IMPORTANT CONSIDERATIONS FOR LEAKAGE CONTROL OF EXPOSED GEOMEMRANE-LINED PONDS

R. THIEL* AND J.P. GIROUD**

* *THIEL ENGINEERING, PO Box 1010, Oregon House, CA, 95962, USA*
** *JP GIROUD, INC., 5837 N. Ocean Blvd, Ocean Ridge, FL, 33435, USA*

SUMMARY: The subject of this paper is exposed-geomembrane-lined ponds whose leakage to the environment is highly undesirable. Such ponds are actually quite common in industrialized settings, and they form an important part of the operating infrastructure of many systems. Examples include process ponds for mining, leachate ponds for municipal and hazardous waste landfills, and wastewater treatment ponds for a whole host of industries and municipalities. The principles discussed in this paper could also apply to less environmentally-sensitive ponds, such as drinking water reservoirs or decorative ponds, where leakage is undesirable. The objective of this paper is to describe some important considerations related to these types of ponds for the design and maintenance of leakage control below the exposed primary liner. The proper implementation of leakage control systems cannot be overemphasized. Case histories of pond liner systems that failed due to non-existent, inadequate or poorly managed leakage control systems are presented.

1. INTRODUCTION

Ponds are designed and constructed for many uses ranging from architectural or decorative purposes, golf courses, recreation or sport facilities, habitat, fisheries, stormwater detention, sedimentation, water storage, chemical containment, and wastewater containment. The extreme pond is a large dam and the resulting reservoir. Ponds can be created in earthwork cuts, fills, or a combination of cuts and fills. The surface of the impoundment area can be created from native or recompacted soils, or enhanced with special soils or geosynthetic liners.

Different types of ponds can have different design criteria related to liquid containment. Some ponds are designed to infiltrate water into the ground, and are thus intentionally built on permeable soils. Stormwater detention and sedimentation ponds often have no particular design criteria related to water infiltration. Probably most ponds are intended to contain liquids with a desirable goal of having as little leakage or infiltration to the ground as reasonably possible. In the extreme case of chemical and strong-wastewater ponds, significant leakage to the environment is unacceptable and may be illegal, depending on the specific circumstances. The subject of this paper is focused on the latter type of ponds, but may have relevance to other types of ponds where leakage would be undesirable. Leakage from a pond can be undesirable for several reasons, including:

- Potential contamination and pollution of soils and groundwater from the leaking fluids
- Possible underground erosion and/or formation of solution cavities, which is a first type of

"geotechnical damage"
- Possible slope instability due to phreatic surface buildup below the liner, which is a second type of "geotechnical damage"
- Potential uplifting of liner reducing the pond capacity and exposing the liner to mechanical damage and excessive stresses due to pressure of gas and/or liquid present under the liner and/or to buoyancy of liner
- Potential loss of valuable clean water, or potential loss of valuable solution (in the case of chemical and production ponds)
- Potential difficulty in maintaining an acceptable liquid level, which may be important in decorative ponds, water reservoirs for recreation or sport activities, reservoirs for pump-storage stations, etc.

Specifically excluded from this paper is a consideration of pond geomembrane liners that are covered with a soil or cementatious ballast layer. Single geomembrane liners constructed over a smooth, firm, relatively low-permeability subgrade, and covered with at least approximately 30 to 60 cm of ballast layer, may provide a high degree of resistance to leakage even when the geomembrane contains defects. This is because the ballast layer will generally prevent gas pressures from uplifting the geomembrane, and will maintain intimate contact between the geomembrane and the soil subgrade, thereby keeping the leakage rate to a very low level even where there are defects in the geomembrane. Depending on the ballast type, size of geomembrane defects, and liquid head in the pond, the leakage rate from this type of pond can be estimated using empirical equations available in the literature. There are other considerations regarding soil ballast layers over pond geomembranes, such as soil type, placement method, pond volume impact, cost, and veneer stability that are beyond the scope of this paper.

2. DEGREES OF LEAKAGE CONTROL

Probably the most fundamental consideration that must be acknowledged when designing exposed geomembrane pond liners is that it must be assumed that geomembranes leak. Acknowledgement of this fact is critical, and the fact of this matter has been well espoused in the literature for nearly 30 years (e.g. Giroud and Goldstein, 1982; Giroud, 1984; Richardson and Hase, 1999; Richardson, 2000). The need to monitor and manage leakage in ponds is commonly discussed at national and international conferences, and regularly taught in courses presented in parallel to conferences or sponsored by professional organizations in many countries (e.g. ASCE in the United States). Design and management techniques for addressing the resulting leakage are required for the reasons mentioned in Section 1. What are the required degrees of leakage control required for various types of ponds? Four scenarios are described in the following paragraphs.

<u>Scenario 1 - No leakage control.</u> This scenario represents a single exposed geomembrane liner placed on a subgrade with no special considerations for control or detection of leakage. Uncontrolled leakage can result in all of the problems listed in Section 1. If the potential consequences of every single item listed in Section 1 are acceptable, then a single geomembrane liner with no leakage control measures is acceptable. In this case, success or failure of the liner system would not result from excessive leakage but could result from other causes such as mechanical damage or deterioration of the geomembrane. In this case the liner system performance would have to be considered "non-critical" since the amount of leakage presumed to be acceptable is likely to be large compared to the very small amount of leakage that could be acceptable in the case of the following scenarios. This in fact is the case with some decorative or many clean stormwater detention ponds.

Scenario 2 - Leakage control but no detection. This scenario presumes that there is a leakage collection system (usually a blanket drainage layer) under the geomembrane. At this point it is useful to clarify nomenclature. Some people might use the term "underdrain" for a leakage collection layer. We will avoid that term because the term "underdrain" is typically reserved for drainage systems under structures where the drainage system is intended to collect and control subsurface water that is already in the ground, and not necessarily to collect leaks. For our purposes, we will call this drainage system a "leakage collection layer". This layer must slope to a discharge point that either drains by gravity, or collects in a sump where it can be pumped out. In a system that provides for collection of leakage but no detection, the liquid would simply "disappear" out of the drainage system, and there would be no direct feedback regarding the pond performance. In this case, success or failure of the liner system would have to be determined on some other type of feedback such as observation of any of the consequences stated in Section 1. This scenario should be reserved to non-critical cases, i.e. cases where the liquid does not contain contaminants harmful to the environment and cases where the leaking liquid is not likely to cause geotechnical damage (as defined in Section 1). An interesting failure, described by Giroud and Goldstein (1982), occurred when such a design was used in a critical case. The structure was repaired with a double liner (as described in the Scenario 4 below).

Scenario 3 - Leakage control with partial detection and management. This scenario represents a system where a leakage collection layer is created below the primary geomembrane liner that would discharge to a location where a fraction of the collected leakage could be observed and possibly even measured, usually via a pipe. Depending on the degree of impermeability of the substrate underlying the leakage collection layer, the amount of observed leakage may be more or less representative of the actual leakage through the liner system. For example, the first author has been involved in a case history where an old asphalt-lined drinking-water reservoir was rehabilitated with a new geomembrane primary liner. A decision was made to use the old asphalt liner as the surface upon which the leakage collection layer was installed, such that the leakage collection layer is between the asphalt and the new primary geomembrane. The leakage collection layer (a geocomposite on the bottom of the reservoir) drains to a stone-filled trench drain that has a discharge pipe that can be monitored. The performance of the new geomembrane is judged in large part by the observed discharge from the trench drain, knowing that in fact the underlying asphalt layer and trench drain are not leak-proof, and that the leakage being reported to the trench drain discharge may in fact not be representative of the total leakage from the reservoir. In pond liner systems of this type, the liquids being contained would have to be considered "non-critical" from the point of view of environmental or geotechnical impairment or economic value, since an unknown fraction of the collected leakage leaks through the base of the leakage collection layer. Success or failure of this type of liner system could be based on the leakage observed discharging from the leakage collection layer, and could also be determined on some other type of feedback such as observation of any of the consequences stated in Section 1.

Scenario 4 - Leakage control with full detection and management. This scenario represents a system where a leakage collection layer is created below the primary geomembrane liner that would convey the collected leakage to a location where it would be observed, measured and managed. Although this system could be used for a "non-critical liquids", in this paper we will consider that this level of management is mandatory for "critical liquids", whose infiltration into the ground is unacceptable for reasons of contamination, and/or geotechnical damage, and/or economics. The monitoring and operation of the leakage collection layer provides direct feedback regarding the pond performance. In this case, it would typically be unacceptable to knowingly have a "leaky" substrate for the leakage collection layer, as the presumed intent is to avoid any leakage into the ground. Thus, the most common design concept for this scenario is to have two geomembranes with an intervening leakage collection layer. The lower geomembrane, called the secondary liner, provides the substrate to the leakage collection layer. The upper geomembrane is often referred to as the primary liner. In this scenario, success or failure is often clearly defined by the measured leakage rate. Often the pond can be said to be operational as long as the leakage removal ability exceeds the leakage rate. When the leakage rate exceeds the ability of the removal system, then the pond would be considered to have "failed", and should be put out of service until the leaks are located and repaired. In some cases the concept of an "Action (or "Allowable") Leakage Rate" may be established where definitive management actions must be taken at predetermined measured leakage rates. Examples of Action (or Allowable) Leakage Rates are as follows:

- A survey conducted by the Geosynthetic Institute (Koerner and Koerner, 2009) indicates that the maximum regulated Allowable Leakage Rate of approximately 4,700 liters per hectare per day (lphd) is acceptable for wastewater ponds in most States of the USA, but that the regulated allowable values range from as low as 120 lphd to as high as 32,000 lphd.
- The province of Alberta, Canada defines the Action Leakage Rate as the amount of leakage that would theoretically occur through two holes per hectare in the primary geomembrane, where each hole has a diameter of 2 mm.
- The USEPA defines the action leakage rate for hazardous waste surface impoundments as the maximum flow rate that the leakage collection layer can remove without the fluid head on the bottom liner exceeding 0.3 m (US Code of Federal Regulations, 40 CFR Part 264.222). As a point of reference, an Action Leakage Rate of nearly 10,000 lphd (approximately 7 liters per minute per hectare) has been suggested by the USEPA (1992).
- If the leakage collection layer is a geonet with a 5 mm thickness, and the maximum allowable head on the secondary liner is 0.3m, then according to the equations presented by Giroud et al. (1997, Eqn 16) a leakage rate from a single defect of approximately 6E-04 m^3/s (36 liters per minute) is potentially allowable. With one such defect per hectare, the Action Leakage Rate would be approximately 50,000 lphd. This volume of leakage could easily be managed by a side-slope riser pump, provided that the riser pipe has an inside diameter of 15 cm, and preferably more, to accommodate the necessary size pump.

3. KEY DESIGN FEATURES

There are several key features that should be considered when designing the liner system for an exposed-geomembrane-lined pond, especially for the critical case described in Scenario 4 of Section 2. The following subsections describe such key design features. A typical example of a design incorporating these features is shown in Figure 1.

3.1 Primary liner

By definition of the subject of this paper, the top-most (primary) liner element for the pond is an exposed geomembrane. Selection of the appropriate geomembrane must be made based on several criteria, including durability and cost. The durability criterion comprises several different aspects including chemical-compatibility with the contained fluids (usually related to a combination of resin selection and material thickness), resistance to ultraviolet degradation and oxidation in combination with various temperature regimes (usually related to a combination of the resin selection, the additive package, and material thickness), and construction and physical-exposure durability (usually related to a combination of the material thickness, elongation properties, tensile strength, and puncture resistance). Other secondary considerations might include aesthetics (e.g. color), ease of repair and maintenance, safety (e.g. providing a textured non-slip surface), and ability to perform electrical defect-detection surveys.

Some designers might consider making the primary liner into a "composite liner" by including a low-permeability mineral component (such as a geosynthetic clay liner, or compacted clay) immediately below the primary geomembrane. If the primary geomembrane was able to maintain intimate contact with the underlying mineral liner, this composite primary liner system would greatly reduce the amount of leakage through a defect in the primary geomembrane. This in turn would reduce the demand on the leakage collection layer and the secondary liner system, greatly reducing the chance of exceeding a predefined Allowable Leakage Rate. However, there would be a significant potential that a defect in the primary geomembrane could allow some liquid to get between the geomembrane and the underlying mineral component, and cause uplifting of the geomembrane due to gas formation, liner buoyancy, or unbalanced liquid pressure in case of fluctuation of the liquid level or turbulence in the pond. In general, unballasted (exposed) composite primary liners in ponds cannot be expected to perform as true composite liners. While the mineral component of such a primary composite liner system would serve to impede the leakage rate into the leakage collection layer, it may tend to act alone as a single mineral liner as the geomembrane uplifts, and equations for predicting leakage through defects in composite liners cannot be used with these systems. If an exposed primary composite liner is proposed, the owner should strongly consider minimizing the risk of holes in the geomembrane by having a first-rate construction quality assurance program and an electric defect-detection survey performed, and be committed to emptying the pond and repairing the geomembrane at the first sign of any leakage or geomembrane displacement. Considering these constraints, the authors do not generally recommend this configuration. Furthermore, the authors would recommend against using this configuration in cases where the geomembrane could be exposed to expected mechanical damage, and cases where there are conditions of quickly-fluctuating water levels and turbulence (e.g. pumped-storage projects, and ponds with aerators).

The geometry of the liner system should be sloped to the low point of the pond, which is usually designated as a sump. The slope on the liner, usually a minimum of 1%, serves several functions, including the following:

- The slope on the top surface of the primary liner allows the contained pond fluids to be efficiently removed since they will drain to the low point where they can be pumped out.
- The slope on the bottom surface of the primary liner is necessary (but sometimes not sufficient depending on the pond size and the bottom slope) to allow gases below the liner to migrate to the high point of the pond bottom and up the slopes, where they can be vented. Perimeter vents at the crest of the slope are commonly installed through the primary liner. The vents also assist in reducing wind uplift on the primary exposed geomembrane.
- The slope on the leakage collection layer and secondary liner allows leakage to drain quickly and efficiently to the low point, where it can be monitored and removed, as described in the following sections.

3.2 Leakage collection layer

The leakage collection layer should have a high fluid transmissivity to allow leakage to quickly and efficiently be conveyed to the low point (usually a sump) in the pond. Given the need to typically deploy a geomembrane both above and below this layer, it is commonly most practical that this layer is created by a geosynthetic drainage layer, such as a geonet or a geocomposite (defined herein as a geonet with geotextiles bonded on one or both sides). A granular drainage layer could also be used, but would be more difficult to place, and would occupy more of the valuable pond volume. Very permeable clean gravels and geonets are generally considered good choices for leakage collection layers because of their high transmissivity rates. Sands, especially fine to medium sands, are considered a poor choice for leakage collection layers because they do not provide rapid leakage detection, and they may very likely result in extensive high heads on the secondary liner system (Giroud et al., 1997).

For a single geomembrane primary liner, leakage through a defect from the overlying geomembrane could be approximated by Bernoulli's equation for flow through an orifice (Giroud, 1984). In fact, the flow regime immediately below a defect may be very complex depending on the head, size of the defect, and the thickness and nature of the underlying leakage collection layer, as described by Giroud et al. (1997). Areas where confined flow conditions exist will have higher effective heads, up to the full depth of the pond, which would greatly increase the potential for significant leakage past the secondary liner in those areas.

As described in the preceding subsection, there should be a slope on the liner system in the bottom of the pond to allow leakage to drain quickly and efficiently to the low point. The designer can use available design techniques to balance the required minimum slope against the transmissivity of the leakage collection layer, anticipated leakage, and leakage travel time from a leak assumed to be located at the furthest point in the pond to the monitoring location (usually the sump). It is important, furthermore, that the leakage collection layer be designed so that it has adequate transmissivity to control the head buildup in the leakage collection layer to be less than the thickness of the leakage collectionlayer. This is because, as soon as the head level in the leakage collectionlayer equals the thickness of that layer, then the head on the secondary liner at that location will instantly increase, possibly to the full liquid depth in the pond. In that case the performance of the liner system and leakage collectionlayer becomes unpredictable, and it is possible that the pond could be considered to have "failed". In fact, this type of failure may be "non-spectacular" and, as a result, may remain unnoticed for some time (hence the importance of defining an Action Leakage Rate, as indicated in Section 2). As mentioned by Giroud and Goldstein (1982), these types of failures can be the worst because they may generate leakage to the subsurface for a long period of time and generate a considerable amount of contamination. In no case should the pond bottom have non-maintainable low spots or back-slopes, as these locations could result in higher effective heads on the secondary liner, which would increase the potential for significant leakage past the secondary liner in those areas.

3.3 Leakage monitoring and removal system

The pond's low point will either drain away by gravity to another containment structure (external sump), or be an internal sump where leakage is collected and pumped out. There is typically a means to monitor the liquid level at the low point between the two geomembranes.

External sumps may have an advantage in that they do not require pumping to maintain pond compliance, but they usually have the disadvantage that there is a pipe penetration in the secondary liner at the low point. Penetrations increase the probability of leakage in the secondary liner system. It may also be difficult to monitor the head buildup at the low point between the two geomembranes unless a separate slope riser pipe is installed for that purpose.

For internal sumps, a slope riser pipe and pump system is usually provided that has automatic liquid level settings for activating and shutting off the pump. Separate data recording of the liquid levels versus time are a common feature in the secondary sumps. The internal secondary sumps are usually locally depressed and filled with a clean open gravel to adequately surround the base of the riser pipe. The base of the riser pipe typically has numerous large perforations, sized in accordance with the gravel gradation, to allow leakage to be pumped out at the maximum rate that it might be delivered to the sump under the worst expected scenario. A heavy geotextile cushion material is often used to line the sumps to help protect the secondary geomembrane from accidental puncture from the gravel or riser pipe.

It is critical that ponds that incorporate a leakage collection layer be monitored; and, if leakage is detected, they must be maintained. Leakage collection layers that are not monitored and maintained will defeat the design, and effectively lead to failure. The second author has investigated the failure of a large double-lined reservoir where the maintenance crew (not informed of the importance of leakage collection) had placed a valve at the outlet of the leakage collection layer pipe and had shut it off indefinitely. As a result, leaking liquid accumulated between the two geomembranes. This caused failure of the liner and the reservoir which manifested itself in two ways: the upper geomembrane was uplifted and torn at its connection with a rigid structure; and liquid leaked into the ground and contaminated the ground water.

3.4 Secondary liner

The secondary liner should be a geomembrane that has similar selection criteria as for the primary geomembrane, but its exposure to the contained fluid chemistry, UV, oxidation, temperature variations, and physical abuse after installation would be expected to be less. To eliminate one possibility of having false leakage readings, due to precipitation water intrusion into the leakage collection layer, it is advisable to weld the primary and secondary geomembranes together in the anchor trench (Figure 1).

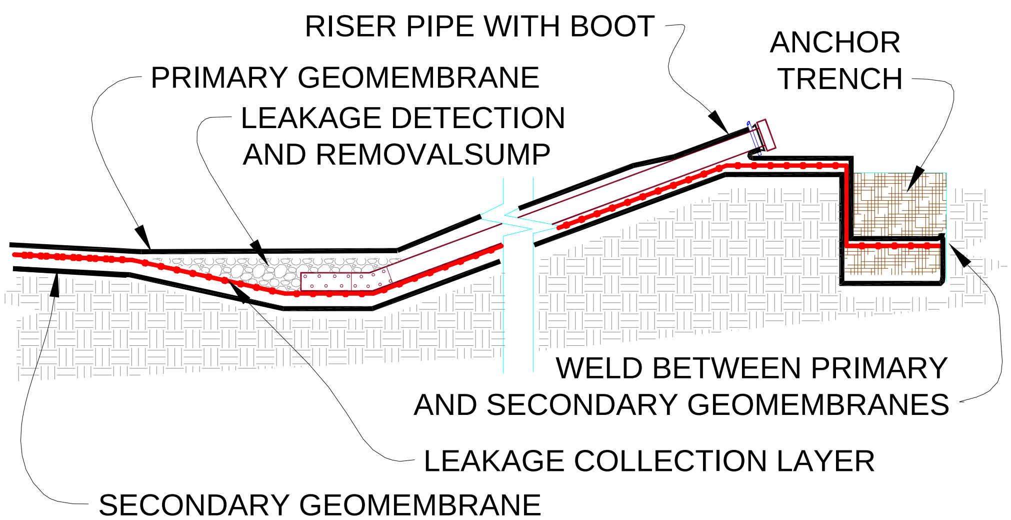

Figure 1. Double-lined pond with leakage collection layer, sump, and extraction pipe.

Some project designers and owners might argue that the secondary liner could be another material besides a geomembrane, such as compacted clay, asphalt, or concrete. While it is true that these alternative types of secondary liners could be considered, these types of liner materials by themselves would generally be considered more "leaky" than a well-constructed geomembrane. Clay-only liners, or liners that might be subject to random cracking such as asphalt and concrete, would allow a certain portion of the collected leakage to permeate into the subgrade, and thus a fraction of the leakage that passed through the primary liner would not be reported to the leakage monitoring point. As a result, the performance of the system would not be accurately known. Further arguments could be made that if "all geomembranes leak", and if the head on a secondary geomembrane liner were allowed to build up to any significant amount (e.g. 0.3m), then leakage through it could in turn be significant. Indeed, this rationale has led the USEPA to require that secondary liner systems for hazardous waste impoundments be constructed as composite liner systems whereby the secondary geomembrane must be underlain by 0.9 m of compacted clay. This requirement has in turn been adopted by several States in the USA for the design of wastewater impoundments, especially those required to contain landfill leachates. In any case, if minimization of leakage past the secondary liner is an important criterion, then the secondary liner system must incorporate an appropriate well-installed geomembrane. Modern electric defect-detection techniques are now readily available to help ensure that the secondary geomembrane is installed with a high reliability, having the smallest possible number of defects that can be achieved with current technology.

If the secondary liner system consists of only geosynthetics, then the subgrade preparation is important. The subgrade should be firm, "unyielding", and smooth so that the overlying geosynthetics would not be subject to puncture, settlement, or burst-type tensile forces. Consideration should be given to relief of fluid pressures that might arise from subsurface water and/or gases; for example through the use of underdrains. Also, the water-line of the pond may be exposed to wave action whose repetitive forces might cause the underlying subgrade to slump or deform. Thus, subgrade soils within the zone of the fluctuating water level might need to have specific requirements for cohesion and strength, which may lead, for example, to using soil-cement.

At this point a general comment can be made that the designer should be aware of the implications of interface shear strength between the various layers of the pond liner system. For example, a geonet leakage collection layer placed on a polyethylene secondary geomembrane will create a very slippery interface that could not be expected to support overlying soil loads, and would even be precarious to walk on. This is true even if the geonet is in contact with a textured secondary geomembrane. If the designer wishes to ensure that the slope liner system is able to carry loads, that could potentially be accomplished in this example by providing a textured secondary geomembrane and having a non-woven geotextile heat-bonded to the geonet. Each design will have its own unique requirements, and for some designs this issue may not be important.

4. CASE HISTORIES OF EXPOSED GEOMEMBRANE POND FAILURES DUE TO NON-EXISTENT, INADEQUATE OR NON-MAINTAINED LEAKAGE COLLECTION LAYERS.

The following case histories are examples of ponds constructed with exposed geomembrane liners in which failures occurred that could have been mitigated or avoided through the proper design and operation of leakage collection layers.

<u>Case History #1.</u> A single-geomembrane-lined drinking water reservoir was designed with a floating cover. Stormwater that was collected on the floating cover was conveyed by flexible pipes down through the bottom liner of the reservoir, and discharged from under the reservoir's dam. The stormwater pipes penetrated through the bottom liner system. Intermittent strip drains, intended to detect and control leakage through the bottom geomembrane liner, were placed between the subgrade and bottom geomembrane. A leak developed in one of the pipe boot penetrations, not very far from a strip drain. The strip drain failed to collect and control the leakage, which preferentially flowed in the stormwater pipe bedding material, eventually causing underground erosion and blowing out a portion of the face of the reservoir dam. A photograph of the sinkhole below the leaking pipe penetration is shown in Figure 2. Although it is easy to point to the leak that formed in the pipe boot as the cause of the failure, it was the first author's opinion that the real failure was due to an inadequate leakage collection layer. Whether or not the pipe boot had been constructed in the best possible manner, leakage at these locations should have been anticipated not only because of the general principle that "all liners leak", but also

because the probability for leaks is much greater at the locations of penetrations. It was clear that the leakage collection system that was installed was inadequate to safely control leakage, and that preferential uncontrolled leakage occurred in exactly the location where it would be most predictable. The remediation of this failure was eventually designed as a double geomembrane liner system with a blanket leakage collection layer.

Figure 2. Photo of sinkhole in Case History #1.

Case History #2. A single-geomembrane lined water reservoir was constructed on gap-graded sands near a river. Small leaks occurred where the geomembrane was attached to a large concrete pipe collar. Over a relatively short period of time, the leakage caused a sinkhole to form in the gap-graded subgrade soils. Photographs of the concrete penetration, and the gap-graded soils near the sinkhole, are shown in Figure 3. As the geomembrane was unsupported over the sinkhole, there was eventually a catastrophic collapse of the geomembrane. The remediation for this problem was to provide a double geomembrane liner system with a blanket leakage collection layer.

Figure 3. Photos of ripped geomembrane next to penetration, and sinkhole in Case History #2.

Case History #3. A single-lined wastewater pond developed holes in the geomembrane. Leakage through the geomembrane, followed by biogas production below the geomembrane, ultimately caused the geomembrane to float. The resulting deformed shapes of the geomembrane are often referred to as “whales”. This condition not only reduced the effective capacity of the pond, but it is suspected that wastewater was allowed to accumulate over a significant area of the pond footprint below the geomembrane and percolating into the subsoils.

This problem could be fully addressed and managed through the installation and operation of a double geomembrane liner system with a leakage collection layer. The leakage collection layer would allow the simultaneous management of liquid leakage via the sump, and of biogas via perimeter vents.

Figure 4. "Whales" in geomembrane of Case History #3 caused by leaking wastewater getting under the single geomembrane and forming biogas.

5. CONCLUSION

Deductive engineering and operational experience clearly show that any critical pond design using an exposed geomembrane primary liner requires a well-designed, monitored, and maintained leakage collection system if the pond is to be expected to function properly.

REFERENCES

ASCE. American Society of Civil Engineers short course on the Design of Waste Containment Liner and Final Closure Systems. This course is has been taught several times per year for the past 15 years in the United States.

Giroud, J.P. and Goldstein, J.S. (1982). Geomembrane Liner Design. Waste Age Magazine, September, 1982, pp. 27-30.

Giroud, J.P. (1984). Impermeability: The Myth and a Rational Approach. Proceedings on the International Conference of Geomembranes, V1, Denver, CO, pp. 157-162.

Giroud, J.P., Gross, B.A., Bonaparte, R. and McKelvey, J.A., (1997). Leachate Flow in Leakage Collection Layers Due to Defects in Geomembrane Liners. Geosynthetics International, Vol. 4, Nos. 3-4, pp. 215-292.

Koerner, R. and Koerner, J. (2009). Survey of U.S. State Regulations on Allowable Leakage Rates in Liquid Impoundments and Wastewater Ponds. Geosynthetic Institute - GRI White Paper #15.

Richardson, G. and Hase, W. (1999). Design Considerations for Surface Impoundments. GFR, V17N2, pp. 18-21.

Richardson, G. (2000). Non-Environmental Surface Impoundments. GFR, V18N5, pp. 26-29.

USEPA. (1992). Action Leakage Rates for Leak Detection Systems. Supplemental Background Document for the Final Double Liners and Leak Detection Systems Rule for Hazardous Waste Landfill, Waste Piles, and Surface Impoundments. USEPA, January 1992.