Designing earthen storage facilities for manure

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Barrington, S. F. and Broughton, R. S. 1988. **Designing earthen storage facilities for manure storage.** Can. Agric. Eng. 30: 289–292. Research has recently demonstrated that the sealing of soils by manure occurs mainly through physical mechanisms governed by the geometry and diameter of the soil pores rather than the saturated hydraulic conductivity. In light of such findings, this paper introduces a new approach to the design of earthen manure storage facilities. This new approach requires the soil to meet a maximum equivalent pore size of 2.0 and 0.45 μm for the storage of ruminant and monogastric animal manures, respectively. A soil's equivalent pore size can be computed from its particle size distribution and porosity. This new approach also requires some groundwater protection for those soils with cation exchange capacities less than 30 meq/100 g even if the soil's equivalent pore size is respected.

INTRODUCTION

Infiltration rates of manures into soils have been extensively measured since 1965 (De Tar 1979). Based upon those early observations, environmental authorities have always used the soil's saturated hydraulic conductivity to water (k) as a design criterion for earthen manure reservoirs. Since the late 1970s, soil sealing mechanisms by manures have been better defined. It is now well established that the soil acts as a screen rather than a seal, accumulating at its surface an impermeable manure mat. Thus, soil pore size and geometry become more important than k in determining the sealing outcome. This paper presents background material by reviewing present design criteria and sealing mechanisms defined within the past 8 yr. Following this review, a new approach to the design of earthen manure storage facilities is introduced.

Present design criteria

Present legislation concerning design criteria for earthen manure storage facilities has been based on the soil's saturated hydraulic conductivity to water.

In 1977, the Pennsylvania Bureau of Water Quality Management (Pennsylvania Department of Environmental Resources 1977) defined an allowable leakage limit for such structures. A manure reservoir was considered inadequately sealed when demonstrating, with manure, a permeability in excess of 10^{-8} m/s. This criterion gave a meaning, in 1977, to the previously undefined term "excessive leakage" used by the U.S. Soil Conservation Services.

In 1982, the Ontario Government presented some basic soil guidelines to its rural municipalities for the acceptance of earthen manure reservoirs. These guidelines required: a k value not exceeding 10^{-6} m/s; a minimum depth to bedrock or any acquifer of 1.0 m; and a soil texture finer than a sandy loam. These recommendations were derived by adding a safety factor to the findings of Miller and Robinson (1981) that feedlot manure runoff could adequately seal a sandy earthen reservoir of k value 10^{-5} m/s.

From 1975 to 1983, the Quebec Ministry of Environment required a soil k value equivalent to that of concrete structures, or of the order of 10^{-9} m/s. In 1983, this criterion was revised to concur with municipal wastewater ponds guidelines that permitted a maximum nitrogen seepage into the soil of 0.6 L $m^{-2}d^{-1}$ for wastewater of 20–30 ppm nitrogen. Extrapolated for dairy and swine wastes of 700 and 3000 ppm N respectively, as well as using a sealing factor of 50 for any soil, these municipal guidelines suggested soil k values of 10^{-7} m/s and 10^{-8} m/s for dairy and swine liquid manures, respectively.

The above guidelines were based on research performed from 1965 to 1980. Since then, interesting findings have better defined the actual sealing mechanisms occurring when manure infiltrates a soil.

Literature review of sealing mechanisms

The mechanisms of soil sealing by manure have been categorized into three distinct groups: physical, biological and chemical. The physical mechanisms of clogging soil pores by manure solids have generally been considered predominant. Nevertheless, the relative strength and origin of each of the three mechanisms was not investigated until the late 1970s.

De Tar (1979) observed the infiltration of dairy manure of various total solids content (TS) into clays and sandy loams. He demonstrated that the slurry TS was the primary factor controlling the long-term seepage rate and that the soil's steady state infiltration rate with water was much less significant. Rowsell (1980) used laboratory columns to measure infiltration rates of natural and sterilized screened feedlot runoff into soils of various textures. As a main sealing mechanism, he suggested the formation at the soil surface of an impermeable layer of manure solids. Rowsell et al. (1985) confirmed this by examining the sealed surface under microscope and finding solids lodged between the soil particles.

Barrington et al. (1987a,b) investigated separately the physical, biological and chemical sealing mechanisms and found the first process to be predominant. Biological and chemical mechanisms were found to intervene, under ambient temperatures exceeding 10°C, to strengthen the physical clogging rather than to create a new seal. Through the use of piezometers, they also demonstrated that the sealing layers were at the organic solid mat above the soil surface and at the manure-soil interface. This suggests that the soil acts basically as a screen holding at its surface the manure solids forming the seal. The finer the diameter of the soil pores with respect to the manure solids, the more extensive the sealing process. Barrington et al. (1987a,b) found little correlation between the soil's k value and the extent of the sealing process. Finally, they demonstrated that the low volumes of manure liquids seeping into the soil are highly contaminated and can result in groundwater contamination if the soil is of low cation exchange capacity (CEC).

These findings suggest the use of soil pore diameters rather than soil k values as design criteria for earthen storage facilities.

DESIGNING FOR OPTIMUM SEALING

To establish the extent of the soil manure sealing process, a relationship must be established between the dimensions of the soil voids and the general particle size distribution of the manure solids.

Soil voids occur either as inter-particle spaces or inter-aggregate spaces. Inter-aggregate voids need not be considered for the design of earthen manure structures as they are destroyed by heavy equipment during the construction of the facility and by the biochemical activities induced by the manure liquids during the first summer of storage (Mirtskhulava et al. 1972; Barrington 1985).

Considering soil void geometry and dimensions between individual soil particles, Kovacs (1981) presented a model of interest. This model describes the effective soil pore diameter by transforming a given soil into one of a single particle size of equivalent fluid permeability:

$$d_e = \frac{4N}{(1-N)} \times D_e \qquad (1)$$

where:

d_e = effective soil pore diameter (μm),
N = soil porosity (fraction),
D_e = equivalent soil particle diameter (μm).

D_e can be calculated from the particle size distribution of the soil:

$$D_e = \frac{1}{\sum_{i=1}^{n} \left(\frac{\alpha_i S_i}{D_i} \right)} \qquad (2)$$

where:

i denotes specific soil particles size classes such as: < 2 μm, 2–20 μm, 20–200 μm, 200–2000 μm, 2.0–20 mm.
α_i is the shape coefficient of the ith particle size class: 50 for clay particles, 15 for silt particles and 10–12 for sandy particles.
S_i is the weight fraction of the ith particle size class.
D_i is the average soil particle diameter for the ith particle size class, such as: 1.1 μm, 11 μm, 110 μm, 1100 μm, 11000 μm.
n is the total number of particle size classes.

Kovacs (1981) also demonstrated that a medium of a single particle size has a porosity (N) of approximately 40–45%. Soils are media of various particle sizes where those of smaller diameter are lodged between those of larger diameter. Thus, soils generally demonstrate a flow contributing porosity of less than 45%. Using this maximum porosity of 45%, it is possible to calculate a maximum d_e. A more accurate relation between d_e and N can be obtained through laboratory compaction trials, as outlined by ASTM (1985).

Using the model of Kovacs (1981), the pore size of unconsolidated soils can be described. Barrington (1985) defined soil d_e values insuring enough manure mat formation at the soil surface for an infiltration rate of the order of 10^{-9} m/s. Barrington (1985) obtained infiltration rates of $5\text{–}10 \times 10^{-9}$ m/s with a coarse sand (d_e = 40 μm) both in the field with dairy manure, and in the laboratory with dairy and swine manures. The laboratory results were obtained under ambient temperatures in excess of 15°C. When temperatures were lower than 5°C, biological mechanisms were weak and in the case of the hog manure, the finer manure solid particles were washed from the manure mat through the soil column. This leaching process was not observed for dairy slurries which formed a random fibrous mat. Jett et al. (1974, 1975), Chang and Ribb (1975) and Overcash et al. (1983) indicated that dairy manures demonstrate a wider particle size distribution than swine manures (Table I). Barrington (1985) therefore suggested maximum d_e values of 2.00 and 0.45 μm for soils having to store ruminant and monogastric animal manures, respectively; these d_e values offer a safety factor above those found experimentally.

Table I. Particle size distribution for manure solids

Author and manure type	Particle size distribution for manure solids (%)				
	<53	53–103	103–250	250–500	>500
	(μm)				
Chang et al. (1975)					
Dairy	38	2	4	7	49
Beef	44	4	6	7	39
Poultry	36	5	8	16	35
Jett et al. (1974, 1975)					
Swine	55	55	55	7	38
Overcash et al. (1983) — Extrapolated values					
Swine	50	2	2	6	40

The suggested d_e values of 2.00 and 0.45 μm correspond to soils of clay content of at least 5 and 15%, respectively, with pore size being calculated from the Kovacs (1981) model and an assumed porosity (N) of 0.45. For all soils of lower clay content, laboratory compaction tests are required to determine whether or not these critical d_e values can be reached by reducing the porosity (N).

Thus, earthen manure storage reservoirs can be built from simple soil tests based on the following guidelines:

(1) If soil clay content exceeds 5 or 15%, for ruminant or monogastric animal manures respectively, d_e values are respected whatever the soil porosity; no further soil testing is required and the reservoir can be constructed using compaction control sufficient for structure stability.

(2) If soil clay content is under 5 or 15%, soil compaction tests are carried out in the laboratory to insure a d_e under 2.00 or 0.45 μm. The reservoir must then be built under soil compaction criteria required by the laboratory investigations.

(3) If, at maximum compaction, d_e values still exceed 2.00 or 0.45 μm, the soil alone is unsuitable and the earthen manure reservoir will never seal satisfactorily. A lining of compacted clay loam, concrete or geomembrane must be used.

Control of the groundwater table below the reservoir's floor should be required for all earthen reservoirs. Without this control, water can infiltrate into the reservoir, diluting the manure as well as lowering its TS and subsequently causing excessive seepage.

DESIGNING FOR GROUNDWATER PROTECTION

Low manure soil infiltration rates do not automatically guarantee groundwater protection. Barrington (1985) has suggested that the lowest possible manure infiltration rate into soils is of

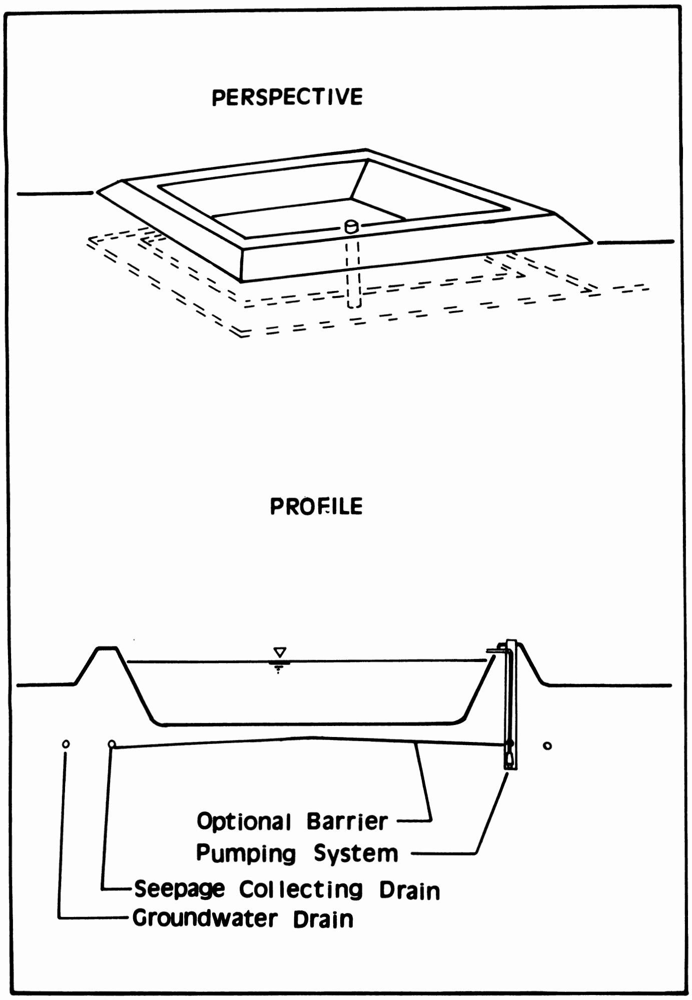

Figure 1. Typical earthen manure storage facility.

the order 0.1 L ms-^{2}d^{-1} or 10^{-9} m/s. Despite such low infiltration rates, these heavily loaded seepages are contaminants. Exfiltrations from swine and dairy manure reservoirs can give cation concentrations of 280 and 60 meq/L respectively (Barrington et al. 1987b). These swine and dairy exfiltrations can lead to groundwater contamination after approximately 6 mo and 3 yr, respectively, for a sandy reservoir of CEC of 5 meq/100 g (Barrington 1985). These durations assume no NH_4 losses through bacterial activity, NH_4 representing 60% of the exfiltrates' total cation load. For clay soils with a CEC of 30 meq/100 g, groundwater contamination would occur after approximately 3 and 15 yr, respectively.

Groundwaters should therefore be protected from manure seepages where earthen reservoirs are built in soils of CEC less than 30 meq/100 g. This CEC can be related to a minimum clay content for a soil of known mineralogy, as the clay micelle's crystalline structure is primarily responsible for the adsorption of cations. Considering the soils generally found in the Province of Quebec, this CEC value of 30 meq/100 g corresponds to a minimum clay content of 30%.

Protection devices for soils of low clay content must be used to intercept most manure exfiltrates and either return them to the reservoirs or dispose of them on cropped surfaces. A simple drain with pumping system meets these requirements. Steady state infiltration models (Kirkham 1958) indicate that this drain need only be installed some 30 cm below the reservoir bottom. Such a protective drain can be limited to only the manure exfiltrates through the use of a separate groundwater table drain (Fig. 1). Where the groundwater table is always well below the reservoir's floor, gravity can possibly draw manure seepage below the protective drain. This case requires the restriction of downward seepage by, at the drain level, either building a clay loam liner or placing a plastic barrier. If clay loam is used it should be spread and compacted in layers of less than 150 mm, until a total thickness of at least 350 mm is achieved. If plastic is to be used, the thickness should be at least 0.25 mm. Joints between the plastic sheets should be double lapped and sealed. The stone-free soil should be placed over the plastic to a depth of at least 200 mm.

CONCLUSIONS

Analysis of soil sealing mechanisms by manure suggest earthen reservoir construction guidelines based upon the soil's effective pore diameter and the soil's cation exchange capacity rather than upon the soil's saturated hydraulic conductivity to water. The soil's effective pore diameter, d_e, can be determined from its particle size analysis and porosity, according to the Kovacs (1981) model. The soil property d_e should meet values of 2.00 and 0.45 μm for ruminant and monogastric animal manures, respectively, in order to achieve infiltration rates in the order of 10^{-9} m/s. These d_e values can be met with soil clay contents of 5 and 15%, respectively, whatever the soil porosity. For soils deficient in clay content, d_e values can be achieved through compaction; if compaction is insufficient, the use of an impermeable liner is necessary.

Despite a sealing to 10^{-9} m/s, the manure exfiltrates still represent a contamination hazard for the immediate groundwaters. Soils of CEC under 30 meq/100 g require a protective drainage device to intercept the manure seepages and either return them to the reservoir or dispose of them on cropped land.

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