

Leaking of Liquid Manure Storages - Literature Review



by:

Ron Fleming, Jennica Johnston, Heather Fraser

Ridgetown College - University of Guelph
Ridgetown, Ontario
N0P 2C0

Prepared for:

Ontario Pork

July, 1999

UNIVERSITY
of **GUELPH**

Leaking of Liquid Manure Storages - Literature Review

Ron Fleming, Jennica Johnston, Heather Fraser

Background

Recently, in southwestern Ontario, liquid manure from a tank under a pig barn entered tile drains located under the tank and contaminated surface water nearby. While this may have been an isolated instance, it focused attention on the ways that liquid manure storages are built on farms. It raised questions about the potential for similar spills to occur on livestock farms where liquid manure is stored. In the particular case mentioned, it appeared that there was a failure to eliminate and/or redirect the drains away from the construction project. How the manure leaked from the manure system and traveled to the tile drains was unclear. This report is an attempt to establish risks involved in this and similar manure handling and storage systems, through a survey of related literature.

It appears that the main issues in this discussion are:

- a) Field drains near farm buildings and manure storage tanks
- b) Integrity of manure storages
- c) Manure transfer systems - from barn to long-term storage

Environmental Problems with Manure Storages

In Ontario, the environmental track record of liquid manure storages has been fairly good. Most environmental concerns have involved odours (barn, storage, spreading) or water contamination at spreading. From a water quality point of view, liquid manure storages are considered to be safer than typical solid manure storages that have no runoff containment. Problems with tank overflows have been addressed with requirements for storage periods of 200 days or more, and many municipalities have specific storage length requirements written in local bylaws. Nonetheless, for whatever reason, storage overflows still occur - an Ontario case study detailing a situation resulting in legal action against the farmers is written up in a brochure by the Livestock Manure Pollution Prevention Project (anon. 1998).

For a period of time around 30 years ago, some farmers built above-ground circular storages about 10 m diameter by 10 m high. A few of these storages had problems with concrete quality and failed, causing large spills. These storages were more prone to failure because of the higher than normal tank pressures - it is not common to have tanks deeper than four or five metres now. There have been cases with in-ground concrete manure tanks of walls cracking, due to uneven settlement, poor structural design or improper backfilling.

Most of the public concern with earthen manure storages is about the potential for leaking from the storages. Typically, neighbours are worried about the potential to contaminate their well water. Manure stored on gravelly soil or shallow, cracked bedrock can pollute groundwater (AAFC and OMAFRA 1994). In the USA (e.g. North Carolina), water pollution caused by bursting and overflowing manure “lagoons” have been recent problems (NRDC, 1999). Many of these storages have been built in sandy soils conditions not considered acceptable in Ontario. Current standards for earthen storage construction in Ontario should give very good protection of

groundwater. Where the problems with earth storages have occurred, surface water has been affected, not groundwater. In isolated cases in Ontario, earth storages have been installed without locating all subsurface tile drains. The Livestock Manure Pollution Prevention Project (anon. 1998) documents one case where faulty storage construction of an earthen manure storage created a problem. A drainage tile was missed during construction of the earthen storage and allowed manure to leak into the existing subsurface tile system. This eventually resulted in a large fish kill in the outlet drain. Ackerman and Taylor (1985) also identified the problem of contamination of subsurface drainage systems with manure. Often the producer is not aware of the problem because the field tile lines are not visible. They identified the potential for tile drain contamination where earthen storages are built over or near an existing tile line and where concrete tank walls crack and settle allowing access of manure to footing tiles.

Movement of liquid manure through soil

To understand the potential for manure leaks from manure storages, we must first look at the potential for manure to move through the soil. Most of the research in the area of manure movement has been in the context of earthen manure storage (see Figure 1) design and evaluation. However, if a concrete tank developed a leak, the same principles would apply.

Manure does not move through soil as easily as water does. Davis et al. (1973) compared the way that clean irrigated water in a lagoon infiltrated into the ground compared to a lagoon filled with filtered dairy manure. The clean water infiltration rate averaged 120 cm/day. The manure water after 2 weeks averaged 5.8 cm/day and after 4 months averaged 0.5 cm/day. The most important sealing mechanism is physical. Biological sealing also contributes but to a much lesser degree. Chemical mechanisms were found to be insignificant (Barrington et al. 1987).

The early approach in Ontario and elsewhere was to specify a maximum allowable saturated hydraulic conductivity for the underlying soil. If this value could not be met, it was assumed that the risk of movement of manure through the soil was too great. Barrington and Broughton (1988) found that the soil's effective pore diameter and the cation exchange capacity were



Figure 1 Earthen manure storage during pump-out

more important in soil sealing than the saturated hydraulic conductivity. For manure from ruminant animals, soils with a clay content of 5% gave effective sealing and for monogastric animals, the minimum clay content should be 15%. The study also highlighted the importance of

compaction of the soil during construction. Hootkany et al. (1994) confirmed that soils with higher clay content had lower permeabilities when compared to lower clay content soils. They also confirmed that compaction of the soil helped to reduce the permeability.

Several studies have shown that properly constructed earthen storages will eventually seal themselves. Fonstad and Maule (1995) found that soil sealing with hog manure occurred over a relatively short period of time. The flow reduction approached 1×10^{-9} m/s. Soil clay content ranged from 9 to 33%. Field testing found that contaminant migration can occur even after soil sealing. Further field testing (Fonstad and Maule, 1996) found that solute movement from earthen hog manure storages was limited to less than 10 metres in most Saskatchewan soils over a period of 20 years. Sewell et al. (1975) found that after an initial movement of manure through the soil, the earthen manure storage appeared to seal itself. Miller et al. (1985) measured concentrations of chloride beneath a large earthen storage pit containing dilute liquid beef manure. This storage was constructed in a coarse-textured sand. Though there was a larger amount initially moving through the soil, after two weeks the infiltration was down to 10^{-8} m/s. After 12 weeks, the pond was effectively sealed. Rowsell et al. (1985) measured infiltration of liquid beef manure (at 5% dry matter) in various soils. They found that the infiltration rate decreased rapidly with time and reached a value of 10^{-8} m/s or less within 30 days on all soils. Culley and Phillips (1982) performed percolation tests using liquid dairy manure on sand, loam and clay soils. Within five to ten days hydraulic conductivity of all soils reduced to about 3.4×10^{-8} m/s.

Sealing of the soil in an earthen storage is most complete on the bottom of the storage. The seal is not as effective along the side walls, where there are cracks caused by wetting and drying, holes from burrowing animals and worms, and channels due to decaying weed roots (Schulte, 1998). McCurdy and McSweeney (1993) recommended that the existence of macropores in the sidewalls of earthen manure storages be considered in designing the storage. Gangbazo et al. (1989) demonstrated the breakdown of the seal with repeated thawing and freezing. In their on-farm study they found that under normal conditions the quality of the ground water would have been protected as long as the storage was built properly initially.

Initial solids content of the manure plays a role in sealing of the storage. DeTar (1979) found that as total solid content of the manure increased infiltration rate of liquid manure into the soil decreased. The infiltration rate for manure with low solids was more sensitive to soil permeability than was the manure having a high solids concentration. In other words, it performs more like water and does not benefit from the physical sealing typical of manure with a higher solids content.

In addition to studies mentioned earlier, there have been several carried out to specifically evaluate possible impacts of existing storages. Nitrogen is the nutrient of greatest concern to groundwater quality and Feng et al. (1992) determined that ammonium was the dominant form of nitrogen leaching from manure storages. In an Ontario study, Fleming (1994) measured concentration of ammonium and nitrate in groundwater samples near four earthen manure storages. Each manure storage had been in use for several years. Two of the storages held dairy manure and two held swine manure. There was evidence that one of the swine manure storages caused elevated levels of ammonium in the groundwater. However, this storage was constructed in sandy soil and therefore did not meet the standards for construction that were in place at the time it was built (Note - this storage has since been decommissioned). Elevated levels of nitrate in

groundwater at other sites appeared to be caused by excess nutrients (fertilizer and/or manure) additions to nearby fields.

In eastern Ontario, Phillips and Culley (1985) found some evidence of movement of manure nutrients into the groundwater below small-scale earthen manure storages, especially on fine and medium textured soils. The impact, however, was minimal after three years. The performance of coarse-textured sandy soil was the least satisfactory, at least in the short term. The seepage rate of an unlined dairy holding pond in a clay soil was found to be on the order of 2×10^{-7} m/s (Demmy et al. 1993).

Westerman et al. (1995) found that two swine manure earthen storages located in sandy coastal plain soil continued to have significant seepage after 3.5 to 5 years of receiving manure. Both lagoons displayed seepage over a broad area, however, there was considerable variation among concentrations in various monitoring wells. This confirms what we have accepted in Ontario for many years - that earthen storages built in sandy soils do not always seal properly.

Wall et al. (1999) found that an earthen storage built according to current design standards proved to be effective in protecting groundwater quality during the first few years of operation. They recommended that, due to the high cost of monitoring, it was better to spend more time on site selection, system design, and improved construction and maintenance, and project construction oversight. Monitoring will be discussed later in this report.

While there is a wealth of information available on movement of manure through soil and earthen storage design, there have been no reported studies (at least in the last 20 years) on leaking of concrete tanks and their impact on water quality. When earth tanks are not an appropriate choice, because of site conditions, the default situation has been either a plastic liner (not common in Ontario) or a concrete storage, both of which are assumed to be impermeable. It is generally acknowledged that concrete storages have a small potential to leak if cracks in the wall develop, but that either the crack or the surrounding soil will quickly seal shut with manure solids. The above studies confirm that there is some potential for manure to travel through coarse-textured soils.

Existing Standards - Concrete Storages, Earthen Storages

The existing standards that deal with concrete tank manure tank construction, earthen manure pit construction and transfer of manure from barn to storage, can be grouped into two areas, building code standards that must be followed, and proven “good practices” that are recommended (Best Management Practices). The building code standards tend to be fairly general in that they set performance standards that could be met in many different ways. It is up to the designer to make the appropriate choices based on the individual circumstances. This is true of reinforced concrete design and especially applies to piping systems to transfer manure to long-term storages.

The National Farm Building Code, Section 2.2.1.13. (7) states: “*Manure storage tank walls shall be designed and constructed to prevent leakage of the contents.*” Appendix section A-2.2.1.13.(7) also states: “*In the design of manure tank walls and bottoms to prevent leakage of the contents, account should be taken of all additional loads which may cause cracks, such as thermal effects, shrinkage of the concrete, movement of the structure, choice of components*”

(materials) and installation of the material. Prevention of leakage and of cracks is particularly critical to reinforced concrete structures due to subsequent corrosion of the reinforcing steel.” Reinforced concrete structures are regulated under Part 4 of the Ontario Building Code. These structures must be engineered and the engineer is obligated to supervise on-site as the construction progresses.

Most concrete tanks in Ontario are circular. Covered rectangular tanks are becoming more popular also, where the cover consists of a concrete top or a barn. The designer is responsible for making various assumptions about loadings on the concrete walls. This has led to a variety of designs for concrete tanks over the years. Researchers occasionally fine-tune the assumptions used in the design of these tanks. Jofriet et al. (1996) discussed structural design of liquid manure tanks. In their paper, they have attempted to clarify the hoop tension for different wall geometries. An example of a concrete wall structural detail is shown in Figure 2. A more up-to-date design is shown in Figure 3. Figure 3 shows a pressure relief plug in the tank floor and shows the joint sealer used at the base of the wall to ensure a leak-proof construction.

The field engineers of the Ontario Ministry of Agriculture, Food and Rural Affairs have close ties with many of the farm builders operating in Ontario. They organize training sessions specifically dealing with manure tank design and construction. In these sessions and other frequent contacts, they promote the standards set out in the Agriculture Pollution Control Manual (OMAFRA, 1994). These have become the “official” standards for Ontario. Following are recommendations from this set of standards that are relevant to this discussion.

Concrete manure tanks - water table elevation -

If the groundwater table is allowed to rise above the tank floor, pressure relief plugs should be installed in the floor slab. Alternatively, a drainage system may be installed to maintain the groundwater level below the floor slab. Footing drains should be free-draining and discharge from the drains should be disposed of in such a way as not to pollute the environment.

Earthen manure storages - The infiltration rate of the storage should not be greater than 10^{-9} m/s (equivalent to 3.14 cm/yr).

1. If the clay content of the soil is less than 15% then a liner of clay or synthetic materials must be used.
2. The water table should be below the floor of the storage.
3. The floor of the storage should be 1 m above bedrock

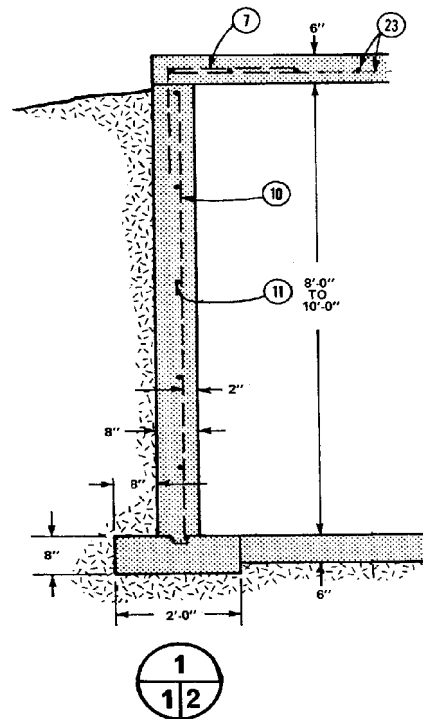
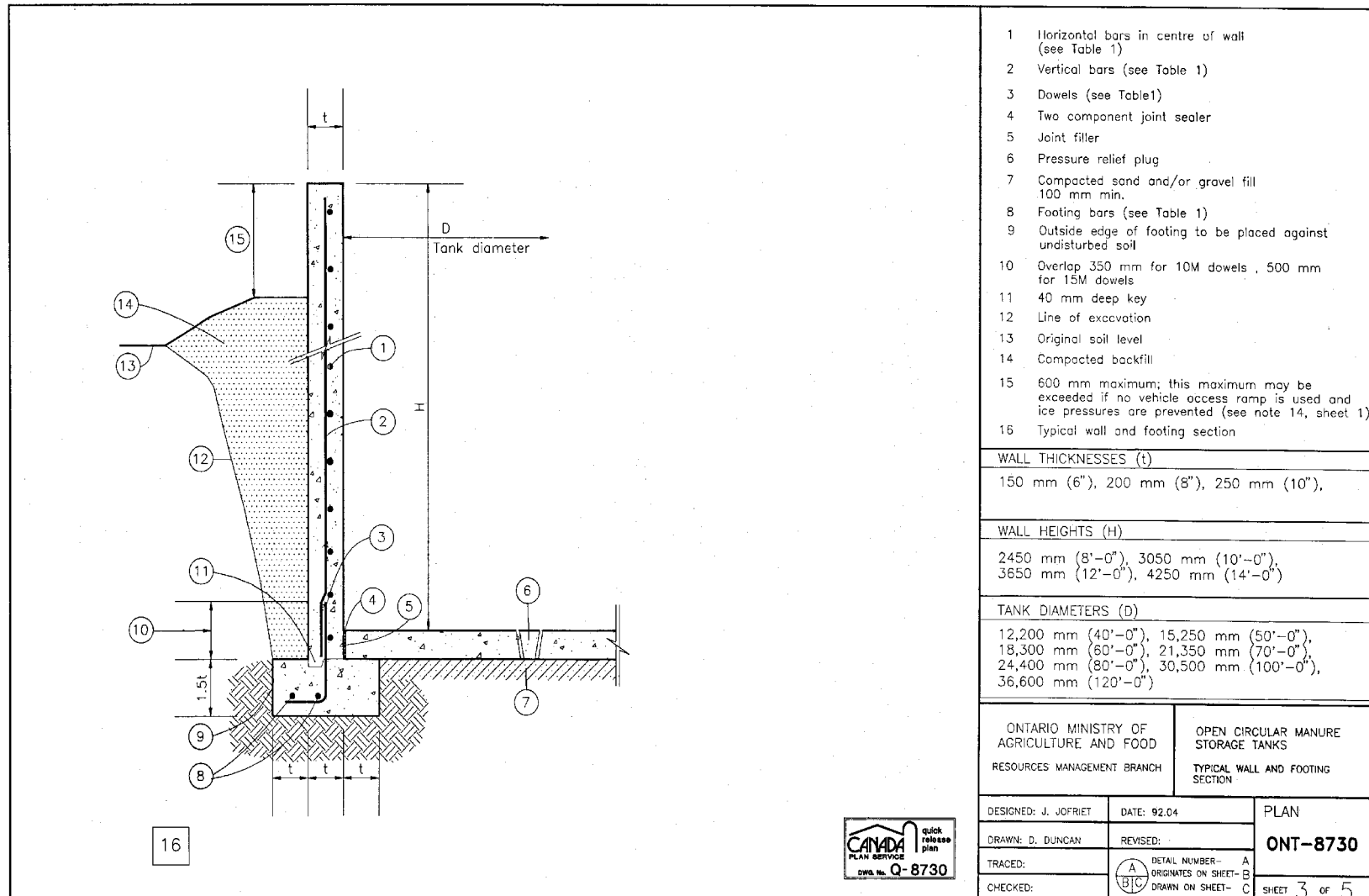


Figure 2 Detail from Canada Plan Service Plan 8712 showing cross-section of in-ground concrete tank with typical wall, footing, floor, and roof details



- 1 Horizontal bars in centre of wall (see Table 1)
- 2 Vertical bars (see Table 1)
- 3 Dowels (see Table 1)
- 4 Two component joint sealer
- 5 Joint filler
- 6 Pressure relief plug
- 7 Compacted sand and/or gravel fill 100 mm min.
- 8 Footing bars (see Table 1)
- 9 Outside edge of footing to be placed against undisturbed soil
- 10 Overlap 350 mm for 10M dowels, 500 mm for 15M dowels
- 11 40 mm deep key
- 12 Line of excavation
- 13 Original soil level
- 14 Compacted backfill
- 15 600 mm maximum; this maximum may be exceeded if no vehicle access ramp is used and ice pressures are prevented (see note 14, sheet 1)
- 16 Typical wall and footing section

WALL THICKNESSES (t)
150 mm (6"), 200 mm (8"), 250 mm (10"),
WALL HEIGHTS (H)
2450 mm (8'-0"), 3050 mm (10'-0"), 3650 mm (12'-0"), 4250 mm (14'-0")
TANK DIAMETERS (D)
12,200 mm (40'-0"), 15,250 mm (50'-0"), 18,300 mm (60'-0"), 21,350 mm (70'-0"), 24,400 mm (80'-0"), 30,500 mm (100'-0"), 36,600 mm (120'-0")

ONTARIO MINISTRY OF AGRICULTURE AND FOOD RESOURCES MANAGEMENT BRANCH	OPEN CIRCULAR MANURE STORAGE TANKS TYPICAL WALL AND FOOTING SECTION
---	--

DESIGNED: J. JOFRIET	DATE: 92.04	PLAN
DRAWN: D. DUNCAN	REVISED:	
TRACED:	DETAIL NUMBER - A	ONT-8730
CHECKED:	ORIGINATES ON SHEET - B	
	DRAWN ON SHEET - C	SHEET 3 OF 5



Figure 3 Tank wall detail from Plan ONT-8730 showing wall, footing, floor (1992)

4. The drainage tiles must be cleared to a distance of 3 m outside the top perimeter of the storage.
5. The storage should be at least 30 m away from any waterway or water storage.
6. The interior side slopes and the floor must be compacted
7. The side slopes should not exceed 2:1
8. Any dykes or embankments should be formed using the same procedures as an earthen dam.

Examples of requirements or guidelines used in other jurisdictions in North America:

1. In Nebraska and Kansas, percolation from manure storages must not exceed 7.3×10^{-8} m/s. (Schulte, 1998)
2. The Natural Resources Conservation Service (NRCS 1995) recommends that concrete storages (liquid-tight) have a minimum thickness for uniform foundations of 125 mm (5 inches) and shall contain distributed reinforcing steel. The Natural Resources Conservation Service (NRCS 1997) has standards for pipelines used to transfer manure to storages.
3. The Canadian Farm Buildings Handbook (Agriculture Canada, 1998) states that storage facilities for manure runoff “should be watertight to avoid polluting the groundwater.”

Existing Construction Practices

In Ontario, existing construction practices typically follow the recommendation in the Agriculture Pollution Control Manual (OMAFRA, 1994) and the Ontario Building Code. Unfortunately, not all builders follow the standards with the same attention to detail. Also, there is relatively little guidance on the design and construction of under-floor drain systems to transfer manure from gutters to long-term storages.

Some manure systems rely on a flushing gutter in the barn. Manure moves through a buried PVC pipe from the gutter to the final storage. This occurs only every several weeks when a plug is pulled. There are three ways that the drain is constructed under the gutter (Johnson, 1999):

1. A “T” connector is used. Both of the horizontal pipes and the vertical pipe fit into this connector. This is harder to construct, however, as the horizontal pipe is usually installed on a slope and the fittings and flanges are constructed to close tolerances.
2. A saddle-T connector. A hole is cut into the top of the horizontal pipe and the saddle-T sits over the hole. It is fastened into place with steel bands, and caulking should be applied to prevent leaks. Figure 4 shows an example of a flush gutter system found in a Canada Plan Service barn plan. The saddle-T connector, designated by item 6 on the drawing, is shown.
3. Probably the most common method in Ontario, and unfortunately the least desirable of the three, consists of cutting a hole in the horizontal pipe and shaping the end of the vertical pipe so that it approximately fits over the horizontal pipe. Concrete may then be applied to help seal the holes.

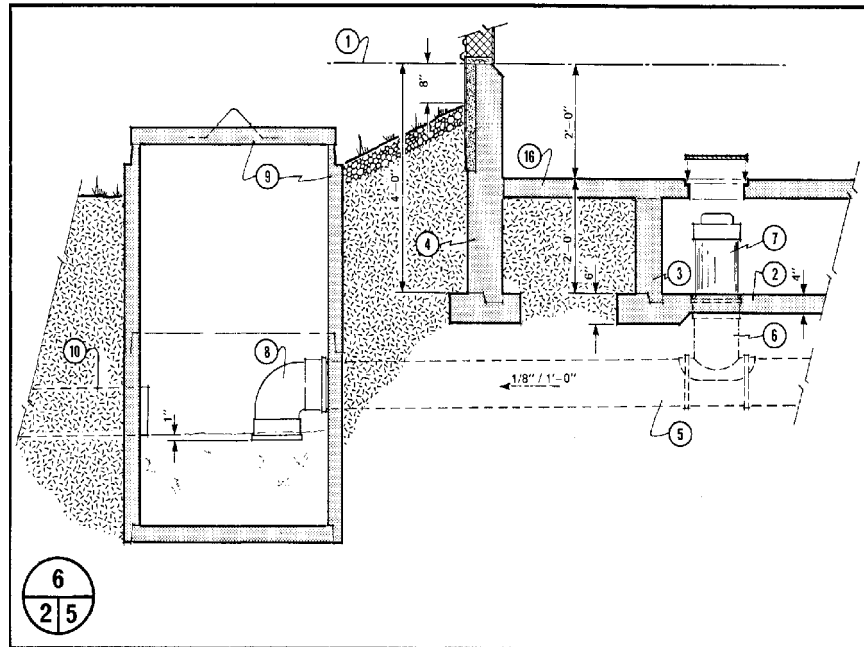


Figure 4 Detail from Canada Plan Service plan 3303 showing Saddle-T pipe connection (item 6) and horizontal drain pipe (item 5) in flush gutter system

While the main concern with the piping systems is at the connection of vertical pipe to horizontal, a further concern involves the integrity of the seal where the pipe extends through the concrete floor of the gutter. As concrete cures, it shrinks and this could potentially leave small gaps between the concrete and the pipe. An anti-seepage collar (or at least a bead of silicone caulking) should be used to prevent leaks at this point (Johnson, 1999).

Struss (1999) reported having experiences with concrete tank leaks on farms in Wisconsin. Some of the main lessons learned from site investigations include:

1. Most joints in concrete structures will eventually leak. This is most often due to poor installation procedures, but is sometimes due to material failure or excessive movement of the joints. They have limited joint sealing options to imbedded non-metallic waterstops. Elastomeric sealants and hydrophilic rubbers don't seem to stand up to long-term immersion in manure.
2. Minimize the number of joints wherever possible. They have tried to maximize joint spacing and minimize construction joints in all concrete designs.
3. All concrete will crack, so the trick is to distribute shrinkage cracking evenly so only hairline cracks develop, and to ensure that all major movement occurs at control joints where waterstops prevent leakage.
4. Granular base coarse material is not always good. If concrete is in direct contact with gravel or coarse sand, any leaks will be distributed to the underlying soil, much like a leach field, and natural sealing will not occur. When concrete is

poured directly on good parent material, any leaks will be better confined to a small area and natural sealing will have a better chance of occurring. If the parent material is highly permeable, a clay sub base may be in order.

Other Recommendations for Environmentally Safe Manure Storages

There is widespread industry support for building storages in an environmentally safe manner. For example, the Canadian Pork Council (1995?) recommends that a manure storage, whether an earthen basin or a reinforced concrete tank, should be structurally sound and water tight. Manitoba Pork (1998?) recommends that earthen manure storages be constructed in clay soils or lined with bentonite or a synthetic liner to prevent seepage in compliance with a permit from Manitoba Environment. In Manitoba producers must produce an engineer's certificate showing that citing, construction and storage requirements have been met. The Livestock Manure Pollution Prevention Project (anon. 1998) recommends digging a trench around the outside of a manure storage facility to ensure that all existing field tiles are intercepted and disconnected. They also recommend monitoring the level of manure in the storage for unusual fluctuations.

Recently, building officials in Ontario received an update on the potential for manure storage leaks and guidelines to follow when dealing with liquid manure storages (Johnson 1999b):

1. Ensure that field drains within 15 m (50 ft.) are effectively cut off and redirected away from structures. It will be necessary to trench around the entire building site at least 1.5 m (5 ft) deep to ensure that all drains have been discovered.
2. Perimeter foundation drains, surrounding either buildings with internal manure storage or external manure tanks should be connected to a monitoring sump or well. A submersible pump will then direct this water either to a storage tank or to a vegetated buffer strip or to a field drainage system (as long as there is provision to allow quick shutoff to the outflowing tile). The farmer must also develop an ongoing monitoring procedure.
3. Manure tanks require engineering, and design drawings should exist. An appropriate schedule for inspection should be agreed upon between the building official and the design engineer. Responsibility for notification for inspection rests with the owner of the project. Appropriate times for inspections would include:
 - commencement of the construction of the building or tank, including identification of tile drainage locations
 - readiness to construct the footings, verifying site preparation
 - completion of any pipes, valves etc. for underground systems which convey manure toward or away from a tank
 - completion of the footings and readiness to construct walls
 - viewing of in-place cribbing, reinforcing and waterstopping.
 - completion of walls, perimeter drains, prior to backfill and verifying preparation for floor construction
 - completion of structure, as constructed drawings filed with municipality

Monitoring Systems to Ensure Groundwater Protection

As mentioned earlier, Wall et al. (1999) recommended that, due to the high cost of monitoring, it was better to spend more time on site selection, system design, and improved construction and maintenance, and project construction oversight. Monitoring systems are not common for manure storages. In fact most monitoring has been carried out as part of a research project. This has typically involved installing a number of piezometers to allow sampling of groundwater. To install piezometers, collect water samples, measure water table elevations, analyze water samples and interpret results takes considerable time and effort (not to mention rather specialized expertise).

On a fairly basic level of monitoring, OMAFRA (1994) recommends that earthen storages be inspected frequently with special attention given to cracks in the berm, leaks, erosion or slumping of the berm. This may or may not alert the operator to the presence of leaks below the ground surface.

Another simple monitoring system is possible, typically installed when the facility is initially constructed. This involves installing tile drains around the perimeter of the storage. These drains serve the dual functions of lowering the water table (so it does not interfere with the structural integrity of the structure) and intercepting any seepage. These drains should collect in a sump (as mentioned above by Johnson) where visual inspection and sampling may be performed. Dalen et al. (1983) recommended that if the bottom of an earthen storage was less than 1.2 m above the water table, a tile drain should be placed around the pond to control elevation of the seasonal high water table and to intercept seepage.

On the subject of subsurface drains, it is interesting to note the difference in philosophy of manure storages between Ontario and elsewhere. Huffman and Feng (1993) simulated the addition of tile drains to intercept and capture lagoon seepage for earthen storages constructed in sand. Interceptor drains proved effective for capturing nitrogen that leached out of the storage. This study has limited applicability in Ontario where manure storages are designed so they do not leak.

It is possible to detect pollution plumes from manure storages without doing any digging. Drommerhausen et al. (1995) used a ground electromagnetic conductivity (EM) meter to measure contamination near earthen manure storages. Conductivity was measured using a transmitter, a receiver and three cables (10, 20, and 40 m). The transmitter coil transmits a primary magnetic field which induces a small current in the earth that generates a secondary magnetic field. The magnitude of the secondary magnetic field is measured at the receiver coil. The study found evidence of seepage or overflow at three of the six earthen storages surveyed. However, the seepage from the loafing areas appeared to pose a greater threat to drinking water supplies.

Summary

On the subject of manure movement through soil, many studies have been done over the years. On the subject of problems with leaking concrete manure storages, virtually no reports are available. That is not to say it is not a problem - it has been more of a headache for the farmer faced with costly repairs. Impact on surface water quality has been limited to those farms with subsurface drains that should have been sealed off. The potential for groundwater impacts seems to exist, but it also seems that poor nutrient management (over-applying crop nutrients) has a much larger impact on groundwater quality (i.e. especially elevated nitrate levels).

The findings of this report may be summarized in three areas:

A - Education needs

1. Farmers and builders need to be aware of the urgency of locating any subsurface tile drains when any liquid manure storage is built.
2. Builders of earth tanks need to be updated on the importance of compaction in reducing the potential for leaking of manure.
3. Builders and farmers need to understand the environmental risks of installing manure transfer systems that have a high potential to develop leaks. "Out of sight - out of mind" is a bad philosophy in this area.
4. The public needs to be aware that manure particles tend to mat over when in contact with soil (under a hydraulic head), creating a physical seal that is very effective in fine soils. Manure does not move through soil in the same way that water moves.

B - Design needs

5. Concrete tank designs may need to be updated to consider currently recommended practices in Wisconsin (and possibly elsewhere) - concerning imbedded waterstops, minimizing joints, using waterstops at all control joints, avoiding granular material for the base of the floor.
6. Leakproof gravity manure transfer systems that are acceptable to builders and farmers must be designed.

C - Research needs

7. An economical and relatively easy system of monitoring the integrity of the seal of liquid manure storages is needed. This will likely take the form of subsurface tile drains with a sump that can be easily accessed.
8. A study of typical Ontario farms, with a variety of ages of manure storages, would help put into perspective the potential for leaking of concrete tanks and the potential to then actually contaminate the groundwater under these tanks.

References

- Ackerman, E.O. and Taylor, A.G. 1985. Ten Reasons Why Livestock Waste Management Systems Fail. from: Agricultural Waste Utilization and Management - Proceedings of the Fifth International Symposium on Agricultural Wastes. American Society of Agricultural Engineers.
- Agriculture Canada. 1988. Canadian Farm Buildings Handbook. Publication 1822E, Research Branch, Agriculture Canada, 155 pages.
- anon. 1994. Best Management Practices - Livestock and Poultry Waste Management. Agriculture and Agri-Food Canada and Ontario Ministry of Agriculture and Food. 49 pages.
- anon. 1998. Manure Spills in Ontario-Actual Case Files. Brochure. Livestock Manure Pollution Prevention Project.
- Barrington, S.F. and Broughton, R.S. 1988. Designing Earthen Storage Facilities for Manure. The Journal of the Canadian Society of Agricultural Engineering 30(2): 289-292.
- Barrington, S.F., Jutras, P.J., and Broughton, R.S. 1987. The Sealing of Soils by Manure. II. Sealing Mechanisms. The Journal of the Canadian Society of Agricultural Engineering 29(2):105-108.
- Canadian Pork Council. 1995. Canadian Code of Practice For Environmentally Sound Hog Production. Canadian Pork Council. 28 pages.
- Culley, J. L. B., and Phillips, P.A. 1982. Sealing of Soils by Liquid Cattle Manure. The Journal of the Canadian Society of Agricultural Engineering 24(2):87-89.
- Dalen, L.D., Anderson, W.P., and Rovang, R.M. 1983. Animal manure storage pond groundwater quality evaluation. Paper no. 83-4572. American Society of Agricultural Engineers
- Davis, S., Fairbank, W., and Weisheit, H. 1973. Dairy Waste Ponds Effectively Self-Sealing. *Transactions of the ASAE* 16(1):69-71.
- Demmy, G.G., Bottcher, A.B., and Nordstedt, R.A. 1993. Measurement of Leakage From Dairy Waste Holding Ponds. Paper No. 934017. The American Society of Agricultural Engineers.
- DeTar, W.R. 1979. Infiltration of Liquid Dairy Manure into Soil. *Transactions of the ASAE* 22(3):520-528, 531.

- Drommerhausen, D.J., et al. 1995. Electromagnetic Conductivity Surveys of Dairies for Groundwater Nitrate. *Journal of Environmental Quality* 24(6):1083-1091.
- Feng, J.S., Huffman, R.L. and Westerman, P.W. 1992. Modeling of Chemical Transport From Agricultural Waste Lagoons. Paper No. 922620. The American Society of Agricultural Engineers.
- Fleming, R.J. 1994. Impact of Earthen Liquid Manure Storages on Groundwater Quality. Research Report, OMAFRA, Ridgeway College, Ontario. 15 pages.
- Fonstad, T.A., and Maule, C.P. 1995. Earthen Hog Manure Lagoons; Part I: Flux Reduction Due to Sealing. Paper No. 95-508. Canadian Society of Agricultural Engineering.
- Fonstad, T.A. and Maule, C.P. 1996. Solute Migration Beneath Earthen Hog Manure Storages In Saskatchewan. Paper No. 96-200. The Canadian Society of Agricultural Engineering.
- Gangbazo, G., Cluis, D., and Vallieres, M. 1989. Nitrogen Seepage From Earthen-Built Manure Storage Tanks. Paper No. 892002. The Canadian Society of Agricultural Engineering
- Hootkany, A.N., Warner, R.C., Felton, G.K. and Taraba, J.T. 1994. Laboratory Determination of Dairy Waste Lagoon Soil Liner Permeability as a Function of Clay Content, Moisture Content, and Compactive Effort. Paper No. 942531. American Society of Agricultural Engineers, St. Joseph, MI.
- Huffman, R.L., and Feng, J.S. 1993. Interceptor Drains For Lagoon Seepage Capture. Paper No. 934018. The American Society of Agricultural Engineers and Canadian Society of Agricultural Engineering.
- Jofriet, J., Zhang, Y., Johnson, J.W., and Bird, N. 1996. Structural Design of Liquid Manure Tanks. *The Journal of the Canadian Society of Agricultural Engineering*. 38(1):45-52.
- Johnson, J. 1999. personal communication. Ontario Ministry of Agriculture, Food & Rural Affairs, London, Ontario
- Johnson, J. 1999b. Memorandum to: Ontario Building Officials reviewing farm building projects - June 7, 1999. Ontario Ministry of Agriculture, Food & Rural Affairs, London, Ontario
- Majumdar, G., Wulfsohn, D., Maule, C., and Mermut, A.R. 1996. Visual Evaluation of Sealing and Soil Pore Alteration Beneath Poned Hog Manure. Paper No. 96-105. The Canadian Society of Agricultural Engineering.
- Manitoba Pork. 1998. Earthen Manure Storages. Manitoba Pork and Environmental Stewardship Program. Brochure. 11 pages.

- McCurdy.M., McSweeney K. 1993. The Origin and Identification of Macropores in an Earthen-Lined Dairy Manure Storage Basin. *Journal of Environmental Quality* 22(1):148-154.
- Miller, M.H., Robinson, J.B., and Gillham, R.W. 1985. Self-Sealing of Earthen Liquid manure Storage Ponds: I. A Case Study. *Journal of Environmental Quality* 14(4):533-538.
- NRCS. 1995. Waste Storage Facility. Code 313. Natural Resources Conservation Service - Conservation Practice Standard. 6 pages.
- NRCS. 1997. Manure Transfer. Code 634. Natural Resources Conservation Service - Conservation Practice Standard. 3 pages.
- NRDC. 1999. Environmental and Health Consequences of Animal Factories. in: *America's Animal Factories*. Natural Resources Defense Council, Inc.
<http://www.nrdc.org/nrdcpro/factor/cons.html> Accessed July 13, 1999.
- OMAFRA. 1994. Earthen Storage Design and Construction. *Agricultural Pollution Control Manual*.
- Phillips, R.A., and Culley, J.L.B. Groundwater Nutrient Concentrations Below Small-Scale Earthen Manure Storages. from *Agricultural Waste Utilization and Management - Proc. Fifth Int. Symp.on Agr. Wastes*. ASAE. Publication 13-85 p.672-679.
- Rowell, J.G., Miller, M.H., and Groenevelt, P.H. 1985. Self-Sealing of Earthen Liquid Manure Storage Ponds: II. Rate and Mechanism of Sealing. *Journal of Environmental Quality* 14(4):539-543.
- Schulte, D. D. 1998. Do Earthen Structures Leak? *Manure Matters* v.4(1).
http://www.ianr.unl.edu/manure/v4n1_98.html Accessed July 13, 1999
- Sewell, J.I., Mullins, J.A. and Vaigneur, H.O. 1975. Dairy Lagoon System and Groundwater Quality from Managing Livestock Wastes. *Proceedings from the 3rd International Symposium on Livestock Wastes*. American Society of Agricultural Engineers.
- Struss, S. 1999. Personal Communication - email. Agricultural Engineer, Wisconsin Dept of Agriculture, Trade and Consumer Protection, Madison, Wisconsin
- Wall, D.B., et al. Effects of Clay-lined Manure Storage Systems on Ground Water Quality in Minnesota: A Summary. <http://www.ctic.purdue.edu/FRM/ManureMgmt/Paper92.html> Accessed July 13, 1999.
- Westerman, P.W., Huffman, R.L., and Feng J.S. 1995. Swine-Lagoon Seepage in Sandy Soil. *Transactions of the ASAE* 38(6):1749-1760.