Dipole Measurement Density and Dipole Spacing for Electrical Leak Location

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ABSTRACT

Electrical leak Location (ELL) methods are the most technologically advanced way to control leakage from containment facilities. The method used for locating the most significant damage, caused during cover material placement, is the dipole method. Measurement density and dipole spacing both have an effect on the sensitivity of the dipole method, with a higher measurement density and a larger dipole resulting in a more sensitive ELL survey. In order to quantify the benefit of an increase in measurement density and a larger dipole, field trials were conducted by the Author. A three-meter (ten-foot) dipole and a one-meter (three-foot) dipole, both commonly used instruments for dipole testing, were used to measure electrical signal strength at two different offsets from a simulated leak as outlined by both ASTM D7007-16 and ASTM D8265-20. The results of the measurements are presented in order to quantify the benefit of using a measurement density of 1.5 m (5') by 1.5 m (5') rather than 3 m (10') by 3m (10') and by using a 3-meter (10-foot) dipole rather than a one-meter (three-foot) dipole. The results also reveal a fundamental flaw in the standard D7007-16 in specifying measurement density without addressing dipole spacing and in using signal strength to define a leak detection distance. The testing details investigated herein can be used to improve existing standard methodologies and to craft project specifications that maximize both the sensitivity and efficiency of ELL surveys with the end result of locating more leaks more efficiently.

INTRODUCTION

Many variations of the dipole method are practiced, so engineers lean on standardized methodologies in order to ensure a properly applied test. However, there is much room for variability within the standardized methodologies. Significant factors in method sensitivity such as measurement density and dipole spacing are not adequately addressed in either of the standardized practices where the dipole method is used (ASTM D7007-16 and ASTM D8265-20). For that reason, the goal of this paper is to quantify the benefit of an increase in measurement density, reported to be beneficial by ASTM D7007-16 and an increase in dipole spacing, reported to be beneficial by Gilson and Ferreira (2020) and Lugli and Mahler (2016).

ASTM D7007-16 was the first standardized practice for the dipole method. The procedures require the application of measurements in a grid pattern at some spacing, referred to as the measurement density. The determination of the measurement density is controlled by the "leak detection distance". To determine the "leak detection distance", data are acquired along a transect at some offset from an actual or artificial leak. The magnitude of the signal generated by the leak is divided by the "background noise" of the survey area to obtain an "R" value. "Background noise" was defined as the magnitude of voltage oscillations without a leak nearby. The offset distance from the actual or artificial leak when the R value is equal to 3.0 is considered to be the "leak detection distance". The "R" value has previously been questioned for its scientific validity (Gilson-Beck and Ferreira, 2017). At the time ASTM D7007-16 was written, data analysis was performed by viewing graphs of the data along a transect, so presumably the goal was to require a signal that was significant enough to be viewed along said transect and a value of 3.0 times any sporadic background noise seemed reasonable to the original authors of the standard.

The evolution of data acquisition has led to GPS-based voltage maps, where leak signals generate three dimensional patterns on the mapping and a leak signal is easily visible with a very low magnitude signal simply by the characteristic pattern that a leak generates on the voltage map. Additionally, the Author has tested many sites where an artificial leak is barely visible or not visible at all and cannot generate a signal magnitude three times the background noise, but actual leaks are easily detectable. This could be due to the fact that the artificial leak is raised above the geomembrane surface where it is wettest when a site is properly prepared, but mainly because a voltage map can display the characteristic shape of a leak signal regardless of signal magnitude. Also, the signal to noise ratio can be manipulated by taking “noise” readings where they are lowest within the survey area. In some survey areas, there is a high level of background noise but leaks are still easily detectable due to their characteristic signal pattern (Gilson-Beck and Ferreira, 2017).

ASTM D8265-20, which was recently published to enhance covered geomembrane surveys and address the shortcomings of ASTM D7007-16, does not specify a measurement density. This standard simply requires that the artificial or actual leak be “detectable” using the chosen electrical method at the chosen measurement density and the practitioner must demonstrate the detectability on the requisite voltage map. ASTM D8265-20 does require the reporting of the dipole spacing and measurement density used for voltage mapping. This information is useful if, for example, a survey is done with a one meter dipole and a problematic leak is not found. The survey can subsequently be performed with enhanced leak detection sensitivity using a three meter dipole.

The Author commonly utilizes either a one-meter or a three-meter dipole, depending on the application. The one-meter dipole is typically only used when the survey area is too small for a three-meter dipole. When the Author uses a one-meter dipole, a measurement density of one meter by one meter is always used, since the leak detection distance is noticeably smaller with a one-meter dipole. At some sites, both dipole sizes were present and the Author noted that very small leaks were detectable with the three-meter dipole but not with the one-meter dipole. Dipoles larger than three meters are physically unwieldy, since it must be carried by the operator throughout the survey area and picked up and set down for each data point acquired. ASTM D7007-16 states that dipole spacing is typically 0.2 to 1 m for water-covered surveys and 0.5 to 3 m for soil-covered surveys.

It was Lugli and Mahler (2016) who first reported that the leak signal along a transect, from peak to peak, is directly proportional to the dipole spacing. The physical size of the leak signal, rather than the magnitude of the signal, was indicated by Lugli and Mahler as a criterion for determining measurement density. A 30% increase in signal strength and a 300% increase in peak-to-peak signal length was demonstrated by Lugli and Mahler when the dipole spacing was increased from one meter to three meters along a transect directly over a simulated leak.

The measurements produced by Lugli and Mahler were from a computer simulation model. This paper is the first publication known to the Author to obtain field measurements of a leak signal at several commonly used measurement density offsets for dipole method surveys. Both one and three meter dipoles are used for direct comparison of two different dipole measurement densities along transects of the same leak signal.

BACKGROUND

The physics of a leak signal propagating through soil material, how that signal is measured by a dipole method testing apparatus, and how dipole method voltage mapping is used in leak location surveys are described here in order to provide the fundamental background for understanding the results obtained by this study.

Applied Voltage. A DC voltage is applied across an installed geomembrane by inserting a current injector electrode into the cover material and inserting a current return electrode into the underlying conductive layer. Geomembranes are sufficiently electrically isolative that an intact geomembrane will restrict current flow, while current will readily flow through holes in the geomembrane, as long as those holes are electrically conductive (i.e. filled with water and/or soil). The current flowing through a leak will create a bull's eye pattern in the voltage field, with the eye centered on the leak. This is due to the series of voltage drops leading to the hole from all directions, similar to what the surface of water does when a drain is pulled, creating a funnel shape in the water surface, as shown in Figure 1.

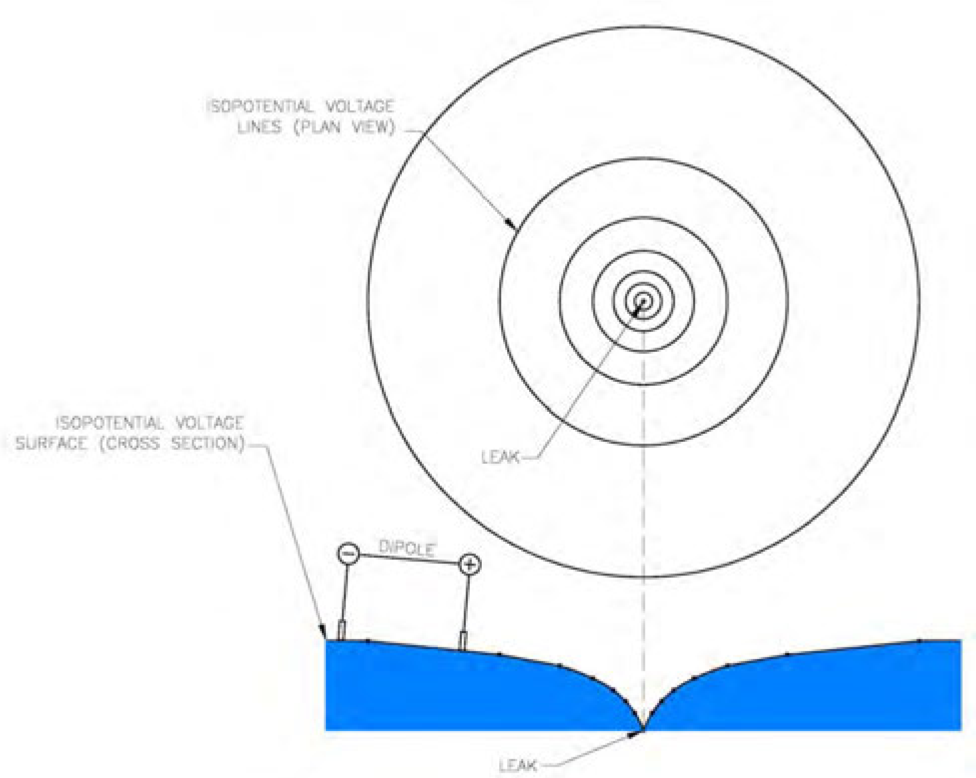


Figure 1. Water surface analogy of voltage field at leak location.

Dipole Method. The definition of the dipole method is the measurement of voltage across a surface using two closely spaced electrodes. The spacing of the electrodes is kept constant as the dipole travels across the surface. Therefore, the dipole is actually measuring the voltage gradient as opposed to absolute voltage potential. When approaching this bull's eye-shaped dip in the voltage field, and when measuring from front electrode to rear electrode, a drop in the voltage value will be measured, with the peak occurring when the front electrode is nearest the leak. The voltage value will then go to near zero when the dipole is straddling the leak, and then the voltage value will spike when the rear electrode is directly over the leak, as shown in Figure 2.

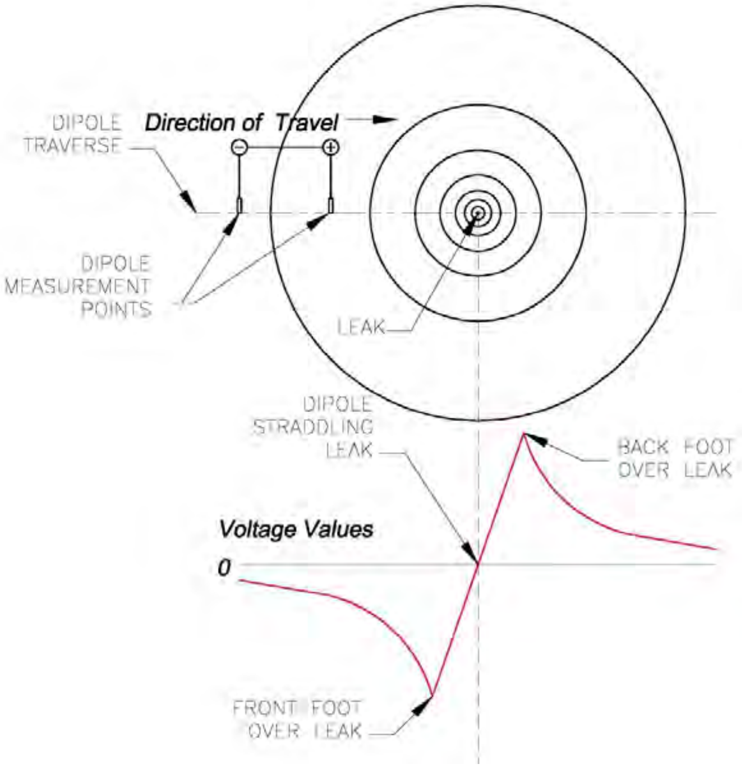


Figure 2. Leak signal traveling directly over a leak, as measured by a dipole.

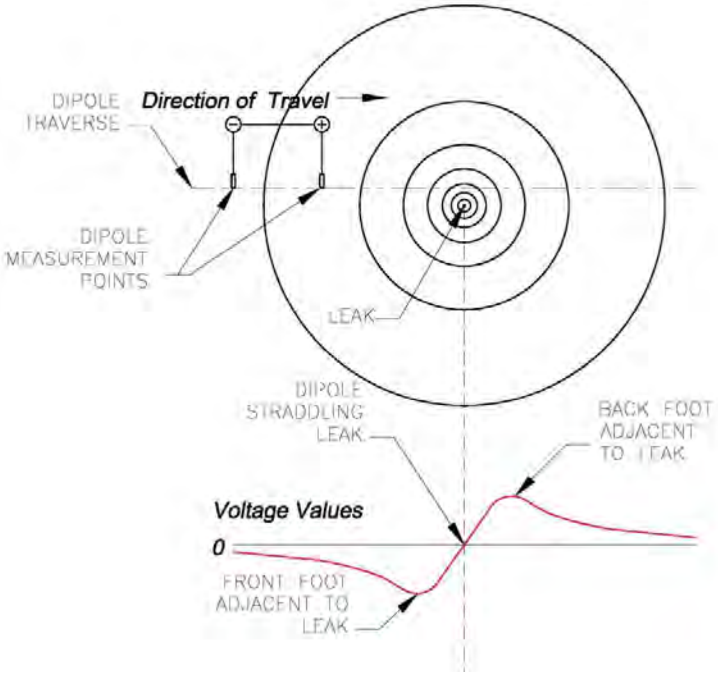


Figure 3. Leak signal at an offset from a leak, as measured by a dipole.

Leak Signal. The leak signal itself drops off logarithmically with distance from the leak as approximated by Figures 2 and 3. The magnitude of the signal as measured by the dipole will therefore also attenuate with increasing offset distance from the leak, as shown by Figure 3. A dipole with a larger spacing between measurement electrodes will result in a larger voltage differential measurement, since a larger dipole crosses more voltage contour lines. The voltage differential is what determines the detectability of a leak.

Dipole Method Voltage Mapping. A voltage map generated by the dipole method will look different than an isopotential voltage map (used to portray plan view leak signals in Figures 1-3). On a dipole method voltage map, the dip followed by a peak can be seen in two dimensions by a butterfly-like signature, as shown in Figure 4. Leak signatures feature a positive circular peak stacked directly on top of a negative peak, with closely spaced contour lines between the two peaks. The colors on the map represent voltage values in order to easily recognize a shift from positive to negative values. Negative values are represented by red changing to blue with increasing magnitude and positive values are represented by green changing to yellow with increasing magnitude. The negative/positive polarity of the entire survey area is created by the current injector electrode. The characteristic leak signal voltage pattern is opposite that of the current injector electrode, since current is exiting the survey area at current leakage locations and entering the survey area at the current injector location.

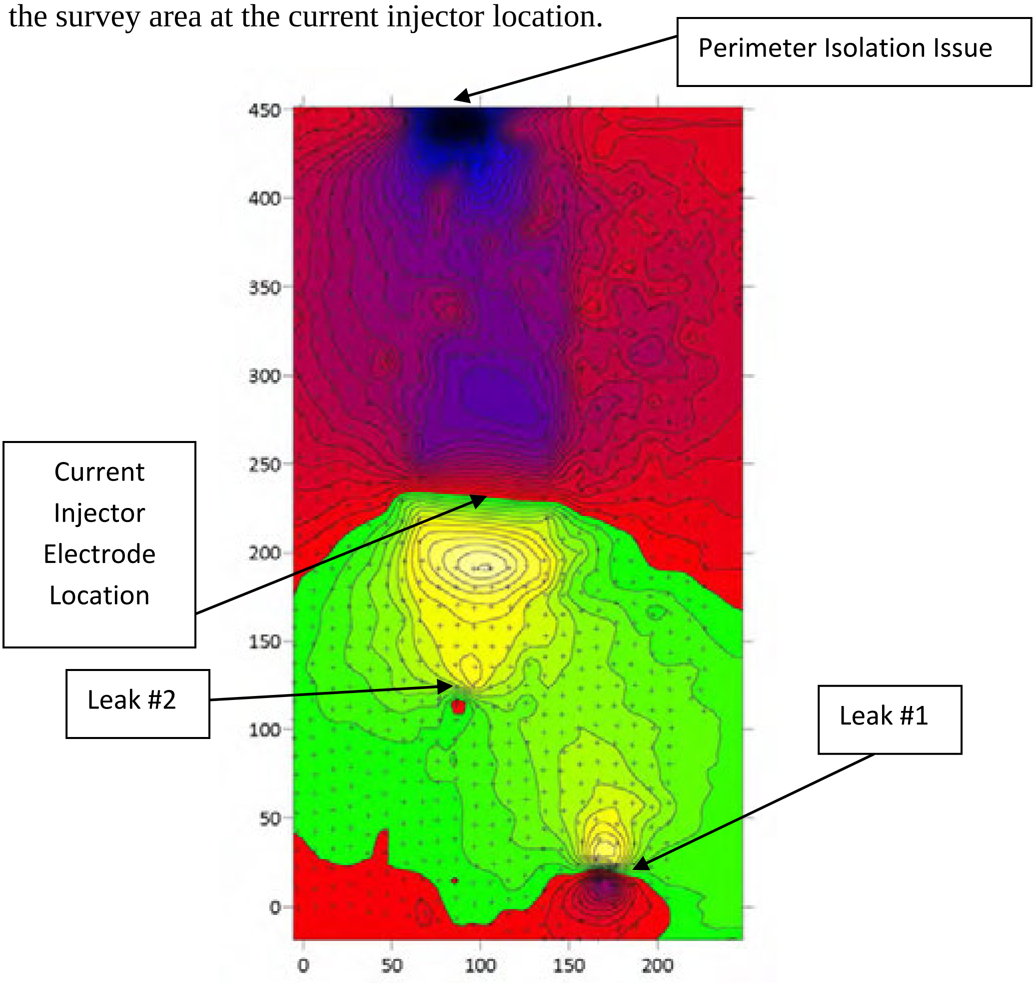


Figure 4. Voltage map created by dipole measurements.

TESTING SET UP

A DC voltage was introduced between two electrodes. The applied voltage value was adjusted in order to keep the dipole voltage meter from maxing out when the dipole was placed directly on the electrode used to simulate the leak signal. The same applied voltage was used for all trials.

Materials and Methods. A circular stainless steel electrode was inserted into a soil layer to simulate the signal generated by a leak. A stationary physical grid was laid out up to a distance of 7.6 meters from the electrode. Each dipole apparatus was spaced along the measurement lines so that each dipole would straddle the electrode at the closest measurement point to the electrode at the specified offset. A three meter dipole and a one meter dipole were used, each one using the same copper sulfate reference electrodes and voltage meter for measurements. For each dipole and offset, multiple readings were taken along the transect and the values were averaged to produce the values published here. For each dipole spacing, measurement densities of 1.5 x 1.5 meters and 3 x 3 meters were simulated using a 0.75 meter and 1.5 meter offset, respectively. One additional trial was done simulating a 1 x 1 meter measurement density using a one meter dipole.

RESULTS

Results are displayed both graphically and along transects that would be displayed as part of a dipole method voltage map with the same color coding method of voltage values used for Figure 4. The scales of the graphs for each measurement density are kept the same for comparison. The zero voltage line is shown in bold to show when the voltage values change from negative to positive, a key indicator of detectability. Values under the zero line correspond with the red/blue/black regions of the adjacent map and values above the zero line correspond with the green/yellow/white regions of the adjacent map. The contour interval for all of the color coded voltage maps is 0.005. The graphs more readily depict the signal strength (vertical distance between peaks in the voltage values), while the voltage maps more readily depict the leak detection distance. For the voltage maps, the leak is detectable as soon as a negative value is measured as the dipole approaches the leak (initially shown by red). The distance from the simulated leak to this color shift on the map is defined here as the “leak detection distance”. The dipole direction of travel is from bottom to top. The Y-axis of the voltage maps represent meters, with increasing Y-values representing distance from beginning of transect. The leak is located approximately at a Y-value of 7.6. The location of the leak is not exactly shown by the mapping, because when the dipole is straddling the leak it can be either slightly positive or slightly negative, since it is highly improbable to land exactly on a value of zero.

It is common for leak signals in the field to be lopsided, usually caused by the location of the current injector relative to the leak, since a stronger current density will be present on the side of the leak closest to the current injector. The data presented here shows that the leak is slightly more detectable in the “fore” rather than the “aft” side of the simulated leak. This tendency should not be viewed as testing error, but as a typical feature of field measurements.

The testing results presented in Figures 5 through 9 are also summarized in Table 1. A leak detection distance of greater than 7.6 meters means that the distance exceeded the limit of the testing area. The signal magnitude is the voltage differential, from peak to peak.

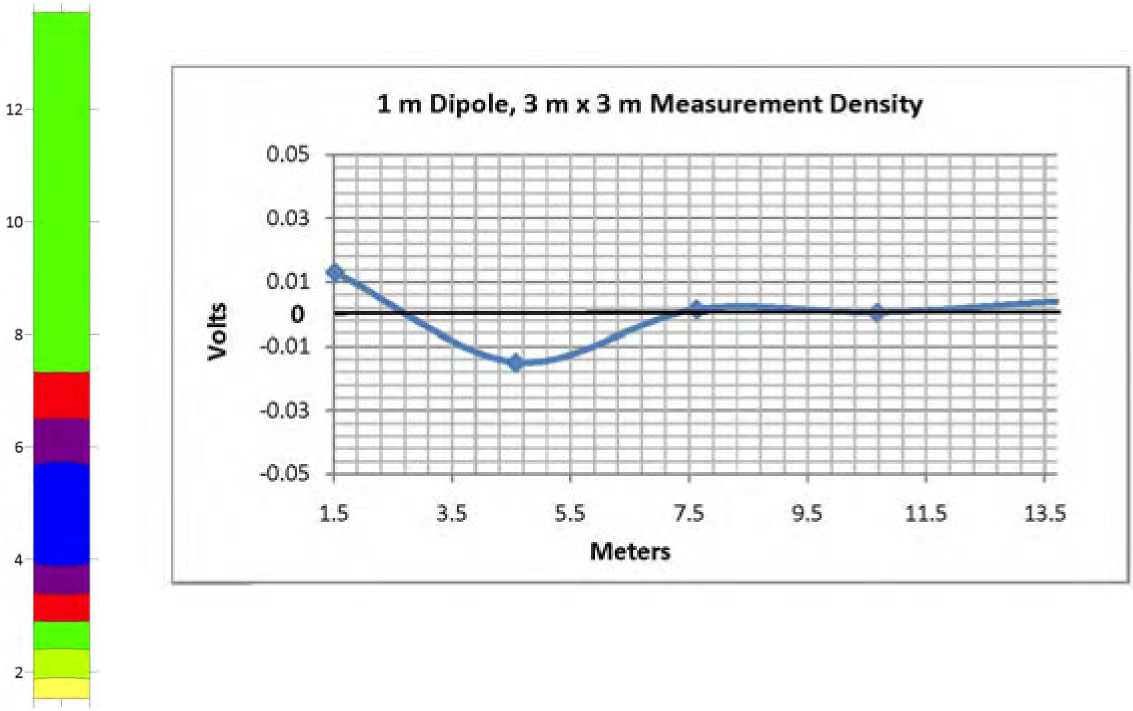


Figure 5. Signal detected by one meter dipole at 1.5 meter offset.

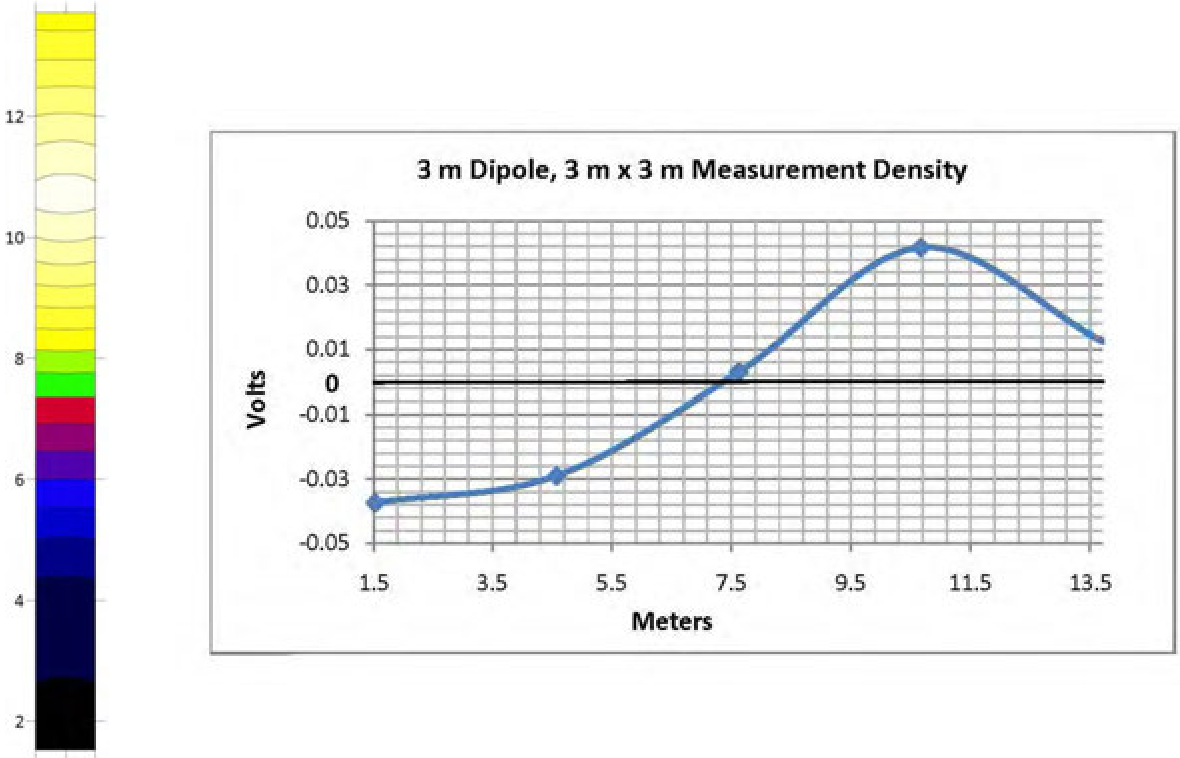
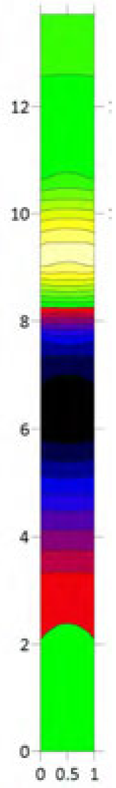


Figure 6. Signal detected by three meter dipole at 1.5 meter offset.



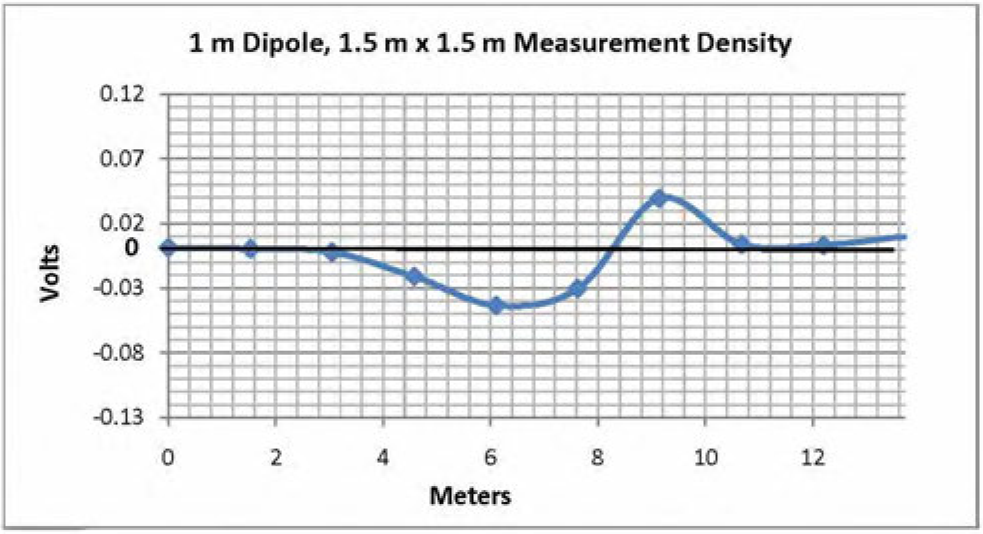
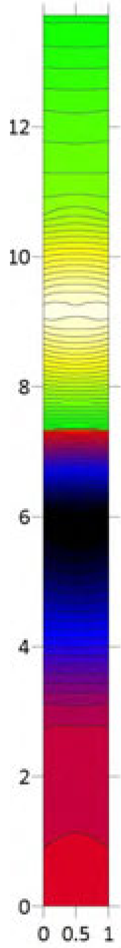


Figure 7. Signal detected by one meter dipole at 0.75 meter offset.



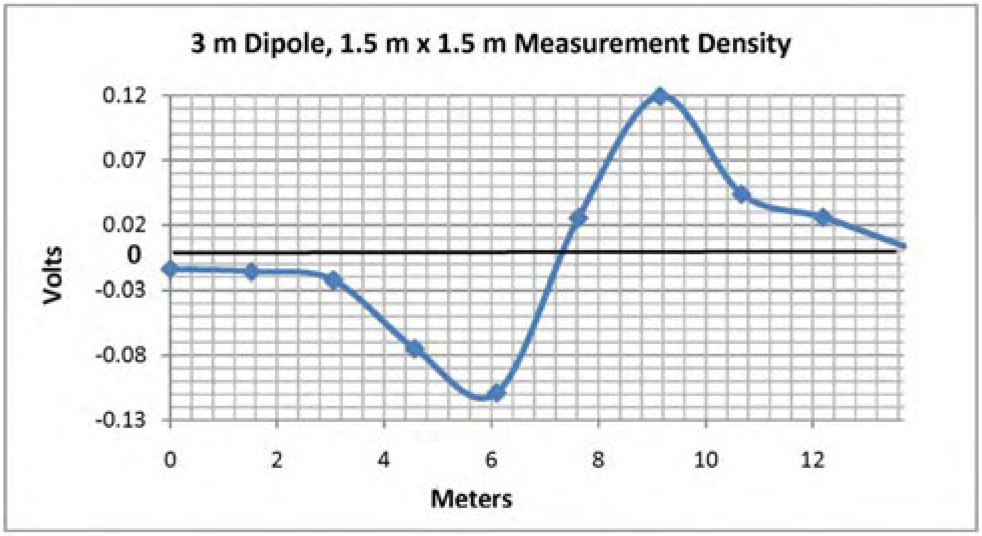


Figure 8. Signal detected by three meter dipole at 0.75 meter offset.

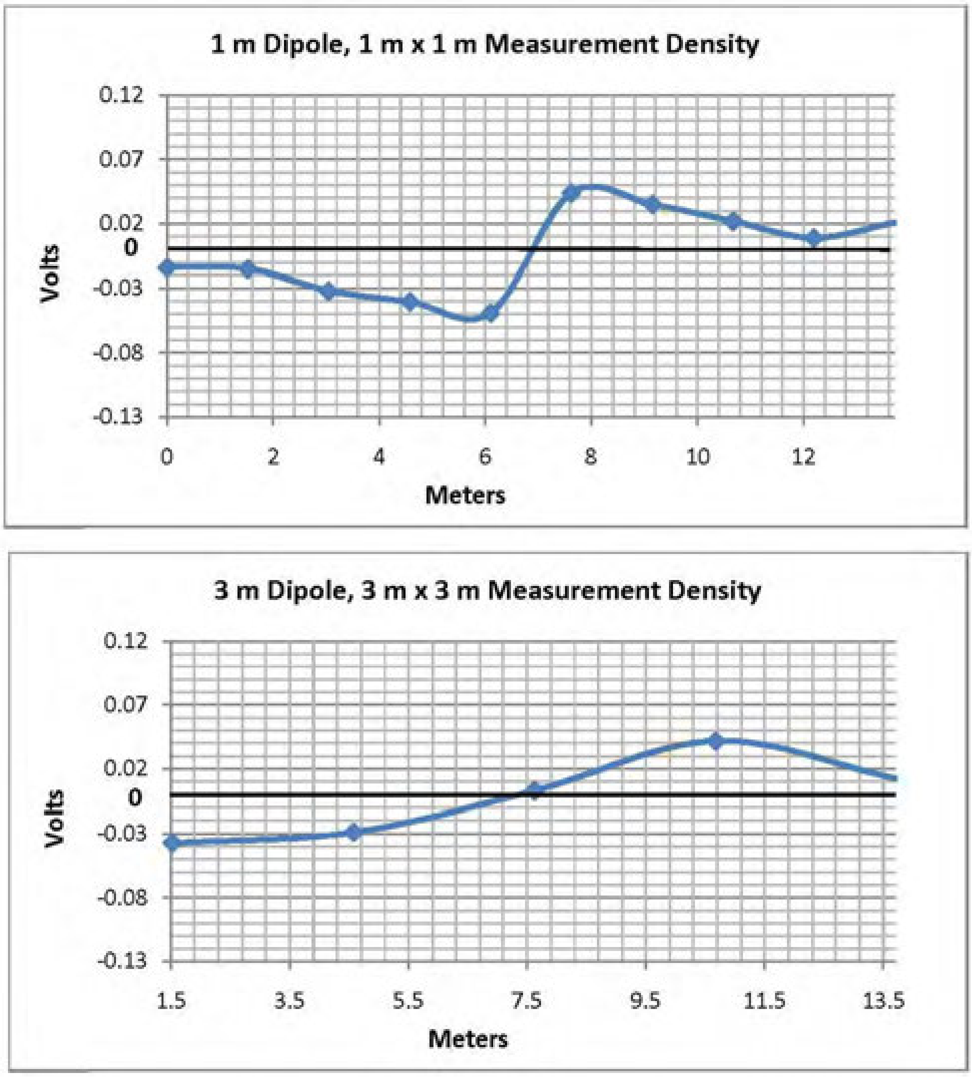


Figure 9. Comparison of signal detected by one meter dipole at 0.5 meter offset and signal detected by three meter dipole at 1.5 meter offset.

Trial	Description	Signal Magnitude	Leak Detection Distance
1	1 meter dipole, 1.5 meter offset	0.019 V	4.7 meters
2	3 meter dipole, 1.5 meter offset	0.079 V	>7.6 meters
3	1 meter dipole, 0.75 meter offset	0.083 V	5.2 meters
4	3 meter dipole, 0.75 meter offset	0.229 V	>7.6 meters
5	1 meter dipole, 0.5 meter offset	0.093 V	>7.6 meters

Table 1. Numerical Summary of Testing Results.

DISCUSSION

In order to quantify the benefit of a larger dipole spacing, trials 1-4 were analyzed. For a three meter by three meter measurement density, the three meter dipole increased the signal strength by 315% when compared to the signal measured by the one meter dipole. For a 1.5 meter by 1.5 meter measurement density, the three meter dipole increased the signal strength by 176% when compared to the signal measured by the one meter dipole. However, this does not capture the most important aspect of the testing, which is the leak detection distance. The only trial of the one meter dipole that approached the leak detection distance of the three meter dipole was the one meter by one meter measurement density (Trial 5). It is interesting to compare the one meter dipole at a one by one meter measurement density to the three meter dipole at a 3 meter by 3 meter density (Figure 9). The signal strengths are about the same, but the leak detection distance of the three meter dipole is larger, as determined by the Y-axis value on the far left side of the graphs.

Since the leak detection distance of the 3 meter dipole exceeded the testing area in every case, the benefit of increasing the measurement density can best be quantified by analyzing the one meter dipole trials. Increasing the measurement density of a one meter dipole from 3 meters by 3 meters to 1.5 meters by 1.5 meters, which quadruples the number of data points required, only increased the leak detection distance by 11%, even though the signal strength increased by 337%. In fact, with the larger offset, the peak to peak signal distance is larger. Lugli and Mahler argue that the peak to peak distance should determine the maximum offset between survey transects (i.e. measurement density). Even though an exact measurement for leak detection distance for the three meter dipole trials was not obtained, a comparison can be made by looking at the voltage value on the left side of the 3 meter dipole graphs at the same location along the transect. The increase in measurement density with the three meter dipole actually resulted in a faster attenuation of the signal, from a value of approximately -0.03 to -0.02 at the same location along the transect. This shows that there is no significant increase of leak detection distance with an increase in measurement density. In addition, these results show that it is inappropriate to determine a measurement density by using the signal strength along an offset distance, as prescribed by ASTM D7007-16.

Measurement density has been argued as a method of increasing sensitivity by practitioners of D7007-16, however those practitioners generally use one meter dipoles. There is certainly an increase in sensitivity when a one meter dipole changes from any measurement density other than one meter by one meter, which is the maximum prescribed by ASTM D7007-16. Practitioners using a three meter dipole have long been resistant to this claim, since excellent sensitivity is always achieved with a three meter dipole as long as site conditions are good. In fact, the Author has tested many problematic sites with a three meter dipole where the measurement density was increased in order to increase sensitivity and this method has only ended up costing owners more time and resources while not solving the problem (i.e. locating the hole(s)). It is also telling that ASTM D7007-16 prescribes a measurement density for water-covered areas of 0.4 meters by 0.4 meters when the artificial leak is not detectable (using 0.2-1 m dipole) and for soil-covered areas a measurement density of 1.0 meters by 1.0 meters when the artificial leak is not detectable (using a 0.5 – 3 m dipole). The tighter measurement density was likely prescribed for water-covered areas because the typical dipole testing apparatus was smaller, resulting in a smaller leak detection distance.

CONCLUSION

It is clear from the results that a larger dipole spacing enhances the leak signal and increases the leak detection distance. A one meter dipole, even when applying the maximum measurement density prescribed by ASTM D7007-16, cannot achieve the level of sensitivity of a three meter dipole at a three meter by three meter density. On a practical level, this means that surveying with a one meter dipole at this measurement density will take nine times as many measurements as the three meter dipole to get close to the same level of leak detection sensitivity. Nine times as many measurements results in a survey that takes nine times longer.

Part of the dysfunctionality of ASTM D7007-16 is that an ELL practitioner assumes a specific measurement density as part of the bidding and proposal stage of a project. A lump sum cost is given for that measurement density. If the measurement density must increase after the project is awarded, then a change order would have to be issued, which is not always allowed. In addition to the additional cost, the survey would take additional time. Construction schedules are very tight and every day is accounted for. A one day survey turning into nine days of surveying would be problematic for most projects. From a practical perspective, project specifications should therefore specify a three-meter dipole to get the best price for the least amount of survey time.

It may not be within the purview of a standardized methodology to specify dipole spacing, since there are some physical and technical constraints for this larger structure. For example, the dipole method is sometimes used in physically restrictive areas where a larger dipole would not physically fit. However, the methodologies can certainly specify that the measurement density should be determined by the dipole spacing, since this is the technically correct approach for maximizing the leak detection distance for a given dipole instrument.

Specifying a measurement density with a grid spacing less than the dipole spacing will not likely result in a higher quality survey, but will result in a more costly survey. Therefore, project specifications will get the biggest benefit, both from a technical perspective and economic perspective, by simply specifying a minimum dipole spacing of three meters wherever appropriate.

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