The State of Electrical Leak Location: New technologies and improved methodologies

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Abstract. The introduction of installed geomembranes revolutionized containment system effectiveness for the protection of groundwater quality and water resources. After over six decades of installing geomembranes and evaluating their performance, it has become clear that simply specifying the use of a geomembrane is not enough. Even the addition of Construction Quality Assurance (CQA) is often not enough. In order to ensure that an installed geomembrane will perform in accordance with its design intent, it must be tested for leaks before operation and sometimes even during operation. Several decades after the introduction of geomembranes, Electrical Leak Location (ELL) methods were developed in order to locate leaks in them once installed. The methods have undergone many stages of evolution since their inception and continue to be improved today. This paper details where the technologies began and the current state of the practice as well as the currently available state of the art. Newly developed technologies from across the globe are presented in order to showcase cutting edge capabilities. The spectrum of methodologies used by various practitioners is also presented and detailed. This paper will assist designers and facility owners to choose the best ELL solution in order to ensure containment facility performance, which is critical to the sustainability of the modern world.

1 Introduction

ELL techniques were developed simultaneously in two different areas of the world. In the United States, the research was funded by the U.S. EPA [1]. At about the same time, they were also developed in Slovakia [2]. Methods were subsequently developed for covered (with soil and/or water) and bare geomembranes. All ELL methods depend on a sufficiently electrically isolative geomembrane over a sufficiently electrically conductive medium and utilize an applied voltage across the geomembrane in order to detect breaks in the resistivity of the geomembrane corresponding with leak locations. The various methods use different applied voltages and different measurement apparatuses.

Although a handful of standardized ASTM practices and guides have been developed, it is the belief of this author that these methods will never be strictly a science. There will always be some art to their application, in part due extreme differences in site conditions which necessitate novel methodological adjustments to uphold data acquisition quality. The

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development of the art of the methods should be welcomed, as it is through various attempts at method improvement that more robust methods are developed and existing methods improved. Some of these practices will never be standardized, since they may not be useful for all applications. This highlights the importance of the experience of the practitioner for the successful application of the methods, especially with challenging site conditions. The best ELL equipment available in the hands of an inexperienced practitioner can be completely ineffective. Conversely, rudimentary equipment can yield excellent results when applied properly.

The introduction of commercial equipment to inexperienced practitioners caused the industry to doubt the technology in many instances. In fact, a standard guide was developed for the intentional placement of leaks at locations unknown to practitioners in 2014 by a consulting engineer who wanted a means of checking survey quality (ASTM D7909, [3]). Although this sounds like a good idea on paper, creating intentional leaks can compromise survey quality and place unnecessary financial and practical burdens on projects. A better alternative is to utilize standards and specifications that provide a means of third party quality control such as ASTM D8265 [4], which will be discussed in the following sections.

1.1 History

The various aspects of ELL technology have been organized into the following categories: 1- equipment, 2- methods and 3- materials. These categories tend to feed into each other and their histories and evolutions are intertwined.

1.1.1 Equipment

In the past, all ELL equipment used commercially was internally developed and used for the sole use of a service provider. This is beginning to change. TRI Environmental, Inc. (TRI) was one of the first companies to develop equipment for commercial sale. The multifunctional kits were not meant for large-scale projects; they were meant to be sold to site owners who could use the equipment at intervals. The equipment was extremely simplistic in comparison with equipment used by most existing practitioners. However, it did provide a means for new practitioners to emerge. Equipment acquisition never caught on with site owners/operators. Existing consultants in the geosynthetics industry were acquiring the equipment and attempting to compete with the existing practitioners. These attempts largely failed, since at the time, TRI did not have staff with field experience who could help navigate the difficult site conditions that new practitioners inevitably faced. Although TRI did not have prior experience with the methods, it was Vice President Sam Allen’s belief that this service was so crucial to installed geomembrane quality that someone had to step up to help make this service more widely used, starting with commercially available equipment.

Vector Engineering, Inc. (Vector) of Grass Valley, California, USA partnered with Solmers of Quebec, Canada in to gain field training for ELL methods in 2003. After a two-year equipment use agreement with Solmers ended, Vector purchased the first equipment fabrication attempts of an independent mechatronic engineer named Jared Hamilton. In 2005, Vector won the contract for soil-covered ELL of an 850-acre reservoir. Hamilton developed equipment for this project that could not only rapidly acquire data, but also organize the data using GPS in order to create voltage maps of the survey area. This project resulted in the birth of the ten-foot double dipole system with GPS-based data acquisition that is still used today. Years later, TRI acquired the intellectual property rights to the equipment and began to offer this equipment for both sale and rental starting in 2012, with the addition of staff with field experience who could offer field training and consulting. Equipment prices became much higher than what was previously offered and sales and rentals were extremely spotty. TRI's legacy with ELL might have come to an end, but was reinvigorated when TRI staff was asked to perform ELL after several companies failed to find the source of leakage at a landfill cell leaking beyond the allowable level. TRI has been performing surveys ever since and halted sales after years of learning that even the best equipment in the hands of someone without significant experience is not the best way to serve the industry.

Sensor was probably the second company to sell commercial leak location equipment and they continue to do so today. Most notably, they developed arc testing technology in 1999 and brought it to a trade show in the United States in 2013 after over a decade of successful use in Europe. This resulted in the publication of the first arc testing method standard practice (ASTM D7953, [5]) in 2014.

1.1.2 Methods

The first standardized practice developed for ELL was the dipole method for soil and water-covered geomembranes (ASTM D7007, [6]) in 2003. This standard has largely remained unchanged since its first publication. It can be performed with extremely rudimentary equipment, which makes its use widespread among practitioners who have not invested in more advanced technology. This does not mean the method does not work; it is possible for an experienced practitioner to find all the leaks in a lining system when site conditions are good. However, there is no way for a third party to review the testing results adequately. Data recording is required for soil-covered surveys, but not for water-covered surveys. Water-covered surveys are performed quite differently than soil-covered surveys, since that method consists of a very simple methodology where an alarm is produced by the equipment when it passes over a leak. Since soil-covered equipment is not submerged in water where it can continuously monitor data to convert to an audible tone, data recording and subsequent data analysis is required for soil-covered only, per ASTM D7007.

The water puddle method (ASTM D7002, [7]) was also first published in 2003 and has basically remained unchanged since. All of the bare liner testing methods including water puddle, water lance (ASTM D7703, [8]), arc testing (ASTM D7953), and spark testing (ASTM D7240, [9]) consist of a similar technology as water-covered dipole method testing where an alarm is produced by the equipment when it passes over a leak. It would not make sense to include any sort of data measurement recording for this type of testing. However, oversight is simpler than with the dipole method, since the alarm can be heard by someone watching the testing being performed.

ASTM D8265 was born from two questions posed; 1- how can the effectiveness of ELL testing be reviewed by a third party in report format, and 2-how can ELL be used to ensure that no leaks remain in a lining system? This standard was first published in 2019 and has been informed and modified by research and field experience several times since its first publication.

1.1.3 Materials

GSE Environmental was the first manufacturer to produce a product specifically to enable ELL methods. In 1992 they developed conductive-backed geomembrane, which provided a conductive layer in intimate contact with the electrically insulative geomembrane. Soon after, they adapted Holiday Testing technology to their conductive-backed product and the spark testing method (ASTM D7240) was born. This product with the companion spark testing equipment allowed for installers to do a bare geomembrane ELL test. One remaining issue was that the product could not subsequently be tested using the dipole method, since the panel overlaps created isolation issues. In 2015, GSE launched their Leak Location Liner installation guidelines, which were patented in 2017. Using these installation guidelines, any method can be performed on the installed product.

The use of conductive geosynthetics is particularly useful for double-lined containment facilities where the leak detection layer does not consist of an electrically conductive medium. This is because successful testing of a geomembrane using ELL requires that the underlying layer be sufficiently electrically conductive. By specifying conductive-backed geomembrane as the primary geomembrane, the topmost geomembrane can be tested without filling the leak detection layer with water, enabling a bare geomembrane test. Since testing the primary geomembrane of a pond after filling using ELL is not always feasible or practical, conductive geosynthetics fill a crucial quality control niche.

2 Current Practices

Practices used throughout the world are largely dependent on the locally available technology and services, in addition to the testing support capabilities. For example, in water-scarce areas of the world, arc testing is preferred to water puddle testing for bare liner testing.

Currently, any bare geomembrane method may be applied to any bare liner project even if it is not the method specified, as long as a justification is provided and agreed upon (ASTM D7002, ASTM D7703, and ASTM D7953). However, bare liner testing can be just as nuanced as covered geomembrane testing and site-specific configurations can challenge a method’s limitations [10]. It is becoming more widely known that arc testing may not be effective on newly installed repair patches, so the water puddle method is generally preferred where it can be used. However, water-based methods are not as effective as high voltage-based method on extreme slopes (steeper than 3H:1V). If applied water cannot be retained inside of the testing area, then arc testing should be used. Currently, designers generally specify one method for an entire project without attention to project-specific geometry. Method advantages and limitations are discussed more thoroughly in the ASTM Standard Guide for Selection of Techniques for Electrical Leak Location of Leaks in Geomembranes (ASTM D6747, [11]).

Covered geomembrane testing is being performed by rudimentary equipment without data recording capabilities. This relies completely on the operator’s ability to recognize a leak signature in real-time. This is not compliant with ASTM D7007, but it is being done. In order to be in compliance with ASTM D7007 for soil-covered surveys, data must be recorded and analyzed post-survey. However, the data analysis method is not detailed and the data is not required to be provided as part of reporting. String lines are manually placed throughout the survey area as a guide and data is acquired by instrumentation with no specification regarding probe reactivity with the cover material. The author has witnessed dipole voltage measurements from a crudely built instrument being off by an order of magnitude when compared with measurements obtained through electrically isolated dipole probes. Manually organized data is being analyzed in graphical format, which is difficult to interpret and wildly subject to human error. Only the most egregious damage is likely being located using these rudimentary methods, which is still better than not having the method performed at all.

Covered geomembrane testing is also being performed using high precision GPS-based data acquisition and advanced instrumentation for both soil and water-covered survey areas. For some GPS-based technology, string lines are not necessary, since the equipment software can create a local coordinate system and guide the operator(s) along straight lines throughout the survey area. One requirement of ASTM D8265 is that the data acquisition locations be plotted on a voltage map, so that a reviewer can confirm that the entire survey area was covered. The voltage map also displays the noise of the data acquisition relative to a leak signal. Requiring a voltage map of the survey area as part of reporting requirements will automatically increase survey quality, as a responsible ELL contractor will strive for the collected data to be defensible. It also portrays a complete picture of the testing results, as a reviewer can quickly determine the effectiveness of the testing by how difficult or easy it is to spot a leak signature in the data set.

Permanent monitoring systems can be installed as part of facility construction in order to monitor the integrity of a containment system throughout the site life. A site owner can choose from many configurations, from more precise leak location(s) to a simple alarm that alerts the operator once a leak has developed somewhere. The most advanced systems can alert an operator via cell phone that a leak has developed in the lining system and report where the leak is (within a few meters). A mobile ELL method would still be required to get a more precise leak location. Additionally, mobile ELL methods are used during the construction of permanent monitoring systems in order to ensure that the systems go online starting with zero leaks.

3 New Technologies

The latest and greatest technologies are presented here using the previous three categories.

3.1 Equipment

As mentioned previously, data recording may not make sense for bare geomembrane surveys. However, a new technology has entered the market, which can track the movement of someone performing bare liner testing via GPS. This would at least show that the entire lined area has been traversed by the equipment operator.

Solmax, who acquired GSE Environmental, now offers an advanced spark tester that can be used with their Leak Location Liner product. The spark tester is constantly auto-calibrating so that leaks are successfully detected without excessive false positive alarms. The spark tester features a testing probe that conforms to the geomembrane surface to avoid the false negatives that can results from the testing probe being too far away from the geomembrane surface.

Automatic data collection rovers have emerged on the marketplace for both soil and water-covered surveys. Some of these data collectors are available to the public for use commercially. These systems have mostly not yet been publically evaluated for economy and data quality, though reported data collection speed is on par with current technologies. One exception is the rover for water-covered survey areas developed by Liquid Integrity Systems (LIS), which is not commercially available for purchase. GPS-based data is collected and analyzed by experienced geophysicists. A proprietary noise-cancelling technology is used to remove unwanted signal such as electrode drift or atmospheric noise to boost leak signals.

The 10-foot double dipole system with GPS-based data acquisition for soil-covered survey areas or water-covered survey areas that are shallow enough to wade through is currently the state-of-the-art. The speed, precision, and sensitivity of the data collected by this system cannot be matched by the automatic rovers that have newly emerged on the market. After nearly two decades of use, it has become clear that this system offers advantages beyond simply speed, sensitivity and accuracy. A proprietary data acquisition method developed by Jared Hamilton and currently owned by TRI uses the double dipole to create a voltage map not only in the direction of dipole travel, but also a second voltage map perpendicular to the direction of travel by using voltage measurements acquired across the front and back dipole feet, respectively. The detectability of any given leak will depend on the angle of the dipole. Typical dipole surveys are only performed using a single dipole angle, but the double dipole acquires data in two directions. A similar technology is used by LIS to map the "full field" field strength and direction rather than voltage measurements in only one direction, as their unmanned surface vehicle employs a similar double dipole configuration. Figure 1 shows an example of the parallel and perpendicular mapping technology used by TRI where a leak would likely have been missed had only a single dipole angle been used to acquire data.

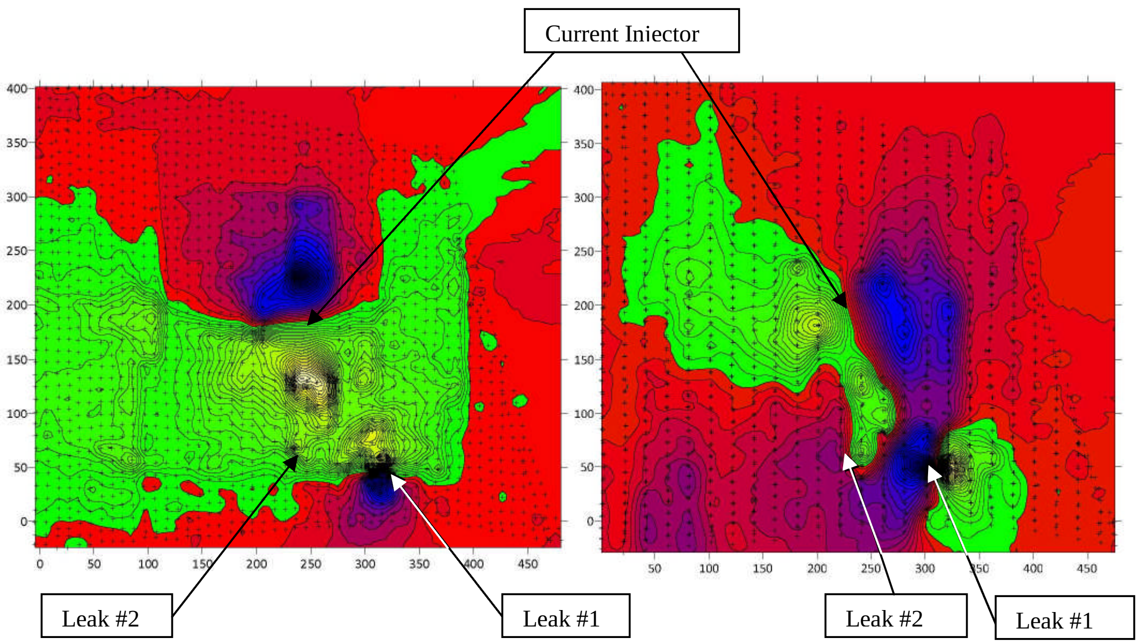
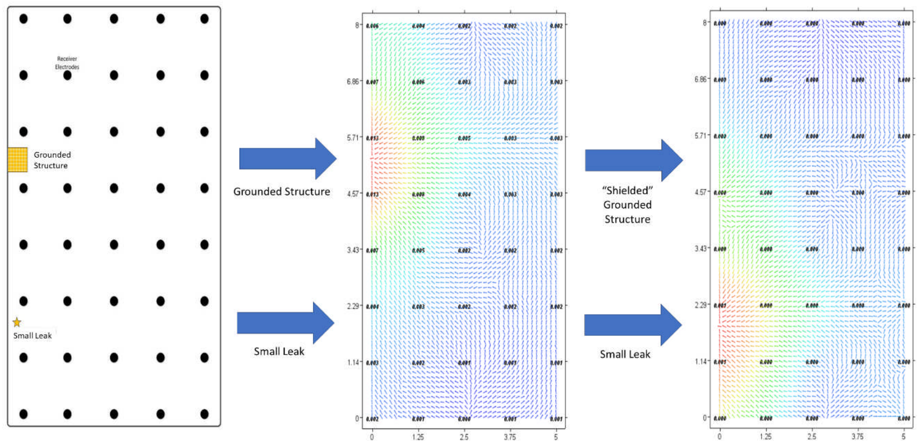


Fig. 1. Parallel (Left) and Perpendicular (Right) Voltage Maps.

3.2 Methods

ASTM D8265 was updated most recently to control data acquisition precision via GPS and currently serves as the most advanced state-of-the-practice for covered geomembrane testing. It should be noted, however, that the goal of the method is not only to standardize dipole method testing sensitivity and precision, but also to make the results of testing transparent to a third-party reviewer. As covered geomembrane testing effectiveness is highly dependent on site conditions [12], simply specifying this method does not guarantee an effective test. However, the effectiveness of the testing will become clear through the reporting requirements of ASTM D8265, which only reinforces the importance of hiring an experienced ELL testing company.

One of the largest drawbacks of covered geomembrane testing is the requirement for survey area isolation. A new proprietary technology has been developed by LIS, referred to as a "current shield", which can be placed at locations that cannot be successfully electrically isolated. This technology does have limits, however. It has been successfully used when the features causing the isolation issues are limited to discrete locations. The perimeter of the survey are still requires electrical isolation. One case of successful use is where the perimeter is isolated, but there is a ductile iron pipe or concrete penetration in place below the level of the water of a filled impoundment that cannot be electrically isolated. The current shield can be used reduce broad current leakage and hence strong signal from the pipe, allowing leaks signals to be detected.



Leak detection data collected adjacent grounded structure and small hole shown in left panel. Central panel data is dominated by grounded structure. Data on right is taken with current shield applied.

Fig. 2. Current Shield Technology (Figure Courtesy of LIS).

Filled pond testing has always been a challenge for testing precision using existing technologies such as a remote drag probe. Dipole method testing using a remote drag probe is inherently imprecise because the probe is towed back and forth across an impoundment and the location of the probe at the time of data acquisition is estimated by the length measured off on an attached cable. Many owners have been frustrated by not being successful at finding the locations of leaks causing signals measured by a drag probe. The unmanned surface vehicle developed by LIS can locate a leak precisely via GPS in lagoons up to approximately six meters deep. It can be used in conductivities up to five times that of seawater. Additionally, sonar can be deployed to measure sediment depths over the lining system. The LIS team has also developed a submarine that can be used inside of sealed impoundments such as lagoons with covers in place.

The quality of permanent monitoring system installation is variable, with the longevity of installed components in question for systems that are cheaper to install. Components that are highly resistive to corrosive environments are extremely expensive, putting more qualified permanent monitoring installers at a disadvantage to competitors. Since interest in these systems is increasing, a new ASTM standard practice is currently being developed in order to ensure that the systems will function effectively for the life of the site as well as uphold detection quality.

After nearly a decade of placing leaks in lining systems as a means of ELL quality control, ASTM D7909 has been revised so that the testing effectiveness can be checked before the test is applied rather than waiting for a blind leak to be detected or not and having that be a pass/fail criterion. Before beginning the test, the functionality test is performed on an actual leak (referred to as a "known leak") rather than an artificial leak in order to more accurately assess site conditions. If there is a problem with detection, there will be a chance to remedy the source of the problem before testing begins. However, if the problem is a larger leak in the survey area that needs to be found before sensitivity can be restored, this type of situation takes significant expertise to recognize and subsequently navigate.

3.3 Materials

Previously, the only conductive geosynthetic with a successful track record was conductive-backed geomembrane. Several companies manufacture this product, but only the Leak Location Liner product sold by Solmax can be installed in such a way to enable ELL methods other than spark testing. However, there are several companies who now offer electrically conductive products, from an electrically conductive paint that can be used on roofing materials, to conductive geotextiles which can also be attached to a geonet to form a geocomposite. It should be noted that these products may not be tested by the manufacturers using all of the available methods with their respective applied voltages and current carrying capacity requirements. With insufficient current carrying capacity, geosynthetics products can catch on fire. Extremely high levels of current are sometimes used for ELL surveys carried out in highly conductive mediums [13]. It is therefore next on the agenda for the industry to create standards around these products.

4 Conclusions

The proper and widespread application of ELL technologies is the next crucial step in improving groundwater protection from industries such as landfilling, mining, and wastewater treatment and storage. Poorly conducted ELL testing is a threat to the industry adoption of these technologies. As the use of this technology becomes more widespread, it is crucial to uphold survey quality by employing best practices and requiring testing results that can be reviewed by a third party. Along with this, persons performing oversight should learn how to interpret testing results. Practices such as creating blind leaks in lining systems should be used carefully with much forethought and should never be substituted for hiring an experienced ELL company with a solid track record for producing quality testing results and successfully locating leaks. The ELL industry has come a long way since its inception, from rudimentary equipment being used with little to no oversight to high precision instrumentation with voltage mapping capabilities. These types of innovations and improvements will continue as long as they are in demand.

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