SEAL FORMATION BENEATH ANIMAL WASTE HOLDING PONDS

A. Cihan, J. S. Tyner, W. C. Wright

ABSTRACT. *The objectives of this study were to measure the sealing effectiveness of swine and dairy waste applied to a variety of soil textures and to develop a suitable model for describing the sealing process through time. Dairy and swine waste were applied to soil columns packed with sand, silt loam, or clay. A seal developed that reduced the infiltration rates to approximately 10^{-6} cm s^{-1} or less within the 54 to 60 day testing period. Throughout the test, the infiltration rates into the clay soil were lowest. Yet as time passed, the differences between soil types diminished. Swine waste applied to sand required more time to develop a seal than all other combinations of waste and soil. A model was developed that describes cumulative infiltration as function of elapsed time, waste height, waste total solids content, and soil hydraulic conductivity. After a stable seal develops, the model predicts that only the seal properties (not the soil properties) are responsible for limiting infiltration. During the seal-dominated phase, a plot of cumulative infiltration versus the square root of time is linear, and the respective slope is dependent on a lumped parameter (K_{seal}/α). A review of available waste infiltration datasets from the literature revealed that K_{seal}/α can be estimated from the total solids concentration of the waste (R^2 = 0.87). Predictions of K_{seal}/α were not improved by including the hydraulic conductivity of the soil into the estimate or by analyzing the dairy and swine waste datasets separately. This suggests that neither soil hydraulic conductivity nor waste type greatly affect the infiltration rate during the seal-dominated phase of infiltration.*

Keywords. *Animal waste, Clay liner, Confined animal, Dairy, Lagoon leachate, Sealing.*

Liquid waste is commonly stored in soil-lined ponds to limit the pollution of groundwater. These soil liners are an alternative to more expensive impermeable liners. Many states require that the soil lining a pond have a saturated hydraulic conductivity of less than 10^{-6} cm s^{-1}. Researchers have found that liquid manure forms a seal as it passes through soil liners, creating a further reduction of infiltration rate. Chang et al. (1974) set packed soil columns with loam, sand, or silty clay in the bottom of a dairy manure lagoon for 64 days. Based on measurements from columns removed at various times, they found that all soil types had a similar effective sealed hydraulic conductivity value of approximately 10^{-5} cm s^{-1} within one week. After a month in the lagoon, water movement in the columns was not detectable (less than 1.3×10^{-6} cm s^{-1}). Hills (1976) investigated the effect of head, soil type, soil additives, and soil thickness on the infiltration rate of dairy manure with 0.5% to 0.6% total solids (*TS*). He showed that soil thickness and soil additives had a negligible effect on infiltration rate after about 16 weeks, at which point the infiltration rates through loam, silt loam, and sandy loam soils dropped to a constant flux of about 8.3×10^{-7} to 1.1×10^{-6} cm s^{-1}.

De Tar (1979) studied the effects of soil type, elapsed time, and total solids content of dairy waste on the infiltration rate. He found that the infiltration rate at approximately two weeks was inversely proportional to the waste total solids concentration with a coefficient of determination (R^2) of 0.924. However, he found a poor correlation between water infiltration and waste infiltration rates into different soils. He also observed that waste infiltration rates decreased as temperature increased. Culley and Phillips (1982) conducted laboratory-scale experiments of dairy waste infiltration into clay, loam, and sand soils. They found that all soil types had similar fluxes (4.6 to 6.9×10^{-7} cm s^{-1}) within 10 days. Barrington and Madramootoo (1989) conducted a study to independently measure the hydraulic conductivity of the soil and overlying seal after applying swine waste by placing piezometers at locations just above and below the soil-seal interface. They found that the hydraulic conductivity of saturated soil was not related to the amount of sealing, but the soil texture was a factor.

Tyner and Lee (2004) derived a steady-state two-layer model to analyze the effect of seal and soil parameters on the infiltration rate from animal waste ponds. Their model predicted that soil thickness has no effect on the infiltration rate. A sensitivity analysis, which was run over a wide range of conditions, predicted that infiltration rate is highly dependent on seal hydraulic conductivity and minimally dependent on soil hydraulic conductivity.

Tyner et al. (2006) examined the ability of dairy waste to seal undisturbed silt loam monoliths containing large macropores. After 85 days, a 2.45 m head of dairy waste produced an average flux at 8.7×10^{-7} cm s^{-1}. They found that the phenomenon of dairy waste sealing a soil appears analogous to a filter cake growing atop a filter, since the cumulative length of infiltration was linearly proportional to the square root of time. This research did not attempt to characterize infiltration prior to the development of a seal.

Submitted for review in June 2006 as manuscript number SE 6501; approved for publication by the Structures & Environment Division of ASABE in August 2006.

The authors are **Abdullah Cihan,** Graduate Student, **John S. Tyner, ASABE Member Engineer,** Assistant Professor, and **Wesley C. Wright, ASABE Member Engineer,** Research Associate, Department of Biosystems Engineering and Soil Science, University of Tennessee, Knoxville, Tennessee. **Corresponding author:** John S. Tyner, 2506 E.J. Chapman Dr., Knoxville, TN 37996-4531; phone: 865-974-7130; fax: 865-974-4514; e-mail: jtyner@utk.edu.

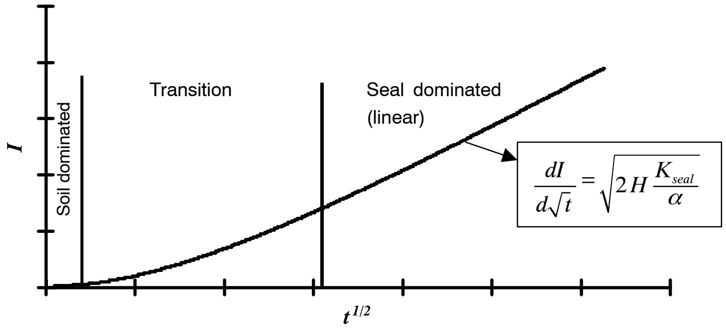

Figure 1. The three phases of waste infiltration into a soil.

The objectives of this study were to measure the sealing effectiveness of swine and dairy waste applied to a variety of soil textures and to develop a suitable model for describing the sealing process through time. In addition, we will characterize a key parameter of our model using previously published waste infiltration datasets available in the literature.

THEORY

Following a filter cake growth analogy, as a seal forms atop a soil, the seal thickness is proportional to the cumulative length of infiltrated waste, or:

$$L_{seal} = \alpha I \tag{1}$$

where L_{seal} is the seal thickness, I is the cumulative length of filtrate, and α is a coefficient relating L_{seal} and I, which is dependent on the solids concentration in the waste and the average pore size of the seal (Tyner et al., 2006; Abboud and Corapcioglu, 1993; Tosun, 1986).

According to Darcy's law, the infiltration rate through a seal and soil in series is described by:

$$q = \frac{dI}{dt} = K_{ave}\left(\frac{H}{L_{soil} + L_{seal}}\right)$$
$$K_{ave} = \frac{L_{soil} + L_{seal}}{L_{seal}/K_{seal} + L_{soil}/K_{soil}} \tag{2}$$

where q is flux, t is elapsed time, L_{soil} is soil thickness, L_{seal} is seal thickness, H is head loss across entire seal and soil thickness, K_{ave} is the average hydraulic conductivity of the soil-seal system, K_{soil} is the hydraulic conductivity of the soil, and K_{seal} is the hydraulic conductivity of the seal. Substituting equation 1 into equation 2 and solving for I gives:

$$I = \frac{K_{seal}}{\alpha}\left[-\frac{L_{soil}}{K_{soil}} + \sqrt{\left(\frac{L_{soil}}{K_{soil}}\right)^2 + \frac{2Ht}{K_{seal}/\alpha}}\right] \tag{3}$$

At late times, after the resistance of the seal becomes large compared to the resistance of the soil, i.e., $(L_{soil}/K_{soil})^2 << 2Ht/(K_{seal}/\alpha)$, equation 3 can be simplified to:

$$I = \sqrt{2Ht\left(\frac{K_{seal}}{\alpha}\right)} \tag{4}$$

Equation 4 predicts that cumulative infiltration at late times is proportional to $\sqrt{H}$, $\sqrt{t}$, and $\sqrt{K_{seal}/\alpha}$.

A graphical representation of I versus $t^{1/2}$ as predicted by equation 3 is presented in figure 1. When a head of liquid manure is initially applied to a saturated soil, the initial in–

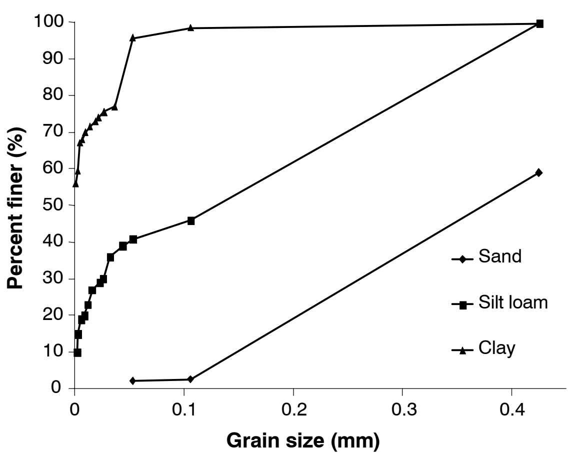

Figure 2. Particle size distribution of sand, silt loam, and clay.

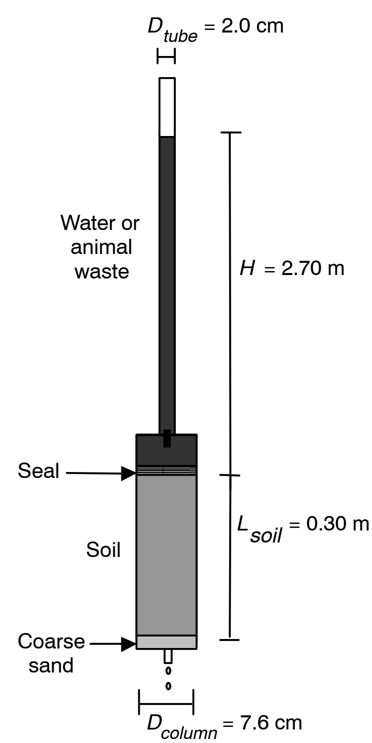

Figure 3. Schematic demonstration of the experimental setup.

filtration rate is linearly dependent on K_{soil}, since $L_{seal} = 0$ in equation 2. As time passes, a transition phase occurs with the rapid decrease in infiltration rate as the solids in the waste accumulate atop and within the upper layers of the soil. During the transition phase, the infiltration rate depends on both soil and seal properties. At late times, the seal properties become dominant and the soil properties become negligible, which is represented by the linear relationship between I versus $t^{1/2}$. Using the late-time seal-dominated slope, $dI/d\sqrt{t}$ (fig. 1), and a known H in conjunction with equation 4, K_{seal}/α can be calculated:

$$\frac{K_{seal}}{\alpha} = \left(\frac{dI}{d\sqrt{t}} \right)^2 \frac{1}{2H} \tag{5}$$

Later, we will present an empirical correlation between the lumped parameter K_{seal}/α and TS. This procedure allows prediction of I at late times from H, t, and TS.

Materials and Methods

Three soils of varying hydraulic conductivity were chosen to test the sealing capability of swine and dairy waste. The subsoil of a Dewey series (NRCS, 1988) was collected on a farm in Dandridge, Tennessee. This heavy clay represents a soil that might typically be used to construct a pond liner. A Sequatchie series (NRCS, 1961) silt loam (topsoil) was collected on the second terrace of Fort Loudon Lake at the Plant Sciences Unit of the University of Tennessee's Knoxville Education and Research Center. The third soil was commercially available bagged play sand. Particle size distributions were determined for each soil by wet sieve (method D1140; ASTM, 2005) and hydrometer (method D422; ASTM, 2005) analysis (fig. 2). Soil textures were determined using the USDA nomenclature system. The silt loam and clay soils were air dried for 3 days and passed through a soil grinder to break up any structure. A standard proctor density test (method D698; ASTM, 2005) was conducted on the clay to determine its optimum gravimetric moisture (26%) and corresponding dry bulk density (1.26 g cm^{-3}). A proctor test was not conducted on the sand or silt loam.

Table 1. Physical properties of the soils and the wastes.

	Sand (%)	Silt (%)	Clay (%)	K_{soil} (cm s^{-1})	Median Grain Size d_{50} (mm)
Sand	94	--	--	1.10×10^{-3}	0.30 to 0.40
Silt loam	57	32	11	1.07×10^{-5}	0.10 to 0.15
Clay	5	36	59	2.31×10^{-7}	<0.001

The clay soil was moistened to its optimum moisture content. The silt loam and sand were moistened to 15% and 10% gravimetric moisture content, respectively, which facilitated soil packing. Soils were hand-packed into PVC columns (7.75 cm inside diameter) with 10 cm lifts using 25 blows of a standard proctor hammer. Between each lift, approximately half of the previous lift was re-disturbed in order to minimize the formation of compaction layers. A total of 30 cm of compacted soil was placed into each column. A PVC cap with a small drain hole was partially filled with coarse sand and placed on the base of each soil column. A total of 24 columns were packed: eight each with clay, silt loam, or sand.

A clear 3 m pipe (2.0 cm inside diameter) was affixed to the top of the PVC columns such that a head of wastewater could be applied (fig. 3). Initially, a 2.7 m head of water was placed on each column to determine the saturated hydraulic conductivity by the falling head method (method D5856; ASTM, 2005). The eight measurements of hydraulic conductivity from each soil type were within 5% of their respective mean (table 1). The water was pumped from the columns after the hydraulic conductivity testing was complete.

A 2.7 m head of waste was placed on each column. The gravimetric total solids content (TS) of the waste was determined to be 2.1% for dairy and 1.1% for swine. Of the eight columns of each soil type, half were treated with dairy and half with swine waste. When infiltration reduced the head of waste by approximately 10 cm, the waste was refilled to the original 2.7 m of head.

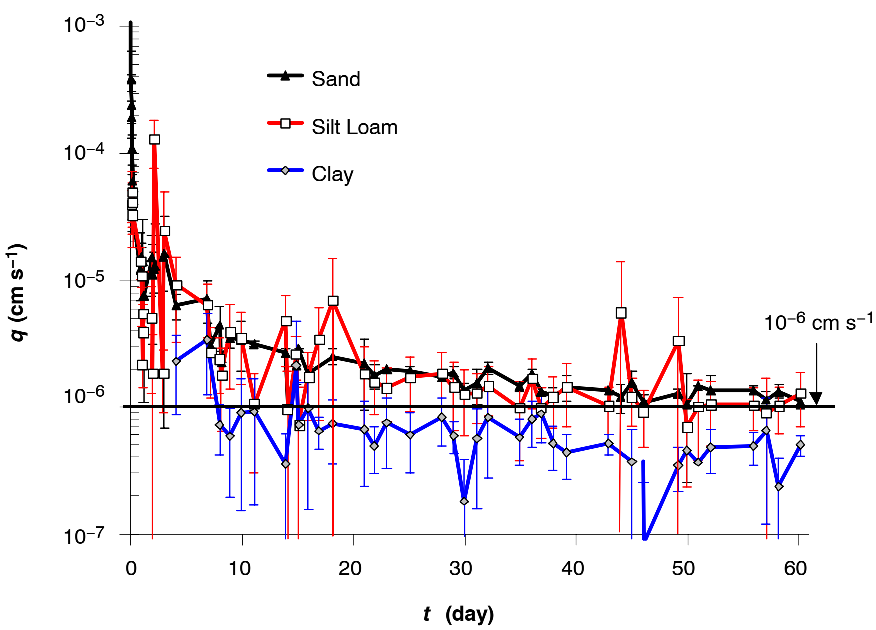

Figure 4. Average dairy waste infiltration rate (error bars indicate ±1.0 std dev).

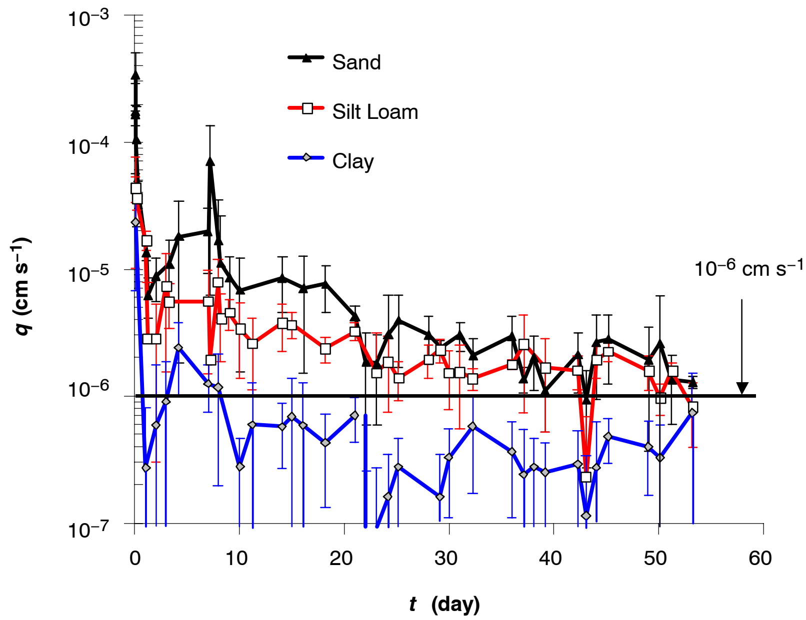

Figure 5. Average swine waste infiltration rate (error bars indicate ±1.0 std dev).

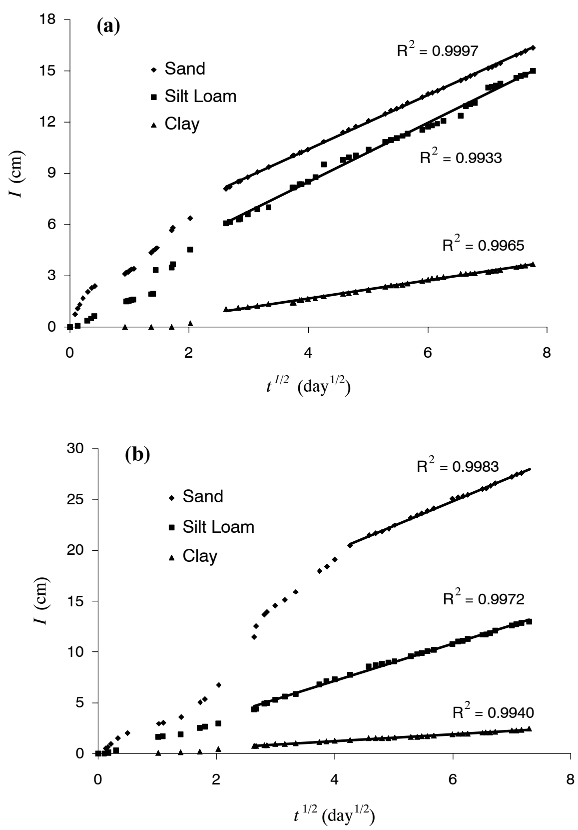

Figure 6. Fitting of equation 4 to the late-time data for (a) dairy waste and (b) swine waste.

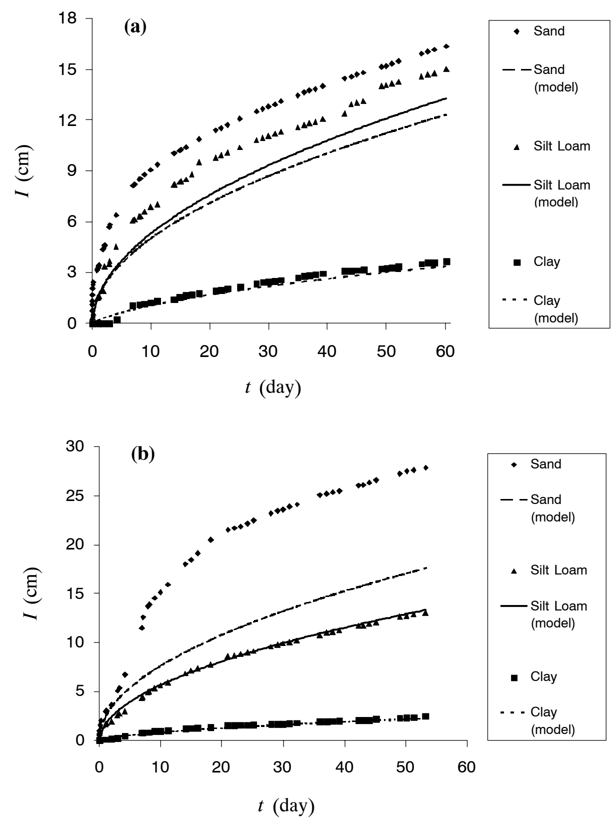

Figure 7. Comparison of the model results with the experimental data for (a) dairy waste and (b) swine waste.

RESULTS

The average infiltration rates for each combination of soil and waste type (four columns each) are plotted in figures 4 and 5. The error bars show ±1.0 standard deviation of the infiltration rate at each time interval. Infiltration rates initially decreased rapidly for the sand and silt loam columns with dairy waste. The height of waste in the clay columns initially rose due to the swelling of the clay when dairy waste was applied and is therefore not plotted for days 0 to 4 (fig. 4). However, this effect was not observed in clay columns with swine waste applied. As time passed, differences in infiltration rates between soils, while initially very high, decreased for both waste types. Infiltration rates for all soils and waste combinations approached a value of approximately 10^{-6} cm s^{-1} or less within 50 days. For both waste types, the clay col–

Table 2. Comparison of K_{seal}/α values for different soil and liquid manure types.

Soil Type	K_{soil} (cm s^{-1})	K_{seal}/α (cm s^{-1})	TS (%)	I vs. $t^{1/2}$ at Late–Time R^2
Dairy Waste				
This study (duration 60 days)				
Sand	1.10×10^{-3}	4.85×10^{-8}	2.10	0.99
Silt loam	1.07×10^{-5}	5.80×10^{-8}	2.10	0.99
Clay	2.31×10^{-7}	5.37×10^{-9}	2.10	0.99
Tyner et al., 2006 (duration 84 days)				
Silt loam	3.69×10^{-5}	4.63×10^{-8}	2.3	0.99
Hills, 1976 (duration of tests 1 year)				
Silt loam	1.74×10^{-6}	1.88×10^{-7}	0.53	0.99
Sand loam	1.74×10^{-6}	1.26×10^{-7}	0.53	0.99
Loam	1.74×10^{-5}	1.04×10^{-7}	0.53	0.99
De Tar, 1979 (duration approx. 15 days)[a]				
Weikert	5.50×10^{-6}	1.04×10^{-5}	0.12	0.99
shaley clay	5.50×10^{-6}	8.62×10^{-6}	0.26	0.99
	5.50×10^{-6}	6.15×10^{-6}	0.38	0.99
	5.50×10^{-6}	8.28×10^{-7}	1.10	0.99
Morrison	1.23×10^{-3}	1.61×10^{-5}	0.12	0.98
sandy loam	1.23×10^{-3}	3.70×10^{-6}	0.25	0.99
	1.23×10^{-3}	1.02×10^{-6}	0.58	0.99
	1.23×10^{-3}	3.92×10^{-7}	1.40	0.99
Hogerstown	5.56×10^{-5}	5.06×10^{-6}	0.36	0.99
clay	5.56×10^{-5}	6.53×10^{-7}	1.80	0.99
	5.56×10^{-5}	1.89×10^{-7}	2.40	0.98
	5.56×10^{-5}	9.14×10^{-7}	1.40	0.98
Huntington	1.23×10^{-3}	9.14×10^{-6}	0.29	0.99
gravelly	1.23×10^{-3}	7.52×10^{-7}	1.70	0.99
sandy loam	1.23×10^{-3}	4.86×10^{-7}	1.50	0.99
	1.23×10^{-3}	1.76×10^{-7}	3.60	0.99
	1.23×10^{-3}	2.94×10^{-7}	4.50	0.98
Swine Waste				
This study (duration 54 days)				
Sand	1.10×10^{-3}	1.12×10^{-7}	1.10	0.99
Silt loam	1.07×10^{-5}	6.61×10^{-8}	1.10	0.99
Clay	2.31×10^{-7}	2.40×10^{-9}	1.10	0.99
Barrington and Madramootoo, 1989 (duration approx. 65 days)				
Clay loam	8.83×10^{-3}	9.56×10^{-9}	5.00	0.96
Sand	9.60×10^{-3}	9.40×10^{-9}	5.00	0.98
Clay loam	8.83×10^{-3}	7.33×10^{-9}	5.00	0.95
Clay loam	8.83×10^{-3}	1.02×10^{-8}	5.00	0.97
Sand	9.60×10^{-3}	1.34×10^{-8}	5.00	0.96

[a] K_{soil} values estimated from soil texture using pedotransfer functions.

umns had the lowest infiltration rates throughout the test. However, the reduction of K_{ave} due to sealing was the least for the clay columns, given that their K_{soil} was very small.

Figure 6 presents the cumulative infiltration versus the square root of time. All combinations of wastes and soil types entered the seal-dominated phase after 7 days, with the exception of swine waste applied to sand, which required 18 days. From 4 to 6 days (1.4 to 2.4 d$^{1/2}$), the swine infiltration rate into the sand abruptly increased. Apparently, a seal had begun to form but then partially failed, only to re-form again at 18 days. Although the particle size distribution of solids in the two wastes was not measured, often swine waste is less fibrous and may have had difficulty establishing an initial seal layer across the large pores in the sand.

Table 3. Predictions of K_{seal}/α from TS, K_{soil}, or both TS and K_{soil}.

	Swine	Dairy	Swine and Dairy
TS	Insufficient data	$R^2 = 0.86$, $n = 24$	$R^2 = 0.87$[a], $n = 32$
K_{soil}	$R^2 = 0.41$, $n = 8$	$R^2 = 0.02$, $n = 24$	$R^2 = 0.05$, $n = 32$
TS and K_{soil}	Insufficient data	$R^2 = 0.87$, $n = 24$	$R^2 = 0.88$, $n = 32$

[a] Relationship is given in equation 6.

The value of K_{seal}/α was calculated for each of the six curves in figure 6, and the coefficient of determination (R^2) for the seal-dominated portion of the data are shown (fig. 6). Using the K_{seal}/α values and measured K_{soil} and H in conjunction with equation 3, the cumulative length of infiltration was predicted for each waste and soil combination (fig. 7). The model predictions for dairy and swine waste infiltrating into clay match the measured data well. Predictions of infiltration into the silt loam were less accurate for dairy waste than for swine waste due to excessive measured dairy leakage at early times. For both waste types, the modeled cumulative infiltration into the sand underpredicted the measured data, particularly for the swine waste. This was likely because the larger pores created by the large-diameter sand particles initially had difficulty trapping the waste solids.

The values of K_{seal}/α were also calculated from animal waste infiltration data previously published in the literature (Hills, 1976; De Tar, 1979; Barrington and Madramootoo, 1989; Tyner et al., 2006). Table 2 presents the K_{seal}/α values from this study and from the previous studies, along with the soil type, K_{soil}, TS, waste type, and the R^2 of the fit during the seal-dominated phase. Since De Tar (1979) did not report K_{soil} values, we estimated those respective K_{soil} values based on soil texture using a pedotransfer function model (Schaap et al., 2001).

We attempted to find functions that predicted K_{seal}/α from the table 2 inputs of TS, K_{soil}, or both TS and K_{soil} using curve-fitting software. This process was completed for swine only, dairy only, and both swine and dairy waste when sufficient data were present. A summary of results describing the fits is shown in table 3.

Predicting K_{seal}/α from only K_{soil} achieved small R^2 values, particularly when dairy waste was included. Apparently, K_{soil} had little impact on the seal-dominated phase infiltration rate. Predicting K_{seal}/α from only TS achieved large R^2 values, with almost no difference between different combinations of waste types. This suggests that swine waste may seal less robustly than dairy waste (a common assumption) merely because it typically has a lower TS and that other differences between the waste types are not significant.

The fitted relationship at late times between K_{seal}/α and TS from both waste types:

$$\frac{K_{seal}}{\alpha} = 2.37 \times 10^{-5} \exp\left(\frac{-TS}{0.21}\right) \tag{6}$$

and the corresponding measured data are presented in figure 8. K_{seal}/α decreases rapidly as TS increases from 0% to approximately 1.0%, and then asymptotically approaches zero. When taken within the context of equation 4, this demonstrates the very strong relationship between a high TS and less infiltration.

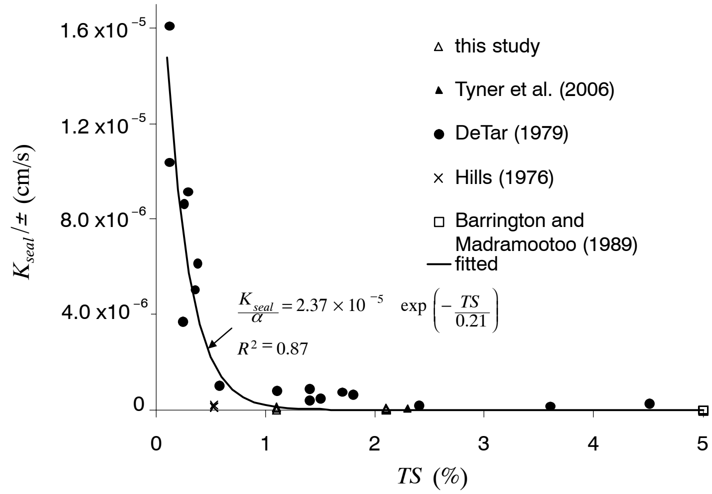

Figure 8. Comparison of observed and fitted results for K_{seal}/α (cm/s) versus TS (%) for swine and dairy waste.

Conclusions

Applying dairy or swine wastes to soil columns packed with sand, silt loam, or clay reduced the infiltration rate to approximately 10^{-6} cm s^{-1} or less within 54 to 60 days. The clay soil had the lowest infiltration rates throughout the test, yet these columns benefited the least from sealing. As the test progressed, the differences in infiltration rates between soil types decreased.

A time series model describing three phases of infiltration (soil dominated, transition, and seal dominated) was presented. Initially after placing waste during the soil-dominated phase, only the soil provides resistance to flow. As a seal begins to grow, there is a transitional phase in which both the soil and the seal provide resistance to flow. At later times, only the seal provides resistance to flow, and infiltration is linearly correlated with the square root of time. The model underpredicted infiltration into the sand during the soil-dominated and transition phases, presumably due to the difficulty of forming a seal on the larger-pored media.

By fitting the model to our late-time data and also to other waste infiltration datasets from the literature, we found an exponential relationship between K_{seal}/α and TS ($R^2 = 0.87$). The fit between K_{seal}/α and TS was not improved by analyzing the dairy and swine data separately, which appears to indicate that both waste types behave similarly during the seal-dominated phase. Attempts to predict K_{seal}/α using both TS and K_{soil} were only slightly better ($R^2 = 0.88$) than when K_{soil} was excluded, which indicates that soil hydraulic conductivity is not particularly useful in predicting infiltration rate during the seal-dominated phase.

Acknowledgements

The authors are grateful for the continued cooperation and assistance of the William Barr Dairy Farm in Loudon, Tennessee, and the Pierce Swine Farm in Athens, Tennessee.

References

ASTM Standards. 2005. *Construction, Soil and Rock* (I), vol. 04.08. West Conshohocken, Pa.: American Society for Testing and Materials.

Abboud, N. M., and M. Y. Corapcioglu. 1993. Numerical solution and sensitivity analysis of filter cake permeability and resistance to model parameters. *Transport in Porous Media* 10(3): 235-255.

Barrington, S. F., and C. A. Madramootoo. 1989. Investigating seal formation from manure infiltration into soils. *Trans. ASAE* 32(3): 851-856.

Chang, A. C., W. R. Olmstead, J. B. Johanson, and G. Yamashita. 1974. The sealing mechanism of wastewater ponds. *J. Water Poll. Control Fed.* 46(7): 1715-1721.

Culley, J. L. B., and P. A. Phillips. 1982. Sealing of soils by liquid cattle manure. *Canadian Agric. Eng.* 24(2): 87-89.

De Tar, W. R. 1979. Infiltration of liquid dairy manure into soils. *Trans. ASAE* 22(3): 521-528.

Hills, D. J. 1976. Infiltration characteristics from anaerobic lagoons. *J. Water Poll. Control Fed.* 48(4): 695-709.

NRCS. 1961. Soil Survey of Loudon County, Tennessee. Washington, D.C.: USDA Natural Resources Conservation Service.

NRCS. 1988. Soil Survey of Jefferson County, Tennessee. Washington, D.C.: USDA Natural Resources Conservation Service.

Schaap, M. G., F. J. Leij, and M. Th. van Genuchten. 2001. Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *J. Hydrology* 251(3-4): 163-176.

Tosun, I. 1986. Formulation of cake filtration. *Chem. Eng. Sci.* 41(10): 2563-2568.

Tyner, J. S., and J. Lee. 2004. Influence of seal and liner hydraulic properties of the seepage rate from animal waste holding ponds and lagoons. *Trans. ASAE* 47(5): 1739-1745.

Tyner, J. S., W. C. Wright, and J. Lee. 2006. Lagoon sealing and filter cakes. *Trans. ASAE* 49(2): 527-531.