Assessing the hydraulic conductivity beneath clay-lined earthen manure storages

R. Sri Ranjan, K. Manokararajah and C. Wiebe

Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba R3T 5V6, Canada. Email: Sri_Ranjan@Umanitoba.CA

Sri Ranjan, R., Manokararajah, K. and Wiebe, C. 2005. **Assessing the hydraulic conductivity beneath clay-lined earthen manure storages**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **47**: 6.1-6.7. Earthen manure storages are an economical way to store liquid hog manure during the winter months for subsequent land application. The manure is mechanically agitated prior to injecting on adjacent fields. Even though the clay-lined earthen manure storages are constructed according to guidelines, which set the maximum saturated hydraulic conductivity of the earthen liner to less than 10^{-9} m/s (The Environment Act 1998), the long term integrity of the clay beneath the storage has not been clearly established. A protocol has been developed to successfully collect core samples and test for the integrity of the clay liner beneath earthen manure storages. Using the falling head permeameter method, significant difference ($p = 0.005$) in saturated hydraulic conductivity was observed between liner samples ($n = 24$) collected from the bottom and the sides of the manure storage. Significant differences ($p = 0.018$) were also observed in saturated hydraulic conductivities measured using confining pressures of 20 and 35 kPa ($n = 19$). The results show the critical need to define the confining pressure at which the falling head permeameter tests should be carried out. Previous research has shown that earthen manure storages have the ability to self-seal/clog due to the settling of biosolids. However, the sealing ability of the biosolids was found to be marginal. The impact of freeze/thaw and wetting/drying cycles was also found to be marginal. **Keywords:** hydraulic conductivity, clay barriers, pollution, confining pressure, manure storage.

Les réservoirs en sol s'avèrent économiques pour l'entreposage du lisier de porcs durant les mois d'hiver en prévision de son application sur les sols cultivés. Le lisier y est agité mécaniquement avant l'injection dans les champs adjacents. Même si les réservoirs munis d'une couche imperméable en argile sont construits selon les directives qui déterminent que la conductivité hydraulique saturée de la couche d'argile ne doit pas être supérieure à 10^{-9} m/s (The Environment Act 1998), l'intégrité à long terme de cette couche d'argile n'a pas été déterminée. Un protocole a été développé pour prélever avec succès des échantillons et les tester pour vérifier l'intégrité de la couche d'argile sous les réservoirs en sol. En utilisant la méthode du perméamètre à charge hydraulique décroissante, des différences significatives ($p = 0,005$) de conductivité hydraulique saturée ont été observées entre les échantillons de couche imperméable ($n = 24$) provenant du fond et ceux provenant des parois d'un réservoir en sol. Des différences significatives ($p = 0,018$) ont aussi été observées dans les conductivités hydauliques mesurées en utilisant une pression uniforme de 20 et 35 kPa ($n = 19$). Les résultats démontrent la nécessité de définir la pression uniforme qui doit être utilisée pour réaliser les tests avec le perméamètre à charge hydraulique variable. Des études antérieures ont démontré que les réservoirs à lisier en sol ont la capacité de s'auto-imperméabiliser en raison de la sédimentation des solides organiques. Cependant, la capacité des solides organiques à imperméabliser s'est avérée négligeable dans cette étude. L'impact des cycles gel - dégel et humidification - séchage s'est aussi avéré marginal. **Mots clés**: conductivité hydraulique, couche d'argile, pollution, pression uniforme, entreposage du lisier.

INTRODUCTION

The abolition of the grain transportation subsidy has made value-added production an attractive means to increase farm income in Manitoba. As a result, there has been an expansion of the hog industry in southern Manitoba. The expanded hog operations have contributed to the accumulation of large amounts of manure that need to be stored and subsequently applied to the field without adverse impact on the environment. During the winter months, when land application is not permitted, earthen manure storages have been used as an economical method of storage. Several studies have indicated that the earthen storages have the ability to self-seal after some time (Barrington et al. 1987; Barrington and Madramootoo 1989; Davis et al. 1973; Dirmeyer 1961; Hills 1976; Miller et al. 1985; Rowsell et al. 1985; Sewell 1978). However, improperly constructed clay-lined earthen manure storages have the potential to permit seepage and lead to groundwater contamination in the vicinity of the storage (Huffman and Westerman 1993; Westerman et al. 1995). The potential for groundwater contamination from manure storages can be assessed by measuring the hydraulic properties of the soil layer at the bottom of the storage.

Different methods have been used in the past to assess the extent of seepage beneath manure storages (Miller et al. 1985; Shani and Or 1995; Westerman et al. 1995). Water samples collected from groundwater monitoring wells near the manure storages have been analyzed for the presence of pollutants. Unfortunately, by the time the water samples show traces of contaminant, the surrounding groundwater aquifer may already be contaminated to the point where it will not be economically feasible to undertake any aquifer remediation. Another way to assess the potential for seepage is to measure the hydraulic conductivity of the bottom liner itself. Attempts have been made to measure the hydraulic conductivity in situ (Shani and Or 1995). Alternatively, soil core samples can be collected from the soil layer at the bottom of the manure storage and the hydraulic conductivity can be determined in the laboratory. However, collecting soil core samples from the bottom of earthen manure storages is not a trivial task because of problems with accessibility. There is also the potential for contamination of the groundwater below the storage if the hole resulting from the coring is not sealed properly after sampling.

The manure storages in Manitoba are pumped twice a year to spread the liquid manure on adjacent fields. Prior to spreading, the storages are agitated mechanically to facilitate thorough mixing of the supernatant liquid with the sludge settled at the bottom. Since the storages are never pumped dry, only the sides of the storages become exposed to the atmosphere. This exposure could lead to the development of dessication cracks in the soils. Ciravolo et al. (1979) have reported the rupture of manure storage seals formed by the settling of the biosolids, leading to seepage, due to drying of exposed subsoil during recession of the lagoon water level. The gas release from microbial activity from soil beneath the seals was also reported to be contributing to an increase in hydraulic conductivity of the liner (Ciravolo et al. 1979). In addition to the wetting/drying cycles, the sides of the storages also undergo freeze/thaw cycles during the winter months which may also impact the hydraulic conductivity of the clay-liner itself.

The objective of this research was to characterize the hydraulic conductivity of soil beneath clay-lined earthen manure storage as affected by the depth and location of sampling points. In this study, a method of collecting the core sample and, thereafter, properly sealing the sampling hole is described. The soil core samples were collected from the bottom and sides of an earthen manure storage for subsequent hydraulic conductivity measurement in the laboratory. This paper also presents effective protocols for the collection of soil core samples from the bottom of manure storages as well as hydraulic conductivity testing procedures in the laboratory.

LITERATURE REVIEW

In Manitoba, manure storages are required to be constructed with at least two meters of clay soil having a saturated hydraulic conductivity of at most 10^{-9} m/s (The Environment Act 1998). In addition, proximity to surface water resources and the potential for groundwater contamination are assessed prior to the granting of the permit. During construction, the soil is excavated and a berm is formed on the perimeter of the storage. Regulations that came into effect in 1994 require the use of a sheeps-foot roller for compacting the soil. Even though the storage is inspected prior to first use by measuring the saturated hydraulic conductivity of two soil core samples collected at random locations, no further monitoring program is in place to assess the integrity of the clay-lined layer. The manure is a valuable source of crop nutrients and is injected into adjacent agricultural lands. As mentioned previously, mechanical agitators are used to agitate the manure so that the sludge settled at the bottom is well-mixed prior to pump-out. The mechanical agitation has to be carried out carefully to avoid any damage to the clay layer underlying the sludge. If the integrity of the clay layer is compromised during agitation, the resulting leak will continue undetected until the contaminants appear in nearby wells. Westerman et al. (1995) conducted chemical analyses of water samples collected from various distances away from manure storages. The ammonia-N and nitrate-N concentration was found to be continuing to increase in nearby monitoring wells even after being in operation for over five years. The ammonia-N, Cl, and EC were found to be the best indicators of seepage from manure storages in those studies. The ammonia-N also tended to move much farther than nitrate-N. In similar studies conducted by Ritter and Chirnside (1990), the nitrate-N and chloride ion movements were found to be highly correlated. They also found that clay-lined animal waste storages located in sandy loam soils with high watertables lead to degradation of groundwater quality.

Previous research has shown that the suspended solids in the manure have the ability to clog the pores in the liner and cause the formation of a seal at the manure-soil interface (Barrington et al. 1987; Robinson 1973). However, Vandevivere et al. (1995) have found that the ability of biomass to reduce the saturated hydraulic conductivity is dependent on the soil texture. Fine-textured soils were found to show a more pronounced reduction compared to coarse textured soils. Davis et al. (1973) have observed a decrease in infiltration rates by a factor of 200 with liquid manure application compared to water applied to the soil. They attributed this decrease to clogging of the soil pores by suspended solids in the liquid manure. However, Humenik et al. (1980) have expressed caution in planning storages in areas with very permeable soils, high watertables, or underlying rock fissures. Hills (1976) and Chang et al. (1974) have also shown that significant quantity of effluent could leak prior to the formation of a limited seal.

Chang et al. (1974) investigated the effect of drying on subsequent hydraulic conductivity measurements on cores previously submerged under liquid manure. In sandy soils, the hydraulic conductivity increased by a factor of 300 some 125 days after the recovery of the soil core samples. However, in clayey soils, the increase was about a factor of 8 . They found that the seal formation was not permanent and prolonged drying of the soil could contribute to an increase in saturated hydraulic conductivity back to the original level.

De Tar (1979) conducted a study using double-ring infiltrometers. The infiltration rate of liquid manure was found to decrease with an increase in concentration of the total solids. With low concentration liquid manure, the infiltration rates were more sensitive to the permeability of the soil. De Tar (1979) also observed that the sealing took place within four days of applying the manure. Miller et al. (1985) investigated a storage pond that received supernatant liquid from beef cattle manure after the solids had been removed by centrifuging. The pond also received runoff water from the upstream areas. Even though the sealing ability was expected to be low due to the removal of the solids, the pond effectively sealed within 12 weeks of addition of supernatant liquid manure. Miller et al. (1985) also observed the accumulation of ammonia-N in the soil below the pond. If the soil was allowed to become aerobic, then there was a potential for transformation to nitrate-N. An earlier study by Miller et al. (1976) found that medium or coarse textured soils are unsuitable for earthen manure storages. They also stress the need to maintain anaerobic conditions beneath the storages to prevent the transformation of ammonium-N to nitrate-N.

METHODOLOGY

Study location

The clay-lined manure storage investigated in this study has been in operation since 1990 and is located in the Rural Municipality of St. Anne, Manitoba (approximately 50 km southeast of Winnipeg). The storage is approximately 38 by 38 m in size. The storage was constructed using a Caterpillar (Model D7) tractor with a dozer blade attachment. The top soil was removed from the entire area and the clay soil was dug out

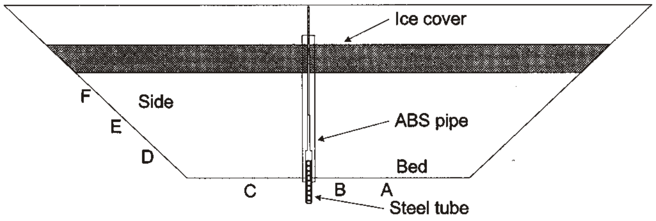

Fig. 1. Positioning of the soil coring device and the sampling locations.

and piled on the perimeter to create a berm. Finally, a smooth roller was used to compact the soil to a smooth finish. Soil hydraulic conductivity measurements done by the falling-head permeameter method on core samples obtained prior to construction indicated the hydraulic conductivity to be less than 10^{-9} m/s. Therefore, there was no regulatory requirement to use a sheeps-foot roller for compacting the soil at the time of construction.

In this study, core-sampling locations were chosen such that representative samples were collected both from the "bottom" of the storage as well as the "sides." The "bottom" here is defined as the flat portion towards the middle of the storage which always remains wet throughout the year. Typically, the storage is never drawn down to a depth below 0.5 m. The "side" refers to the sloped-part closer to the berm which undergoes periodic wetting/drying as well as freeze/thaw cycles (Fig. 1.). Core samples at three different locations each were collected from the bottom and side of the storage for a total of six locations.

Sampling equipment

A triple-pipe sampling assembly was designed and built to address two field problems typically occurring during sample collection. One was to prevent the contamination of the sample during retrieval of the cores and the other was to ensure proper sealing of the sampling hole in the storage bottom after the sample had been retrieved. A steel pipe with a specially designed cutting edge was used as the sample collection device. Shelby tube rings for holding the soil samples were inserted into this steel pipe. The cutting edge was machined to produce a retaining-ledge to hold the Shelby tube sample holders. The entire holder was attached to a long metal shaft which was used as a guide for the sliding hammer during insertion. To prevent any contamination of the sample holder, the steel pipe was inserted through a 3-m long larger diameter (340 mm ID) ABS pipe into the storage. The ABS pipe prevented the liquid manure from coming into contact with the steel pipe during sample collection and also permitted the addition of a bentonite seal after sample retrieval. During previous visits, frozen water in the annular space surrounding the Shelby tubes prevented the samples from being retrieved in the field. Since the ambient temperature remained well below -5°C, it was found to be important to keep the steel pipe corer assembly as dry as possible. This facilitated the removal of the Shelby tube rings from within the steel pipe. The use of the ABS pipe kept the steel pipe relatively dry and also provided accesses to the hole for sealing with bentonite pellets.

Sample collection protocol

The sampling was done when the manure storage had a minimum of 0.6 m thick ice cover. The condition of the ice cover was checked carefully prior to entry into the storage. A powered-ice auger was used to drill access-holes in the ice cover at the desired locations. Since the effluent arrives at the storage in liquid form, well above the freezing point, the ice cover is always open to the atmosphere near the inflow end. Therefore, the effluent beneath the ice cover is usually at atmospheric pressure. Locations were chosen such that three cores were collected from the bottom of the storage and three others were collected from the side of the storage. Depending on the sampling location, the bottom was about 1.2 to 2.4 m below the top of the ice cover. The bottom end of the ABS pipe was covered with a plastic bag before being lowered into the storage. This prevented the supernatant liquid manure from entering the ABS pipe. Once the ABS pipe had touched the bottom of the storage, it was gently pushed down into the sludge layer until firm soil was encountered. The sludge layer varied between 0 and 0.4 m at the bottom and was generally negligible on the sides of the storage. Once the ABS pipe had reached the firm soil, it was gently tapped with a mallet into a vertical position. Since the plastic bag was intact, the ABS pipe still remained empty. The steel tube with a special cutting edge was then inserted through the middle of the ABS pipe. A sliding hammer was used to hammer this tube into the soil. Once the cutting edge pierced through the plastic bag, the soil core sample advanced through the cutting ring into the Shelby tube rings. The sampling tube was hammered down to a depth of 0.32 m from the bottom of the ABS pipe. The ABS pipe was initially pushed to a depth until firm soil was encountered which signified the end of the sludge layer. Figure 1 shows the sampling method and the relative locations from where core samples were collected. Figure 2 provides a detailed design of the coring device. Coring locations A, B, and C were used to collect samples from the bottom. Coring locations D, E, and F were used to collect samples from the side. Figure 3 presents soil profile data obtained at two locations, one from the bottom of the storage and the other obtained from an area adjacent to the storage. The detailed profile of the soil sample obtained from the bottom of the storage shows the 0 m with reference to

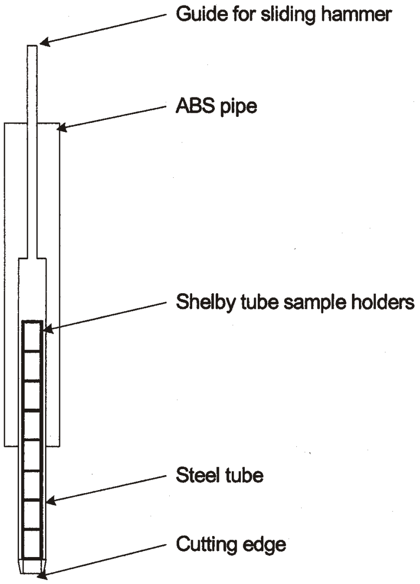

Fig. 2. Detailed view of the soil corer.

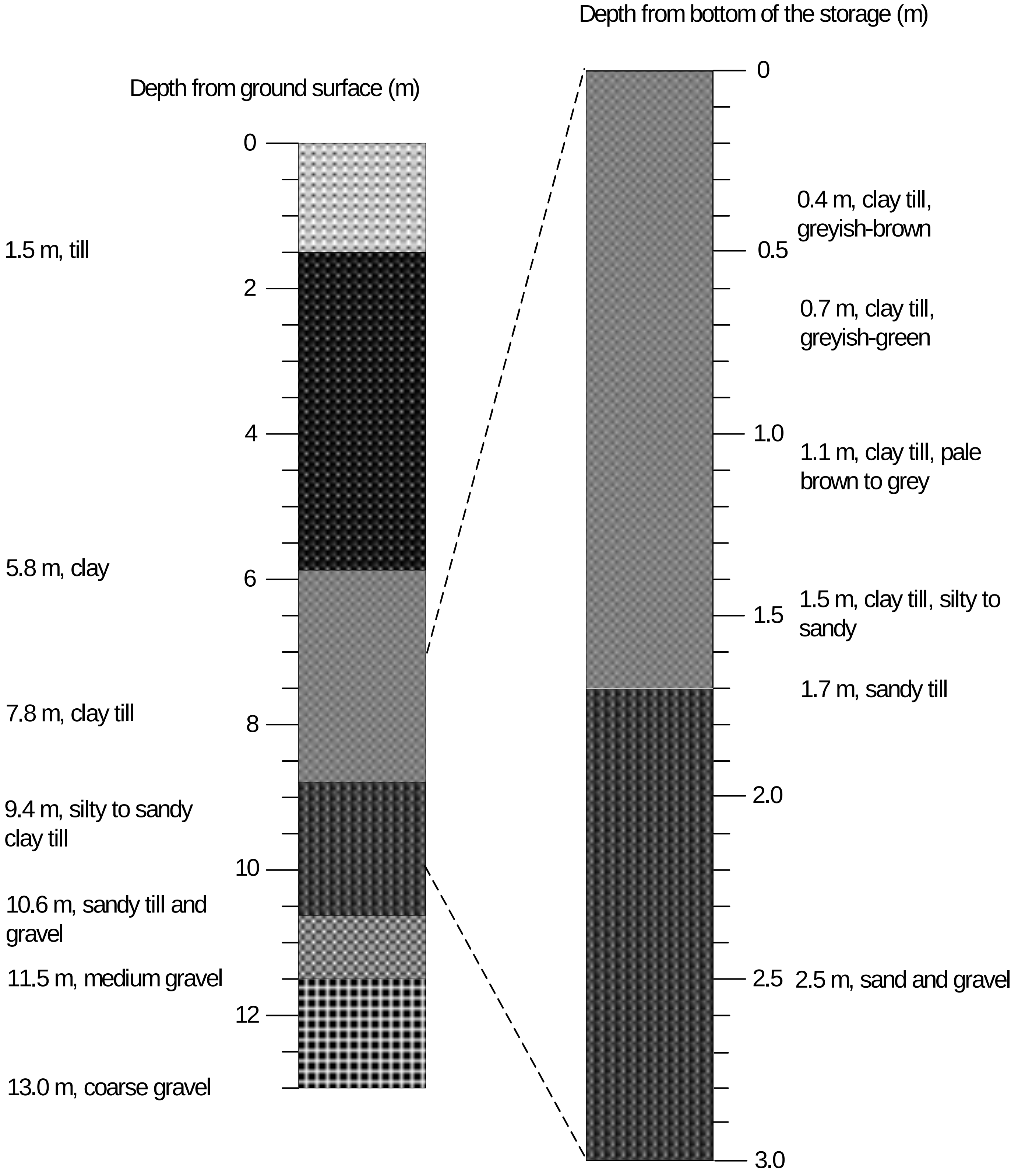

Fig. 3. Soil profile adjacent to the manure storage and in the bottom of the manure storage.

the bottom of the sludge layer. The bottom of the storage is 8 m below the ground surface at this location. The 13 m soil profile was obtained from a core analysis done at a site adjacent to the storage with the 0 m referenced to ground surface. To facilitate the removal of the coring tube from the manure storage, an air gap was created between the steel tube and the surrounding soil by wiggling the coring tube from side to side. Preliminary testing indicated that the lack of an air gap caused the soil

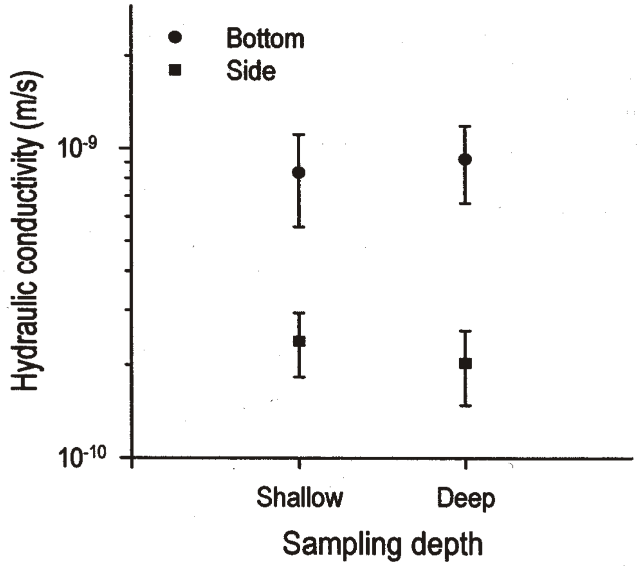

Fig. 4. Comparison of the effect of location and depth on hydraulic conductivity (error bars indicate standard error). Shallow = 0 - 0.15 m; Deep = 0.15 - 0.3 m.

samples to be sucked back out of the Shelby tube rings. The sample tube was then raised using a jack supported on the ice. The ice cover was tested carefully prior to this step and the base of the jack was placed on a wooden platform to spread the load over a larger area. After the coring tube was removed, bentonite pellets were poured through the ABS pipe and pushed and tamped down into the sampled hole using a metal rod. The bentonite pellets expand with the absorption of water and were expected to create a seal in the hole caused by the sampling tube. This practice is quite common in the well drilling industry to create a seal isolating different substrata. The ABS pipe was removed after the sealing was completed. The cutting edge of the coring device was then unscrewed and the Shelby tube sample holders were carefully retrieved with the sample intact. The soil samples were wrapped to prevent dessication and labeled. The coring device accommodated seven sampling rings. Based on the location of the sampling rings, samples coming from immediately below the sludge layer were designated as "shallow" (0 - 0.15 m) and the deeper layers were designated as "deep" (0.15 - 0.3 m).

Hydraulic conductivity measurement

Falling head permeameter tests were conducted to determine the saturated hydraulic conductivity of the sample according to ASTM D 5084-90 (ASTM 1990). The soil core samples were transferred from the Shelby tube rings into flexible wall permeameters. Due to the large number of samples to be tested and the long time needed for ensuring saturation of the samples, three permeameters were used simultaneously for the tests. Filter paper disks and glass beads were placed on both ends of the soil sample to maintain the length during testing. Compressed air was used to provide confining pressure to the flexible wall to prevent by-pass flow of water during testing. The ASTM D 5084-90 indicates that the confining pressure could range anywhere between 7 and 35 kPa (ASTM 1990). Based on preliminary testing, the confining pressure was found to affect the saturated hydraulic conductivity obtained by this method. Therefore, it was decided to conduct the falling head permeameter tests under two different confining pressures applied sequentially. Tests were carried out with a confining pressure of 20 and 35 kPa. The falling head tests were carried out with an initial head not exceeding 0.9 m of water. Falling head permeameter tests were carried out on the soil core samples in a random order. Three permeameters were used simultaneously to complete all the saturated hydraulic conductivity measurements at the two different confining pressures. The laboratory temperature was recorded during each of the tests and the hydraulic conductivity was corrected to 20°C.

RESULTS and DISCUSSION

Impact of the sampling location

Figure 4 presents saturated hydraulic conductivity data categorized by the location and depth of sampling. The saturated hydraulic conductivity (*K*) was found to be significantly ($p = 0.005$) higher in the 12 samples collected from the "bottom" compared to the 12 samples from the "sides". The points on the figure are categorized into the depth of sample collection. However, the depth effect was found to be statistically non-significant. The bottom samples had a *K* which was four times that of the sides. The mean saturated hydraulic conductivity still remained below the 10^{-9} m/s limit set in the guidelines. However, a few samples obtained from the bottom exceeded this limit. During construction, a dozer blade was used to push the soils to the side to create the berm (= "side"). Any compaction of the soil both in the bottom as well as in the side was due to the machinery used for pushing the soil and the smooth roller used for final smoothing. The biosolids settling to the bottom of the storage are expected to clog the pores and cause a reduction in hydraulic conductivity of the soil. Therefore, the soil in the bottom was expected to have a hydraulic conductivity lower than that of the side. However, the measured hydraulic conductivities were greater than that of the side. It is possible that the clogged and marginally compacted clay layer beneath the bottom of the storage may have been scoured during periodic agitations prior to pumping. It was difficult to delineate the clogged layer from visual observations. Closer examination of the core samples collected from the bottom showed that they were poorly structured, tan to grey in colour and contained gravel veins. The samples obtained perpendicular to the side wall, at locations just below the ice cover in the saturated zone at the edge of the storage, had *K* well below the limit and is typical for the clayey soils found in this area. Based on these results, the sides of the storage which were exposed to the wetting/drying and freeze/thaw cycles did not seem to exhibit increased hydraulic conductivity as reported in the literature. The samples from the sides were dark gray in colour, free of any gravel and appeared to be similar to well-structured clay. Soil material located higher up near the surface may exhibit a higher *K* due to the effects of freeze/thaw cycles.

Effect of depth of the samples

The impact of the depth of the samples was evaluated separately for the samples collected from the side and the bottom. The results obtained using a confining pressure of 20 kPa are

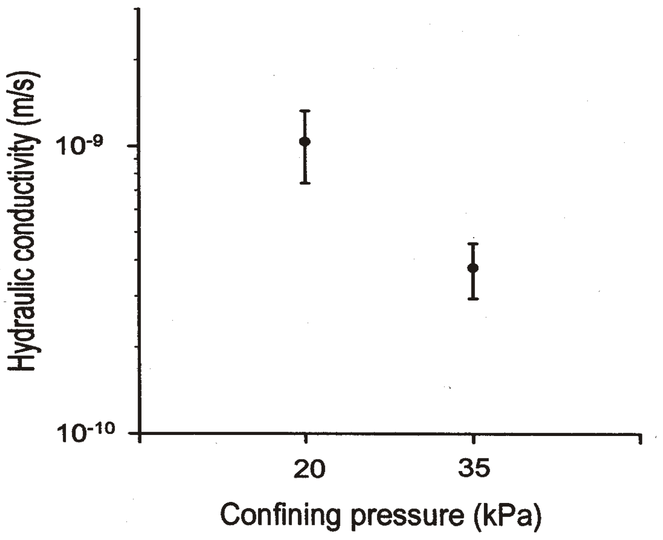

Fig. 5. Comparison of the effect of confining pressure on measured saturated hydraulic conductivity (error bars indicate standard error).

presented in Fig. 4. For the samples collected from the bottom, the shallower samples have a slightly lower average saturated hydraulic conductivity compared to the deeper samples. However, the difference is not statistically significant due to the high variability. The slightly lower average hydraulic conductivity of the shallower samples could be attributed to the partial sealing of the pores by biosolids from the sludge and/or compaction by earthmoving equipment used during the construction. Barrington and Madramootoo (1989) have reported that this seal formation could extend to within the top 10 mm of the soil surface. This phenomenon is reversed for the samples obtained from the sides. The shallower samples from the sides exhibited a slightly higher average hydraulic conductivity compared to the deeper samples. During sampling, very little sludge was found on the sides. The sealing effect of the biosolids is expected to be reduced on the sides because of the lesser hydraulic gradient on the sides and the reduced forces moving the particulates into the soil. The increased hydraulic conductivity could be attributed to the freeze/thaw and wetting/drying cycles experienced by the shallower layers compared to the deeper layers. It should be reiterated here that the difference is not statistically significant due to the high variability of the saturated hydraulic conductivity data. Nevertheless, the trends in saturated hydraulic conductivity as a function of depth observed in this study are similar to the results reported in the literature. Perhaps, further work with a larger data set might reveal a significant trend.

Impact of confining pressure

The lack of a clear guideline for the application of confining pressure prompted this part of the experiments. Figure 5 presents data obtained at 20 and 35 kPa confining pressures. All of the falling head permeameter tests were carried out with an initial head of 0.9 m of water. Using the paired t-test, the mean saturated hydraulic conductivities of 1.04×10^{-9} and 3.77×10^{-10} m/s were found to be statistically significantly different ($p = 0.018$) for the 20 and 35 kPa levels ($n = 19$), respectively. The mean hydraulic conductivity obtained with 20 kPa confining pressure marginally exceeded the maximum limit set in the guidelines. However, the results obtained using a 35 kPa confining pressure showed that the mean remained well below the maximum limit set in the guidelines. Based on existing guidelines and standards of measurement, it is difficult to conclude whether the manure storage meets the limits set by the guidelines. These results indicate the importance of defining the appropriate confining pressure for these tests. The sample size is also not defined in the present guidelines. Without these definitions, it will be difficult to enforce the guidelines as stated at present.

CONCLUSION

A protocol has been developed to test the integrity of clay liners beneath earthen manure storages. Field testing showed that the equipment and the sample collection procedures as described in this paper are very useful for obtaining intact soil core samples from the clay layer. The method used to seal the sampling hole after the core is retrieved was also found to be operationally efficient. The results show the critical need to define the confining pressure at which the falling head permeameter tests should be carried out. This will help in developing a clearer guideline for conducting these tests. Clear guidelines will also be helpful for enforcing the maximum limits set in the farm practices guidelines.

Significant differences ($p = 0.005$) were observed between samples collected from the bottom and the sides of the manure storage. Therefore, the location of sample collection was found to be an important factor. The sealing ability of the biosolids was found to be marginal. The impact of freeze/thaw and wetting/drying cycles was also marginal. Nevertheless, the observed trends are consistent with research results reported in the literature.

ACKNOWLEDGMENT

The authors acknowledge the technical support provided by Mr. J. Putnam and Mr. D. Bourne in this research. Mr. B. Boetcher provided data on core analysis. Funding provided by the NSERC is appreciated.

REFERENCES

ASTM. 1990. Standard test method for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter. *Annual Book of ASTM Standards* D 5084-90: 1161-1168.

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

Barrington, S.F., P.J. Jutras and R.S. Broughton. 1987. The sealing of soils by manure. II. Sealing mechanisms. *Canadian Agricultural Engineering* 29(2): 105-108.

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

Ciravolo, T.G., D.C. Martens, D.L. Hallock, Jr., E.R. Collins, E.T. Kornegay and H.R. Thomas. 1979. Pollutant movement to shallow groundwater tables from anaerobic swine waste lagoons. *Journal of Environmental Quality* 8(1): 126-130.

Davis, S., W. Fairbank and H. Weisheit. 1973. Dairy waste ponds effectively self-sealing. *Transactions of the ASAE* 16(1): 69-71.

De Tar, W.R. 1979. Infiltration of liquid dairy manure into soil. *Transactions of the ASAE* 22: 520-528, 531.

Dirmeyer, R.D. 1961. Clay sealing investigations. Publication CER61RDD20. Fort Collins, CO: Colorado State University Experiment Station.

Hills, D. 1976. Infiltration characteristics from anaerobic lagoons. *Journal of the Water Pollution Control Federation* 48(4): 695-709.

Huffman, R.L. and P.W. Westerman. 1993. Tracking seepage with terrain conductivity survey and wells. ASAE Paper No. 93-4016. St. Joseph, MI: ASAE.

Humenik, F.J., M.R. Overcash, J.C. Barker and P.W. Westerman. 1980. Lagoons: State-of-the-art. In *4th International Symposium on Livestock Wastes*. *Livestock Waste: A Renewable Resource*, 211-216. St. Josephs, MI: ASAE.

Miller, M.H., J.B. Robinson and D.W. Gallagher. 1976. Accumulation of nutrients in soil beneath hog manure lagoons. *Journal of Environmental Quality* 5(3): 279-282.

Miller, M.H., J.B. Robinson and R.W. Gillham. 1985. Self-sealing of earthen liquid manure storage ponds: I. A case study. *Journal of Environmental Quality* 14(4): 533-538.

Ritter, W.F. and A.E.M. Chirnside. 1990. Impact of animal waste lagoons on ground-water quality. *Biological Wastes* 34: 39-54.

Robinson, F.E. 1973. Changes in seepage rate from an unlined cattle waste digestion pond. *Transaction of the ASAE* 16(1): 95-96.

Rowsell, J.G., M.H. Miller and P.H. Groenevelt. 1985. Self-sealing of earthen liquid manure storage ponds: II. Rate and mechanism of sealing. *Journal of Environmental Quality* 14(4): 539-543.

Sewell, J.I. 1978. Dairy lagoon effects on groundwater quality. *Transactions of the ASAE* 21(5): 948-952.

Shani, U. and D. Or. 1995. In situ method for estimating subsurface unsaturated hydraulic conductivity. *Water Resources Research* 31(8): 1863-1870.

The Environment Act. 1998. Livestock manure and mortalities management regulation. M.R. 42/98. Winnipeg, MB: The Province of Manitoba.

Vandevivere, P., P. Baveye, D. Sanchez de Lozada and P. DeLeo. 1995. Microbial clogging of saturated soils and aquifer materials: Evaluation of mathematical models. *Water Resources Research* 31(9): 2173-2180.

Westerman, P.W., R.L. Huffman and J.S. Feng. 1995. Swine-lagoon seepage in sandy soil. *Transactions of the ASAE* 38(6): 1749-1760.