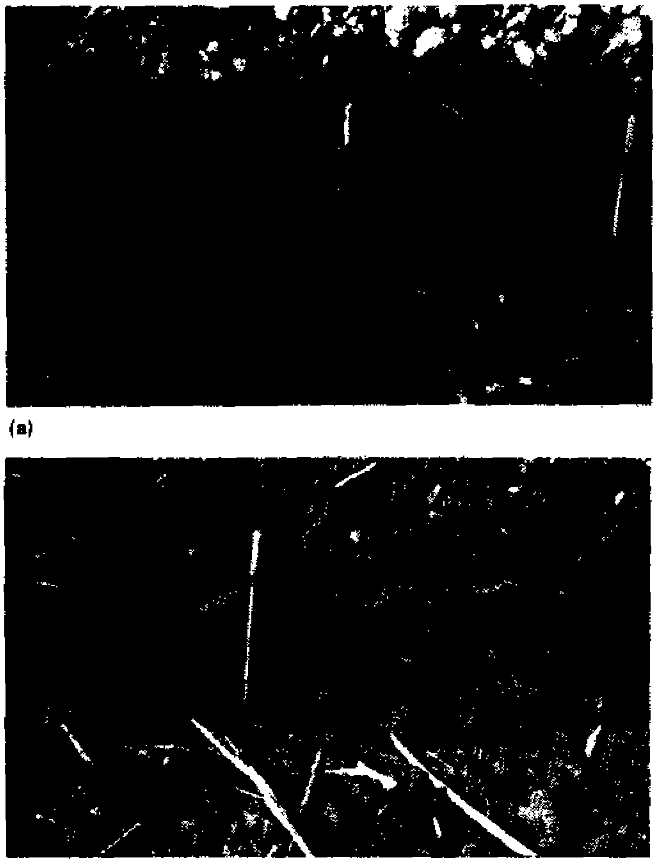
Crack Refilling and Higher Furrow-Bottom Densities

Shrinkage begins to form in Portneuf silt loam soils soon after water leaves recently tilled furrows. The photos in Fig. 2 were taken about 30 m from the upper end of a furrow during the first flow interruption in a section which had been wet for 30 min. Six min after free water left the furrow, visible cracks appeared on the



(a) (b) (c) (d)

Fig. 2—Shrinkage, cracking, and filling of furrow cracks with bed load in Portneuf silt loam soil. (a) Water disappearing at 1120 h. (b) Cracks widening at 1130 h. (c) Water reentering furrow at 1147 h. (d) Cracks closed at 1150 h by sediment filling and swelling.



(a)

(b)

Fig. 3—Cracking of furrow beds on the day following irrigation. (a) Cracking in an interrupted supply furrow. (b) Cracking in a continuous supply furrow.

surface (Fig. 2b). These cracks began when and where air entered the soil layer and eliminated the tensile strength of water as a cohesive force at that point. Since the bed in Fig. 2 was composed of recently disrupted material which had not had time to develop mineral bonds between particles or aggregates, it has practically no cohesive force to hold it together other than the soil water tension (Kemper et al., 1987). Consequently, the cracks extended rapidly in the furrow bed in the 28-min period when free water was not in this section of the furrow (Fig. 2c).

Horizontal swelling during rewetting is less than the prior shrinkage during supply interruption because the bed load carried by the incoming water fills part of the cracks before they swell shut (Fig. 2d). Bed soil densities in the top 20 mm between cracks, measured on the day following irrigation, averaged 1.42 gm/cm^3 for beds of continuous-flow furrows. Widths of representative cracks when the bulk density samples were taken, shown in Fig. 3, illustrate that the soil in the bottom of surged furrows had shrunk less since the irrigation than that in continuous-flow furrows. This suggests that the density differences between beds of interrupted and continuous-flow furrows during the final stage of the irrigation were greater than the 0.1 gm/cm^3 measured difference the day after irrigation.

The percentage of the furrow bed area occupied by shrinkage cracks on the day that the density samples were taken was measured. Shrinkage in the two horizontal dimensions resulted in 8% of the bed surface occupied by cracks in the surged furrows (Fig. 3a) and 13% in the continuous-flow furrows (Fig. 3b). Measured bulk densities and measurements and estimates of shrinkage indicated that, during the final stages of irrigation, the bulk densities were about 1.2 and 1.0 for the top 20 mm of the surged and continuous-flow furrow beds, respectively.

While the difference in bed density between surged and continuous-flow furrows is rather large and contributes to infiltration rate reduction, the relatively low densities involved, even in the surged furrows, raise doubt that the permeabilities of the interior of these beds below their surface constitute the primary restriction on rate of water movement from the furrow.

In a following year, with 27 days and a 20 mm rain between furrowing and the first irrigation on this field, there was no cracking of the soil when the water supply was interrupted for 30 min. Aggregate stability determinations on samples of this silt loam soil indicated that considerable mineral bonding occurs between particles of previously disrupted soil if the soil is wetted and then dries slowly (Kemper et al., 1987). Consolidation and mineral bonding which occurred during and following rainfall wetting were apparently sufficient to prevent surface cracking under tensions created during flow interruption and, thus prevented some of the associated density increases previously described. The first irrigations following tillage normally encounter loose unconsolidated soil conditions which lead to early and extensive cracking during subsequent water supply interruptions.

Deposition of Suspended Sediment

Disintegration of the wetted perimeter in furrows supplied with clean water at "non-erosive' flow rates (USDA-SCS, 1983) was so rapid that an appreciable bed load developed within 2 or 3 mm of the upper end (Brown et al., 1986.) Little suspended sediment was observed in the water at the upper end of the furrows where the most rapid erosion occurred. However, as bed load aggregates rolled and bounced along the bottom of the furrow, they abraded so that within 20 m of the supply end of the furrow, appreciable amounts of fine sediment were generally suspended in the water. Brown and Kemper (1987) reported that a major portion of the suspended clay particles commonly stay in suspension and leave the furrow with the runoff when the tail water runoff rate exceeds 30% of the rate that water is supplied to the furrow. Berg and Carter (1980) reported that an average of nearly 50% of the water applied to fields in southern Idaho via furrow irrigation runs off. Consequently, under continuous supply irrigation, a major portion of the fine sediment is carried out the tail end of the furrows.

When the supply is interrupted before water reaches the ends of the furrows, the suspended sediment is deposited on the furrow bed. Brown et al. (1987) observed that a thin coating of this fine sediment on the furrow bed reduced furrow intake rates by about 50%. Shainberg and Singer (1985) found that fine sediment deposited on some soils reduced infiltration rates to only a few percent of their unsealed rates. Consequently,

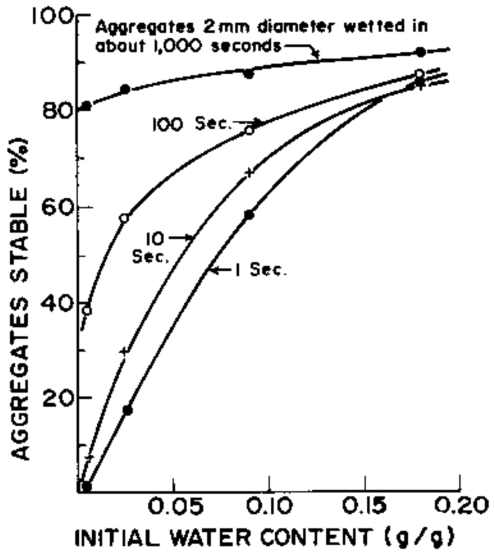


Fig. 4—Effects of initial water content and wetting rate on stability of large aggregates from Portneuf silt loam soil (Kemper et al., 1985b).

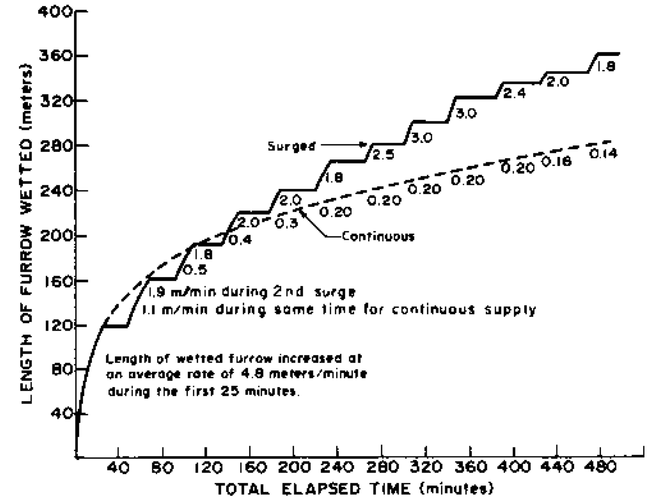


Fig. 5—Wetted front advance rates for continuous supply and surged supply which was interrupted for half of each 40-min cycle. Furrows were in a sandy loam soil near Howell, UT (Bishop et al., 1981).

supply interruption forces deposition of fine sediment on the furrow bed and thereby decreases infiltration.

Surge irrigation flows also create greater shear on the furrow perimeter as the water's leading edge rushes along the bottom of a furrow that has been previously wetted. The leading edge may be only a few millimeters deep, but rapidly increasing depth of water behind the leading edge causes it to travel with velocities that are nearly as fast as flow velocities when the furrow is full of water (Bishop et al., 1981). Shear on the soil surface is proportional to the maximum velocity of the moving water when the cross section is constant. If the maximum velocity is kept constant and the cross section is variable, shear on the soil is inversely proportional to the depth of water in the furrow. Consequently, the thin leading edge exerts shear on the furrow bed, loosens particles which are not firmly anchored to the bed surface and moves them on to new niches in the bed. Thus, shear provides additional suspended sediment which is effective in blocking infiltration as described previously. Such decreases in infiltration rate with increased shear forces exerted by flowing water were noted by Eisenhauer et al. (1983) in controlled flume studies.

Rate of Wetting

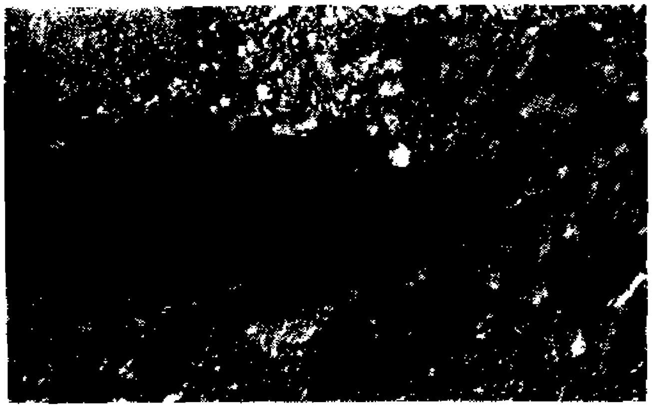
Aggregate stability decreases when rate of wetting is increased (Panabokke and Quirk, 1957). Kemper et al. (1985b) found that stability of large aggregates was highly dependent on the initial water content and rate of wetting (Fig. 4). When large dry aggregates of Portneuf soil are wetted quickly, they disintegrate into small aggregates which can be easily rolled along the bed of a furrow by moving water. Increased furrow supply rate during advance, which increases the stream front advance rate and thus the wetting rate of the furrow bed and sides, resulted in greater increases in sediment removal from furrows than expected from the higher flow rates (Kemper et al., 1985c).

Stream front advance rates were charted while furrows were irrigated by both interrupted and continuous supply at the same flow rates. The wetting front advanced along the dry furrows from 2 to 20 times as fast with surged supply as with the constant supply. Stream front advance data from other surge tests supported this result. Fig. 5 shows advances in a surge test reported by Bishop et al. (1981) in which the stream fronts in surged furrows advanced 2 to 15 times as fast as furrow advance rates with continuous supply. Stream front velocities were about twice as fast under surged supply when the upper ends of furrows were being wetted but were about 10 times as fast over more than half of the furrow length.

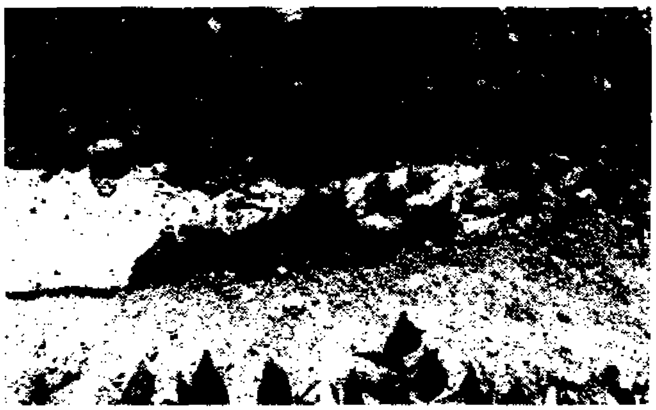
When the rate of stream front advance in continuously supplied furrows was slow (e.g., 0.22 m/min as shown in Fig. 6a), a large portion of the clods in the wetted perimeter were wetted by capillarity, which required about 100 s. However, when water advanced in a dry furrow at a rapid rate under surged supply (e.g., 2.4 m/min as shown in Fig. 6b), the rate of wetting was much faster. Most of the clods which made up the perimeter of the furrow were wetted within a period of 10 to 20 s after the water touched them. When wetting is this rapid, the outer portion of the clod is often wetted before the interior. As water is absorbed into the interior of a clod by capillarity, the trapped soil air is compressed and finally escapes by bursting out of and disintegrating much of the clod. This process generates small loose aggregates which abrade and become fine suspended sediment. During supply interruption, this fine suspended sediment is deposited and helps seal the furrow bed, which decreases the infiltration rate.

FACTORS AFFECTING SURGE MECHANISMS

All of the mechanisms discussed previously which appear to cause interrupted supply to reduce infiltration in furrows in Portneuf silt loam soil depend, to varying degrees, on the amount of breakdown of the soil aggregates. Thus factors which affect aggregate stability and hydraulic shear on the perimeter aggregates will also affect the relative changes in infiltration caused by flow interruption. These factors include the furrow slope and roughness, flow rate, and the condition of the surface soil.



(a)



(b)

Fig. 6—Slow and rapid wetting of furrows in Portneuf silt loam soil. (a) Wetting front moving 0.022 m/min under continuous supply. (b) Wetting front moving 2.4 m/min during a surge following supply interruption. Puffs of dust were actually rising from the top surface of these small clods as water initially surrounded them. After water has covered them, bubbles continue to emerge and are the major constituents of the foam that flows with the wetting front. Clods disintegrated and products were washed away within 5 min.

Advance Rates and Hydraulic Shear

Slow Advance: Surge and continuous supply were compared on four furrows with slopes of 0.001 and four furrows with slopes of 0.003. In these low-slope furrows, flow cross sections were large, water velocities were low, and there was litle sediment movement. With a supply rate of 38 L/min, the furrow bottoms were wetted fairly quickly (Fig. 7), but the extensive portion of the wetted perimeter on the sides of the furrows was wetted by capillarity at a relatively slow rate which appeared to conserve much of the original structure of the wetted perimeter. During supply interruption, a few small cracks developed in the bottoms of the surged furrows but there was essentially no cracking in the upper portions of the wetted perimeter. This indicated little shrinkage or compaction of the soil by the tension that developed in the soil water. This apparent lack of shrinkage (or compaction) of the wetted perimeter was probably due to less disintegration of the soil structure due to slow wetting, and to less tension developing in these furrows. Because of their greater flow cross section, furrows on small slopes have more storage capacity than furrows on greater slopes. Consequently, although water was supplied to these low-slope furrows for half of the time, water remained in the furrows for about 70% of the

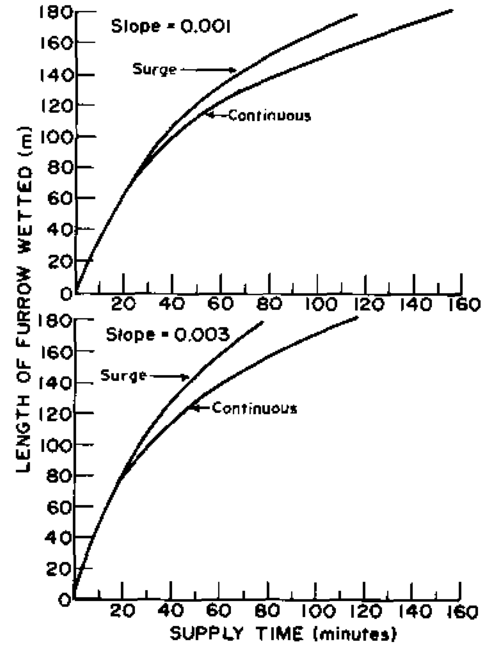


Fig. 7—Lenth of furrow wetted as a function of supply time when low slope furrows in Portneuf silt loam were provided with continuous and surged (20 min on, 20 min off) supply at the rate of 38 L/min.

time as compared to only about 55% of the time for steeper slopes. Consequently, there was only about two-thirds as much time for tension to develop in soil water adjacent to the flatter furrows.

Length of wetted furrow is plotted as a function of supply time for the 0.001 and 0.003 slopes in Fig. 7. The surge advance points were connected for the interrupted supply case to obtain the smooth curves shown in the figure. After water had reached the ends of the surged furrows, they were provided with a continuous supply. Infiltration rates are given in Table 1 for the respective slopes and treatments 2 h after water had reached the ends. Surged supply during initial wetting diminished subsequent infiltration rates to 0.91 and 0.83 of those under continuous supply on the 0.001 and 0.003 slopes, respectively. The average coefficient of variation of the means was 0.045. Total supply time, and thus total amount of water required to advance water to the ends of the furrows, was less for the surged furrows. However, water did not reach the ends of the surged furrows as soon, in terms of total elapsed time, as it reached the

TABLE 1. EFFECTS OF SURGE AND CONTINUOUS SUPPLY DURING WETTING ON SUBSEQUENT FURROW INFILTRATION RATES

Slope	Pretreatment	Basic infiltration rate*	Ratio of infiltration rates (surge/continuous)
m/m		L/m/min	
0.001	Surge†	0.109	0.91
0.001	Continuous	0.120	
0.003	Surge†	0.109	0.83
0.003	Continuous	0.131	

*Infiltration rates were measured by inflow-outflow 6 h after the irrigation began. Listed rates are the average of determinations on duplicate furrows. The average coefficient of variation of the means was 0.045. Supply rate was 38 L/min.

†40-min cycle times, 50% cycle ratio (20-min interruptions) for 4h.

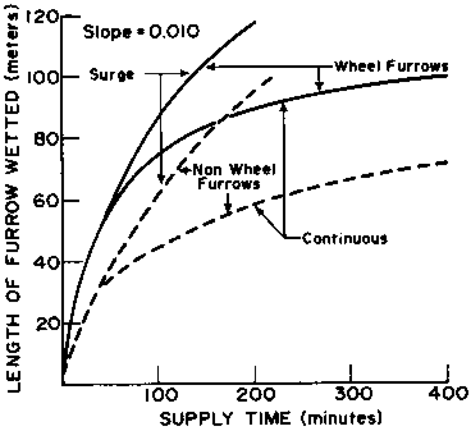


Fig. 8—Effect of continuous and surged water supply on lengths of furrows wetted with and without tractor wheel compaction (supply rate = 19 L/min).

ends of continuously supplied furrows. In contrast, Fig. 8 shows the advance for other furrows on a 0.01 slope in Portneuf silt loam where water reached the ends of surged furrows sooner than in continuously supplied furrows. Infiltration rates following interrupted supply on these steeper furrows were 60% of those following continuous supply, when one 30 min interruption was applied during advance. With three interruptions, (30 min, 45 min, and 60 min, respectively) the surged infiltration rate was only 45% of the continuous rate.

Hydraulic Shear: Independent tests were conducted on a 0.01 slope in June and October 1982, June 1983, and May 1984. Supply time, and thus volume, for water to reach the ends of the furrows under surge flow varied from 0.53 to 1.25 of the time required when the supply was continuous (Table 2). There was a trend for the larger ratios to occur when the paired sets of interrupted and continuous supply furrows had higher rates of supply. The greater hydraulic shear due to increased slopes appeared to enable surged supply to decrease the infiltration rate, but increasing the hydraulic shear further by increasing the furrow flow rate appeared to decrease the surge effectiveness. In an attempt to rationalize these sets of apparently conflicting data, the relative shear stress on the wetted perimeter was calculated according to an equation derived from Manning's equation by Kemper et al. (1985c),

$$T = kS\,(Qn/S^{1/2})^{3/8} \quad \ldots\ldots\ldots\ldots [1]$$

where

T = the average hydraulic shear force per unit area over the wetted perimeter
k = a constant dependent on furrow shape
S = the slope of the furrow
Q = the rate of supply, L/min
n = Manning's roughness coefficient

Assuming that n and k were constant for these furrows, we rearranged equation [1] to the form

$$T/kn^{3/8} = S^{13/16}Q^{3/8} \quad \ldots\ldots\ldots\ldots [2]$$

and describe $T/kn^{3/8}$ as the average relative shear on the furrow perimeter. The respective estimates of this relative shear were calculated for each set of furrows from their slopes and supply rates (Table 2) and are plotted in Fig. 9 against the ratio of the supply time required for water to reach the end of the furrow with surge supply to the time required with continuous supply. Water in the surged furrows took less supply time to reach the ends of the furrows than water in continuous-flow furrows except when shear was high late in the season.

Advance time ratios for wheel compacted furrows (enclosed diagonal crosses on Fig. 9) appear to be higher than ratios for similar uncompacted furrows. Reduced infiltration rates resulting from wheel compaction apparently reduce the range over which surge supply can reduce the infiltration and, consequently, the advance time ratios for the wheel furrows are closer to unity.

Considering only nonwheel furrows, advance time ratios for tests made early in the season (i.e., May and June) appear to segregate from those made later in the

TABLE 2. RELATIVE HYDRAULIC SHEAR ON THE WETTED PERIMETER OF FURROWS AND THE RATIO OF SUPPLY TIME REQUIRED FOR EQUAL-SIZED FLOWS TO REACH THE ENDS OF THE FURROW UNDER SURGED AND CONTINUOUS SUPPLY

Study date	Wheel (W) or Nonwheel (NW)	Slope	Furrow supply rate, L/min	Relative shear equation [2] $(L/min)^{3/8}$	Supply time ratio*	Furrow length, m
May '81	W	0.010	19	0.073	0.70	80
May '81	NW	0.010	19	0.073	0.44	60
Jun '82	NW	0.010	26	0.082	0.53	183
Jun '82	NW	0.010	29	0.086	0.73	183
Oct '82	NW	0.010	19	0.071	0.93	152
Oct '82	NW	0.010	23	0.079	0.98	183
Oct '82	NW	0.010	27	0.083	1.17	183
Oct '82	NW	0.010	30	0.088	1.10	183
Oct '82	NW	0.010	34	0.092	1.25	183
Jun '83	NW	0.010	17	0.069	0.49	137
May '84	W	0.010	19	0.071	0.90	183
Aug '86	NW	0.001	38	0.015	0.74	183
Aug '86	NW	0.003	38	0.036	0.66	183

*Comparative tests were conducted on adjacent furrows. The ratios shown for each test were averages obtained from at least two replications.

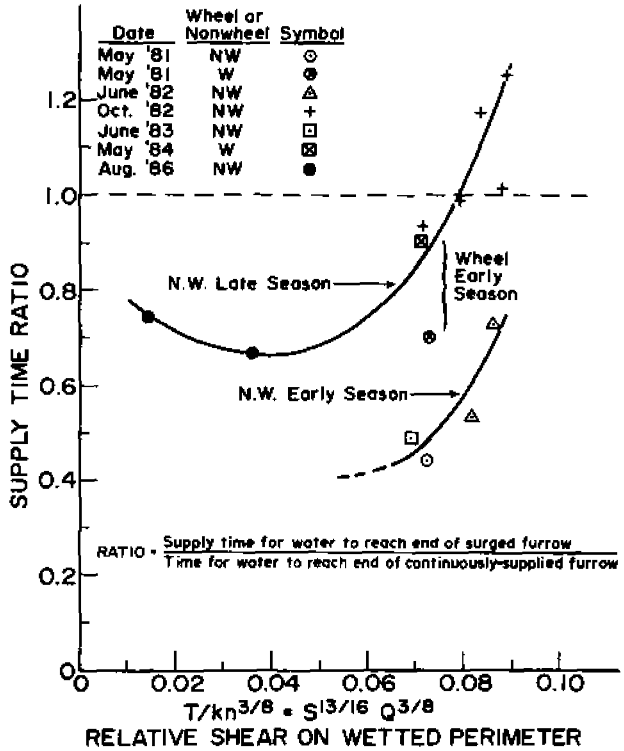


Fig. 9—Ratio of surged to continuous flow supply times required for water to reach the ends of furrows as a function of relative shear on the wetted perimeter.

season (August to October) even though all were first irrigations after recent tillage. This may be due to greater soil cohesion which results in less breakdown and redeposition of soil by the surging process in the latter part of the year. Bullock et al. (1988) found that the cohesion of aggregates and clods from this soil is drastically reduced by freezing during the winter months and increases with time after the soil thaws.

Considering the late-season tests in nonwheel furrows (upper curve of Fig. 9), it appears that increasing relative shear in the range from 0 to approximately 0.05 decreased the advance time ratio (increased the surging effect) while increasing the relative shear beyond approximately 0.07 increased the time ratio (decreased the surging effect). As relative shear on the wetted perimeter increases in the range up to about 0.05, wetting rates generally increase and a larger portion of the clods on the furrow perimeter disintegrate into small aggregates. In this relative shear range, higher supply rates and slopes also increase water velocity and shear on the wetted perimeter, which moves more of the small aggregates from their resting places and transports them down the furrow at a faster rate. The accompanying abrasion results in more microaggregates and primary particles in suspension which more completely plug large pores and strengthens the seal as they settle on or near the soil surface when the water supply is interrupted.

However, when hydraulic shear of incoming water during the surge is sufficiently large to erode the surface seal (relative shear greater than about 0.07), the infiltration rates are higher than for lower relative shear as indicated by the increase in supply time required for water in the surged furrows to reach the ends of the furrow. Scouring of the furrow by the high shear apparently removes some of the fine particles that helped seal both the surged and continuous-flow furrows. This would leave the wetted perimeters of both surged and continous furrows with approximately the same hydraulic conductivities. Greater infiltration per unit of supply time of the surged furrows, indicated by ratios greater than 1.0 at high shear (Fig. 9), may be a result of higher average soil water tensions in the surged furrows and more infiltration opportunity time since water resides in the furrow for a longer time than the supply time.

Brown et al. (1988) observed that sediment deposited on soil surfaces reduced the infiltration rate, which substantially increased tension in the soil water below the sealed surface. They calculated that the gradient of this increased tension was a primary force holding soil particles on the wetted surface against shear forces exerted by flowing water. They also observed that when a small area of the surface seal was removed, soil water tension in the vicinity decreased. The resulting decrease in tension holding the surface seal to the underlying soil allowed the flowing water to erode the surface rapidly in all directions from the point where surface seal removal began. This self aggravating tendency of surface erosion when a seal is involved, caused removal of a major portion of the seal soon after the most weakly held pieces were removed, even when the slope and flow rate remained constant.

The abrupt increase in the advance time ratio, which occurred at relative shears between 0.07 and 0.09 in Fig. 9, probably corresponds with the forces required to remove the most weakly held spots of the surface seal. Consequently, reduction in the force holding the remaining seal allows a major portion of the seal to peel off with little or no increase in hydraulic shear.

The data in Fig. 9 were collected on one specific silty loam soil. Because other soils have different particle size distributions, organic matter contents, and cohesions, it is probable that curves for other soils will be shifted from that shown in Fig. 9. However, the general principles affecting sealing, soil water tension increases resulting from sealing, increased cohesion of the wetted perimeter resulting from those tension increases, and accelerated erosion and infiltration increases when that tension is relieved are probably applicable to similar soils so that curves of somewhat the same shape can be expected to occur for other medium-textured soils.

Crop Residues in Moderately-Sloped (0.005 to 0.015 m/m) Furrows

Anchored crop residue extending into furrows absorbs much of the hydraulic shear force of the flow, and decreases the shear exerted on the wetted perimeter soil. In addition, residue laying across the surface of the water often stops or substantially reduces surface film velocity for 1 to 6 m upstream. In these sections, the perimeter causing drag on the flowing water includes both the commonly considered wetted soil perimeter of the furrow and the air-water perimeter (Kemper et al., 1984). In furrows with substantial amounts of residue (i.e., 25 g/m of wheat straw), the resultant increase in roughness increases the flow cross section and decreases the flow velocity for a given furrow supply rate. The result is slower rates of advance, slower wetting of the soil, decreased hydraulic shear on the soil, and greatly decreased movement of sediment compared to residue-free furrows (Aarstad and Miller, 1981; Berg, 1984; Brown and Kemper, 1987). In general, crop residues in moderately sloped (0.005 to 0.015 m/m) furrows cause their cross-sectional flow areas, flow velocity, rate of furrow advance, and other flow characteristics to be similar to those for furrows with flatter slopes.

Consequently, during surge irrigation of furrows with crop residue, most of the factors discussed in the previous paragraph are active in reducing disintegration of the structure of the furrow perimeter which, in turn, reduces the amount of fine sediment in the water. Thus, sealing of the furrow surfaces when the supply is interrupted is less. In several cases where the furrow slope was in the 0.005 to 0.015 m/m range and substantial amounts of crop residue were left on the surface, there was no significant decrease in infiltration rate following one to three interruptions on the furrow supply. In surge tests reported by Evans et al. (1987) on steep slopes ($S = 0.03$) with an erosive silt loam soil, flow interruption effectively decreased infiltration rates and increased advance rates. This indicates that the residue counteracted the effects of the steeper slopes and resulted in sufficient shear to create a seal but insufficient shear to destroy it.

Compacted Furrows with Low Intake Rates

Decreases in infiltration rates and increases in advance rates in wheel-tracked furrows due to surging are often smaller than in adjacent nontracked furrows (Figs. 8 and 9 and Kemper et al., 1985a). Generally, compacted soils have fewer large pores and consequently, surging, which also reduces the volume of large pores in the wetted perimeter, results in less change on these soils.

For example, many farmers track their fields after the preplant irrigation while the soil is still wet and compact the wheel furrows. In a study field during the preplant irrigation, surging decreased the average supply time to get water to the end of five furrows by about 13% compared to continuously supplied furrows 300 m long. Surged supply during subsequent irrigations did not reduce the infiltration rate significantly below that on continuously-supplied furrows. Surging during the previous year in the same field with spring wheat reduced the supply time required to get water to the end of 140 m long furrows by about 50% during the first irrigation.

SUMMARY

Surge irrigation is an effective method of decreasing infiltration rates in furrows on many soils. Mechanisms causing this infiltration reduction include: (a) consolidation of soil in the furrow beds as tension develops in the soil water during interruption of the flow; (b) filling of cracks, which form in the furrow bed during supply interruption by bed load when water reenters the furrows; (c) sealing of the furrow bed as all of the water in the furrow during each supply interruption enters the soil and deposits its fine sediments in the large pores or as a fine seal on absorbing surfaces, and (d) more complete disintegration of soil particles in the wetted perimeter as a result of faster wetting.

Conditions under which infiltration rate reductions due to furrow supply interruption were relatively small or insignificant on Portneuf silt loam soils included: (a) high shear rates late in the season when soil stability was high, and (b) furrows which had been compacted by tractors or other equipment and had low continuous-flow infiltration rates. Low water velocities due to small slopes or crop residues in the furrows resulted in moderate to insignifcant decreases in infiltration rates due to furrow supply interruption during late season irrigations when soil stability was high.

The largest decreases in infiltration rate due to interrupted supply occurred in the spring when soil stability was low and the wetted perimeter was subjected to sufficient shear to generate fine sediment in the water which helped seal the surface as the water was absorbed during flow interruptions. However, higher rates of shear allowed the succeeding surge of water to erode some of that seal from the surface.

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