Landfill construction quality

Lessons learned from electrical resistivity testing of geomembrane liners.

Information and data continue to grow demonstrating that the modern double composite lined landfill constructed and operated in accordance with New York State's solid waste management regulations, 6 NYCRR Part 360, is proving to be an environmentally sound method of municipal solid waste disposal. Research has shown that the double liner system, which utilizes properly designed and specified geosynthetic construction materials in a modern landfill's containment system, adequately protects groundwater quality by acting as an effective barrier against leachate migration. Today, the environmental containment system construction industry is becoming more adept at constructing these modern disposal facilities. Improvements in the materials of construction and the equipment used to build landfills are helping contractors to bring these facilities on-line faster and easier than before.

One of the tools being used more frequently by facility owners and construction contractors is electrical resistivity integrity testing. Actual liner system leakage points are found using electrical resistivity to pin-point construction-related defects in a geomembrane during and after completion of liner system construction. In New York State, such testing has been required on occasion. In most of these cases, either the facility owner or construction contractor has called in a leak location service at the time of final construction certification, when it has been determined that the upper liner system's performance threshold is not being met. In these instances, the use of electrical resistivity testing was used to locate the geomembrane defects for subsequent repair, and thus has played a critical role in these facilities gaining acceptable containment system performance prior to the facility accepting waste.

Data being collected from these integrity surveys not only help to locate liner system damage, but upon materials engineering evaluation of each hole we can learn which activities contribute to defects in geomembrane installations. Thus, we can pinpoint construction activities that tend to cause the most defects. The purpose of this article is to get the word out to landfill designers, specification writers, and contractors that data being collected from electrical resistivity testing surveys can also help us to improve on landfill construction quality.

How does electrical resistivity testing work?

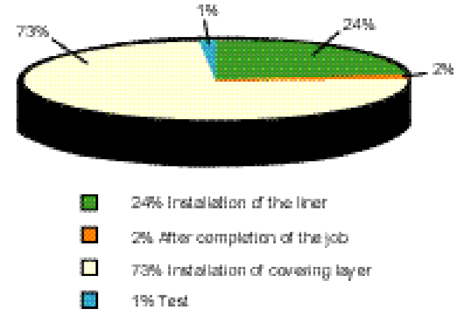
This leak location process involves the application of an electrical potential difference across the geomembrane. Electric current flows only through holes (possible leaks) in the geomembrane. In a perfect installation with a defect-free geomembrane, the geomembrane itself acts as an insulator between the two electrodes, minimizing the flow of electric current.

When using mobile survey equipment, the potential gradients in the soil above the liner are measured, using a handheld survey probe. If a hole is present in the geomembrane, the high current density at the hole is indicated by a localized high potential gradient. The maximum potential occurs when one of the survey probe electrodes is placed directly over the hole. There is no potential gradient when the hole is equidistant between the survey probe electrodes. Thus, the hole location can be pin-pointed.

When permanent installed leak location systems are used, the potential gradients between an electrode above the liner and several electrodes below the liner are triangulated to approximate the hole location. Mobile survey equipment may then be required to locate the hole accurately.

The benefit of this test method is that it can be performed after the geomembrane has been covered with the typical soil or granular drainage layer material. Surveys have been performed successfully on sand, gravel, stone, tire chips (wet), and waste. At this point a hole is still easy to uncover and repair with only about 600 mm (24 in.) of soil material on the geomembrane liner. If care is taken in exhuming and replacing the soil material above the geomembrane, additional damage to the geomembrane is unlikely to occur during the liner repair process. Additional liner damage is also unlikely to occur to the liner due to the subsequent

Figure 1: 1996 leak survey data indicate most damage occurs during covering of geomembranes.



By Robert Phaneuf and Ian Peggs

Photo 1: Many leaks occur on extrusion welds at "T" and "Y" joints and around pipe penetrations.

work being performed on top of the 600 mm (24 in.) of soil cover. Conventional construction quality control and construction quality assurance (CQC/CQA) procedures do not allow us to evaluate the success of the final stages of the landfill construction process, but electrical resistivity testing does. Successful surveys (Peggs and McEuen, 2001) have been performed on geomembranes covered by 4.5 m (14.76 ft.) of municipal solid waste (MSW), 5.5 m (18.04 ft.) of heap leach ore, and 18 m (59.06 ft.) of industrial sludge waste.

To successfully perform an electrical survey, it is essential that there be an electrically conductive layer on both sides of the geomembrane and an electrically conductive medium through any hole in the geomembrane. Therefore, it is not possible to detect a hole through which water is dripping discontinuously, nor is it generally possible to detect a hole in a geomembrane placed on top of a geonet, unless the geonet is backfilled with water/leachate or there is a strong continuous stream leaking to the secondary sump where the water/leachate can be electrically energized.

It is also generally not possible to perform an electrical leak location survey on a geomembrane barrier used in a landfill final cover system where the geomembrane barrier of the cover system is not welded to the bottom liner. This is due to the fact that the electric current will flow from the soil under the cap's geomembrane layer to the soil on top of it, essentially short-circuiting around the edge of the geomembrane layer when it is not seamed to the lower liner.

Are we missing the bigger picture?

As mentioned above, in addition to helping to bring newly constructed and adequately performing containment facilities on-line, data collected from leak location testing are also providing us with meaningful information relative to the cause of these performance-robbing construction-related defects. During technical training events on the need for proper CQC/CQA procedures in the late 1980s and early 1990s, we were told that the majority of geomembrane defects to the liner system occurred during the geomembrane installation process. The underlying basis for this training was an attempt to best ensure quality workmanship in constructing the modern environmental containment system. Through this training, design engineers, facility owners and regulators were informed on the benefits of proper CQC/CQA procedures, reducing the number of liner system defects resulting from facility construction.

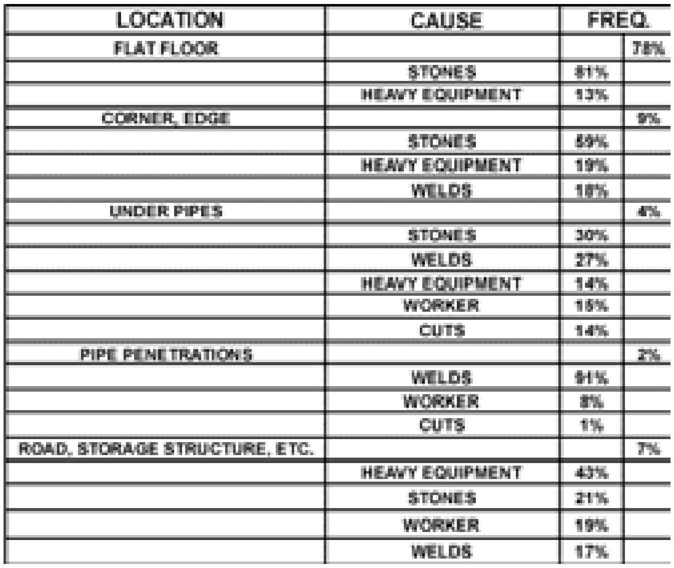
With the help of today's integrity surveys, we have an ability to see how successfully our conventional CQC/CQA programs have been working. Collectively two papers, Nosko et al. (1996), and Nosko and Touze-Foltz (2000), summarize the results of more than 300 electrical resistivity leak location surveys which were conducted throughout the world. In total, both of these leak location survey summaries assessed geomembrane damage found in more than 3,000,000 m^2 (32,290,000 ft.^{2}) of geomembrane installations in 11 different countries. The earlier paper assessed the cause and the amount of damage which was imparted to geomembrane installations during different phases of facility construction and post-construction. The second, more recent paper presents information regarding the origin of the geomembrane holes and characterizes the sizes and locations of the holes.

The findings of the referenced papers are eye-opening to say the least, and should be known and clearly understood by those who are designing, constructing or approving CQC/CQA programs for environmental containment facilities. As shown in **Figure 1,** the 1996 survey data indicate that 24% of damage occurs during geomembrane installation, 73% occurs when soil layers are placed on top of the geomembrane, and 2% occurs during the post construction phase. So, contrary to general perceptions, most damage is not caused by improper seaming. Of the damage that occurs during the initial stage of geomembrane installation, the survey data indicate that:

- 61% of the geomembrane leaks are on extrusion welds at "T" and "Y" joints and/or around pipe penetrations (**Photo 1**).
- 18% of the damage was caused by overheating and melt-throughs.
- 17% of the defects resulted from stones in the subgrade which punctured the geomembrane.
- 4% of the defects were caused by cuts in the geomembrane which were not noted or repaired during installation.

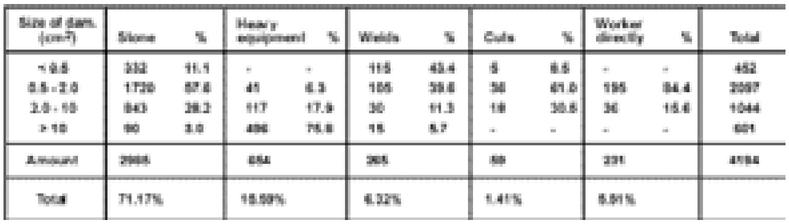
The information is even more alarming when one realizes that the current state-of-practice relies on extrusion welding to repair destructive seam test locations which are typically required to be cut from every 500 ft. of field seam made. Based on these data, designers should, at a minimum, strive to configure liner system designs which will minimize the need

Table 1: Locations, causes and frequency of holes.



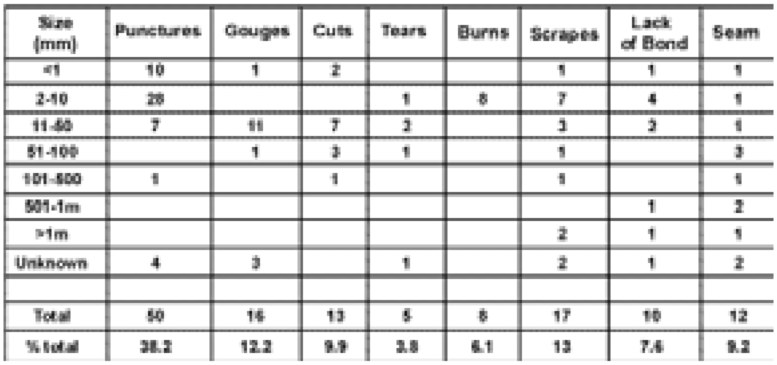
LOCATION	CAUSE	FREQ.	
FLAT FLOOR			78%
	STONES	81%	
	HEAVY EQUIPMENT	13%	
CORNER, EDGE			9%
	STONES	59%	
	HEAVY EQUIPMENT	19%	
	WELDS	18%	
UNDER PIPES			4%
	STONES	30%	
	WELDS	27%	
	HEAVY EQUIPMENT	14%	
	WORKER	15%	
	CUTS	14%	
PIPE PENETRATIONS			2%
	WELDS	91%	
	WORKER	8%	
	CUTS	1%	
ROAD, STORAGE STRUCTURE, ETC.			7%
	HEAVY EQUIPMENT	43%	
	STONES	21%	
	WORKER	19%	
	WELDS	17%	

Table 2: Size ranges of damage.



Size of dam. (cm²)	Stone	%	Heavy equipment	%	Welds	%	Cuts	%	Worker directly	%	Total
< 0.5	332	11.1	-	-	115	43.4	5	8.5	-	-	452
0.5 - 2.0	1720	57.6	41	6.3	105	39.6	36	61.0	195	84.4	2097
2.0 - 10	843	28.2	117	17.9	30	11.3	18	30.5	36	15.6	1044
> 10	90	3.0	496	75.8	15	5.7	-	-	-	-	601
Amount	2985		654		265		59		231		4194
Total	71.17%		15.59%		6.32%		1.41%		5.51%		

Table 3: Holes found in 640,000 m² (6,889,000 ft.²) uncovered liner.



Size (mm)	Punctures	Gouges	Cuts	Tears	Burns	Scrapes	Lack of Bond	Seam
<1	10	1	2			1	1	1
2-10	28			1	8	7	4	1
11-50	7	11	7	3		3	3	1
51-100		1	3	1		1		3
101-500	1		1			1		1
501-1m							1	2
>1m						2	1	1
Unknown	4	3		1		2	1	2
Total	50	16	13	5	8	17	10	12
% total	38.2	12.2	9.9	3.8	6.1	13	7.6	9.2

for extrusion welding. This also helps to strengthen the argument made by many that it is essential for us to strive to find an alternative way to measure seam strength nondestructively, such as the infrared thermography method proposed by Peggs et al. (1994).

The final stages of construction consist of placing the protective/drainage soil layers above the geomembrane. Typically, conventional CQC/CQA requirements regarding the geomembrane liner at this time cease. However, leak location technologies allow for the integrity of the geomembrane to be evaluated after the soil layer is placed. The 1996 leak location survey data indicate that during this stage of construction, as the protective or drainage soil layer is placed above the geomembrane, most of the damage (73%) occurs to the geomembrane. The forensic results of the survey data break down the causes of the damage during this phase of construction as follows:

- 68% of the damage is caused by sharp stones, unacceptable stone size, incorrect techniques of spreading the soil or gravel layer, or no geotextile cushion material being specified to protect the geomembrane.
- 16% of the damage can be attributed to heavy equipment used in spreading the soil or gravel materials on both flat and sloped surfaces. These damage locations often occur at wrinkle/wave locations caused by thermal expansion of the geomembrane and by improper cover soil spreading.
- 16% of the damage results from grade stakes used by the contractor to control the soil layer thickness.

Nosko et al. (1996) also analyzed the early part of the post-construction phase of the waste containment facilities' development. During this phase of facility development, the impacts to the geomembrane can be attributed to the initial placement of waste into the facility for disposal. Conventional CQC/CQA testing is no longer available during this phase of facility development, and typically the disposal facility's operation and maintenance manual will become the guiding document at this time. In New York State, due to the required double liner system and attention to primary (upper) liner system performance monitoring, it is possible to establish an assessment of continued liner system performance after the geomembrane liner has been covered and as the landfill moves into its early stages of operation. However, single-lined landfills have no means other than groundwater monitoring to assess geomembrane integrity after the geomembrane has been covered, unless a leak location assessment is conducted or leak location system is designed into the liner system. Data from the 1996 survey indicate that this stage of facility development is the least dangerous for the geomembrane. The data indicate that only 2% of the total geomembrane defects can be attributed to the post-construction phase. The break down of the causes of damage incurred during the post-construction time period are is follows:

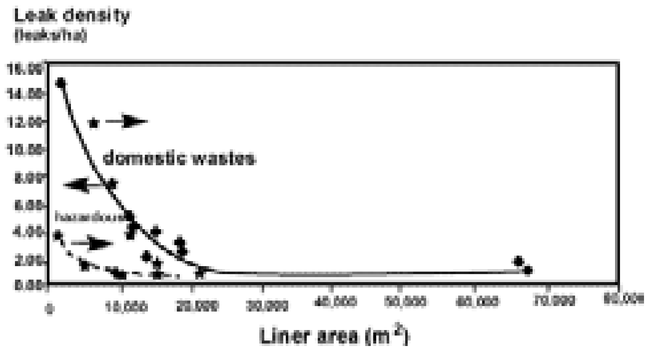
- 67% of the defects were a result from damage caused by trucks or other landfill equipment.
- 31% of the defects were attributed to on-site construction resulting from installation of pipes, drainage systems, sumps, and access roads.
- 2% of the damage was a result of adverse weather and other unplanned calamities, such as fires.

It is interesting to note that the survey data also included a number of test holes in the geomembranes which were made by the facility owners to qualify the leak location service. The survey data indicate that all test holes were located using the leak location technology. The data indicate that the test holes contributed to approximately 1% of the total damage detected in geomembranes.

In an update of these liner defect statistics, Nosko and Touze-Foltz (2000) focused more on the location and size of the defects found. This more recent summary shows, surprisingly, that the majority of the defects, 78%, were located on the lower flat surfaces of the liner, while only 9% were found at the corners and edges of the geomembrane **(Table 1).** This survey also reports that 4% of defects were found under drainage pipes and 2% at pipe penetrations. The balance, 7%, were found under haul roads, temporary material storage areas, and at concrete structures. On the floor, direct worker damage caused 4% of geomembrane defects.

Table 1 also shows the causes of these leaks. On the floor, at corners, and under drainage pipes, stone punctures were the predominant cause of the defects found, while heavy equipment damage provided the next highest number of defects found on the floor and at the corner locations. Welds were the second highest frequency of causes of defects under the drainage pipe locations. Inadequate (extrusion) welds contributed to 91% of defects found at pipe penetrations. On the floor and in the corner locations, inadequate welds were found to contribute to 20% and 33% of the defects found at these locations, respectively. Stones and heavy equipment generated most of the damage found under the haul roads, storage areas, and at concrete structures.

Figure 2: Leak distribution decreases as facility area increases.



Nosko and Touze-Foltz (2000) also characterized the sizes of the defects based on the cause of the defect. What they found (**Table 2**) was that the predominant size of stone-related damage is typically 0.5 to 2.0 cm^2 (0.0775 to 0.31 in.^{2}). Damage resulting from heavy equipment resulted in defects larger than 10 cm^2 (1.55 in^2). Defects which were caused by faulty welds were typically found to be under 0.5 cm^2 (0.0775 in.^{2}) in size, and defects caused from cuts or direct worker damage were found typically to be 0.5 to 2.0 cm^2 (0.0775 to 0.31 in.^{2}).

This information, for covered and uncovered liners, can be compared with leaks found by Peggs and McEuen (2001) in a 640,000 m^2 (6,889,000 ft.^{2}) uncovered liner as shown in **Table 3**. This leak distribution of 2 leaks/ha is in agreement with data generated by Rollin (1999), also for covered and uncovered liners. Rollin shows **(Figure 2)** leak distribution to decrease from about 15/ha to 2/ha as facility area increases beyond about 20,000 m^2 (215,300 ft.^{2}).

The consequences of performing an integrity survey on a newly constructed liner in a landfill cell are shown in **Figure 3**. This was one instance where a leak location survey was required when secondary leachate flow rates were on the order of 60 or 70 gpad (600 and 700 lphd). Upon some repairs being made after the integrity survey, the flow rate was reduced to 7 to 14 gpad (70 to 140 lphd) for precipitation events that had caused much larger rates prior to the repairs being made. Often it is difficult to reduce flow rates to below about 7 gpad (70 lphd), since activity on the liner, particularly an uncovered liner, can cause more damage than is resolved.

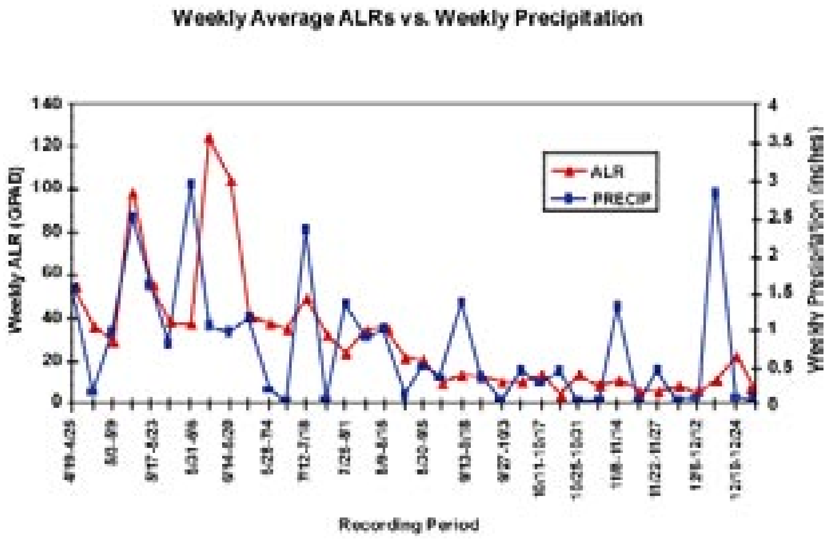
Hence, as a result of these electrical resistivity leak location surveys one can grasp a clear practical picture of the causes, the typical size, and the location of geomembrane defects typically incurred during the construction process.

What the data tell us

The data summarized above indicate that as much as 97% of all geomembrane defects are introduced during the landfill construction process. Thus, one might question the progress made over the years with better seaming equipment, testing methods, and construction procedures. The last item includes the selection of appropriate geomembrane protection systems and cover layer deployment procedures. Fortunately, liner performance and groundwater quality monitoring data indicate that modern landfills are protective of groundwater resources. However, the survey data presented above give us an idea as to where we should focus our efforts to minimize geomembrane installation defects.

With respect to the early phases of construction, the data reveal what many of

Figure 3: The consequences of an integrity survey on a new liner.



*Note: Major liner repair completed 8/11/00

us already realize—that extrusion welding, particularly at pipe penetrations, is more difficult to complete properly. Landfill designers should try to minimize, to the extent practical, the need for extrusion welding during construction. If extrusion welding is done, either spark testing (with a calibration test) or vacuum box testing should be carefully performed on 100% of all extrusion welded field seams, to ensure that they are defect-free. Even then, electrical methods identify leaks not found during vacuum boxtesting. This could be attributed to difficulty in performing vacuum box testing on irregularly shaped extrusion welds, where the vacuum box testing misses portions of the extrusion weld.

In one instance a survey was performed over a 1 acre (0.4 ha) area in the vicinity of the sump of a new MSW cell despite a leakage flow rate of less than 20 gpad (200 lphd) through the primary liner. A depth stake was found to be penetrating the primary geomembrane, but the underlying GCL was functioning properly to seal the leak. Thus, the electrical technology can locate liner damage that does not result in an active leak.

Perhaps the most striking conclusion from the compilation of leak location survey data is that, ironically, most of the construction-related defects are caused by placement of the protective/drainage soil materials on top of the geomembrane liner. Therefore, the CQC/CQA procedures and soil material specifications need to better address how we place protective or drainage soils on geomembranes in the field. Even in cases where cushion geotextiles are used to protect the geomembrane, the construction contractor still has to be aware that significant damage can occur if his equipment operators are not careful and if the geotextile is not adequately robust. Even in the flat areas of the landfill, waves in the geomembrane increase the potential for damage from earthmoving equipment placing soil layers. Therefore, the construction specifications should demand attention to proper wave management by the geomembrane installer. Grade stakes still persist as a common cause of geomembrane defects – survey crews need to be apprised of the concern for the geomembrane and/or use of laser grade controls needs to be specified in construction contracts.

The post-construction time period data indicated that geomembranes were damaged the least during this time. However, in an attempt to minimize geomembrane defects, landfill operators still need to caution their heavy equipment operators and those who use the landfill regarding the importance of minimizing liner system defects. Generally this will involve adherence to the facility's operation manual. Landfill operations have been referred to as "guerrilla activity" and consideration must be given to the frailties of a new liner system under operation of heavy equipment.

At present, leaks cannot be located in secondary liners once the primary geomembrane has been installed. Leaks on slopes cannot be found when there is only a geonet/geotextile composite between the primary and secondary liners—in this case there is not a required electrically conductive layer immediately below the geomembrane. When this situation occurs on the floor of a lining system, the composite layer can be backfilled with water to provide the conductive medium.

Conclusion

The use of summarized electrical resistivity leak location data allows us to take a focused proactive approach to improving upon the quality of environmental containment system construction. This focused approach should include the following considerations:

- Designers, specifiers and installers need to minimize extrusion welded seams. Consideration should be given to the configuration of necessary extrusion welds to ease non-destructive testing, especially in critical containment areas such as pipe penetrations.
- Specifications should call attention to the need for taking more care with extrusion bead stop/starts and at "T" junctions. These locations should also be the subject of careful non-destructive test-