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Project Summary

Innovative Concepts for Detecting and Locating Leaks in Waste Impoundment Liner Systems: Acoustic Emission Monitoring and Time Domain Reflectometry

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A project was conducted to develop reliable, nondestructive methods for detecting leaks in lined waste impoundments before the leachate can seriously damage the ground water. A second goal was to find a technique to locate the precise area where a known leak is occurring. After a preliminary study involving a literature review, a state-of-the-art survey, and a ranking matrix exercise, two techniques were recommended for immediate further study — acoustic emission monitoring (AEM) and time domain reflectometry (TDR). AEM determines the amplitude and frequency responses of sounds emitted when water flows at different rates through soils. TDR is a high-frequency electromagnetic technique that measures the electrical properties of materials in and around the conductors of a transmission line.

Laboratory and field studies were undertaken to evaluate the potential of these two techniques. Results indicated that AEM potentially offers a practical and inexpensive technique for leak detection and monitoring in both existing and planned liquid waste impoundments.

TDR appears to be a practical method for detecting and determining the position and extent of a leak under a small waste impoundment liner. Further testing is needed to determine the usefulness of both techniques in the field, however.

This Project Summary was developed by EPA's Municipal Environmental Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Each year about 35 million metric tons of hazardous wastes are disposed of in impoundments lined with natural or manmade materials. The liners act as barriers to impede the flow of the hazardous wastes to the underlying ground water. But presently, little information exists on the effectiveness of the different liner materials, and monitoring methods are unsatisfactory. Ground water is presently monitored through wells placed hydrologically down stream. Thus wastes must actually be present in the ground water before they are detected, and significant damage may already have occurred. No methods currently exist that can detect the source of a leak in a liner before the leachate reaches the ground water.

The purpose of this project was to develop reliable, nondestructive methods for detecting significant leaks in lined waste impoundments before the leachate can seriously damage the ground water. A second goal was to find an economical technique that can locate the precise area where a known leak is occurring in the liner.

The first step in the project was to identify and evaluate a wide range of techniques for liner leak detection. A preliminary study was conducted for this purpose (M.J. Waller, J.L. Davis, and William Kean, 1981. "Assessment of Innovative Techniques to Detect Waste Impoundment Liner Failures," EPA-600/2-84-041, U.S. Environmental Protection Agency, Cincinnati, OH). After a thorough literature review, state-of-the-art survey, and ranking matrix exercise, this earlier study recommended two techniques for immediate further study — AEM and TDR. AEM determines the amplitude and frequency responses of sounds emitted when water flows at different rates through soils. TDR is a high-frequency electromagnetic technique that measures the electrical properties of materials in and around the conductors of a transmission line.

The present study was undertaken to perform laboratory and field studies to evaluate the potential of these two techniques for detecting leaks under waste impoundment liners.

Acoustic Emission Monitoring

AEM techniques have been used for at least 50 years to evaluate stresses in rocks and metals, but their application to soil structures is more recent. Acoustic emission (AE) techniques have shown potential use in earth stability monitoring, settlement and deformation monitoring, and water flow monitoring through earthen dams. To determine the potential application of AEM for detecting leaks from lined waste impoundments, experiments were conducted to measure the amplitude and frequency responses of sounds emitted when water flows at different rates through different soils and rips in a liner material.

Methods and Equipment

Experiments were carried out with three objectives: (1) to determine whether sounds are emitted when water flows through soils and rips in liners, (2) to characterize the sounds emitted when water flows through soils and rips in liners, and (3) to determine the attenuation of these sounds in water. Laboratory studies were conducted to fulfill the first two objectives, and field studies were carried out to achieve the third.

Soil Columns

The laboratory experiments for determining and characterizing sounds produced from water flowing through soils and rips in liners were conducted in soil columns held by a polyvinylchloride (PVC) duct 4 m long and 30 cm in diameter (Figure 1). Different heights of soils could be placed in the column and water could be passed through the soils at different known rates. Some soil column experiments were conducted using 30-mil PVC sheets with either 5- or 15-cm rips. A microphone was placed in the soil of the columns and the sounds were amplified, processed, and displayed. Special care was taken to reduce unwanted background noise. A spectrum analyzer capable of capturing transient events was used to process the data. The amplitude and frequency response of the output signal was displayed on an oscilloscope, recorded on a digital tape recorder, and plotted on an X-Y plotter.

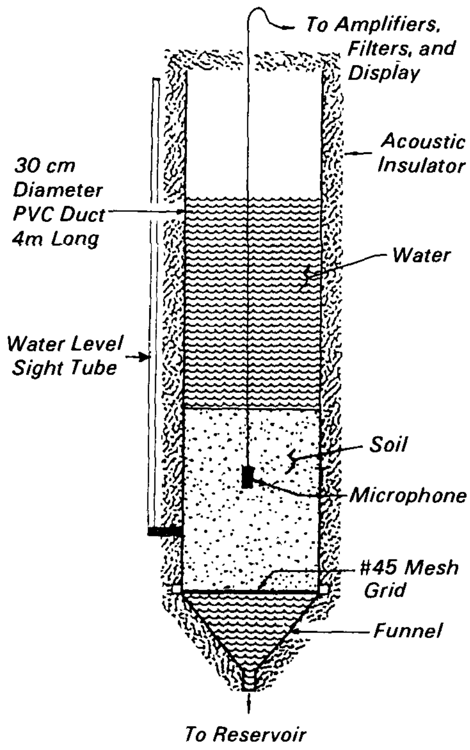

Figure 1. *Schematic diagram of the experimental acoustic emission test arrangement.*

Electronic Equipment

The electronic equipment used to detect, amplify, process, and display the acoustic data included an acoustic receiver (Figure 2), a Weston Acoustic Emission Monitor* with variable gain amplifier of 1 to 5000, a Weston AEM filter unit modified to cover a frequency range of 20 Hz to 5 KHz, a Nicolet 446B mini ubiquitous spectrum analyzer, an analogue X-Y plotter, a sweep oscillator, and a loudspeaker.

Measurement Procedure

The method generally used for laboratory measurements was to place the microphone in the soil being tested (as shown in Figure 1) and let the water flow through the soil. The height of the soil in the column varied from 70 to 150 cm. The microphone was placed 15 cm above the bottom of the soil column (i.e., above the 45-mesh screen). The flow rate and the acoustic spectra were measured, and the spectral data were plotted on the X-Y recorder. The water level was recorded on an X-time recorder. After about every 30- to 40-cm drop in water level, the flow was stopped and a spectrum of the background noise spectra was obtained and subtracted from the response obtained when the water was flowing through the soil.

Soils Tested

The soils used in these experiments were 20/30 Ottawa sand and a pea gravel, with an average grain size of 0.7 mm. The grain size of more than 90 percent of the pea gravel sample fell between 25 and 5 mm, with the remaining portion between 5 and 1 mm.

Water Levels

The water level varied from about 3 m above the soil to just above the soil in each of the experiments; thus falling water head levels occurred during the experiments. The flow rates typically were varied from 0.3 to 1 cm/sec.

Attenuation of Sound in Water

An audio frequency sweep oscillator working over a frequency range from 20 to 500 Hz was used to drive a loudspeaker specially designed to operate underwater. The standard AEM system used throughout these studies was used as the receiver. The AE sensor was moved away continuously from the loudspeaker at a depth of 1 m in a lake whose depth was 2 meters. The sound amplitude over the frequency spectrum was measured as the distance between the source and receiver was varied from 0.2 to 5 meters. The attenuation was measured at 10 dB/m over the frequency range of 100 to 500 Hz in the lake. It was observed that the attenuation of the sounds decreased significantly as the frequency was increased into the kilohertz range.

Results and Conclusions

1. Acoustic signals are emitted when water flows in a turbulent mode through soils. Acoustic signals at frequencies up to 500 Hz are emitted when water flows at rates of 0.3 to 1 cm/sec through a sand and a pea gravel.

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*Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

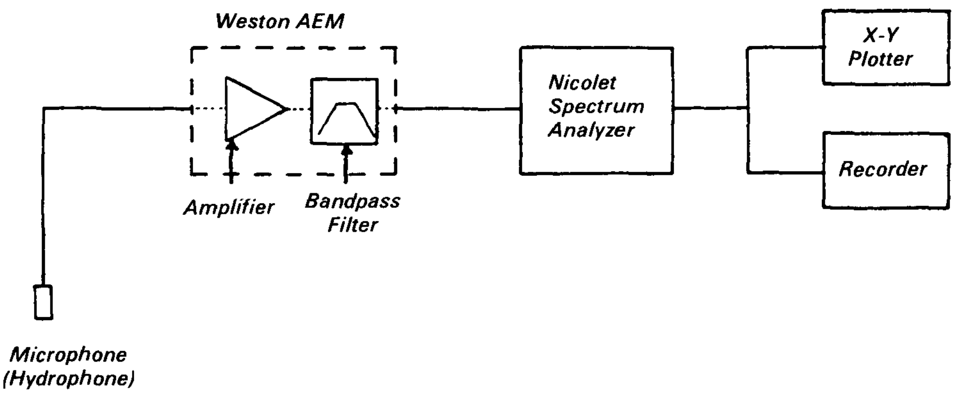

Figure 2. *A block diagram of the electronic equipment used to detect acoustic signals emitted when water flows through soils.*

2. The flow must be turbulent for acoustic signals to be emitted. Turbulent flow occurs at rates down to 0.1 cm/sec (1 gpm in the 30-cm-diameter test column) with the sands tested.
3. The amplitude of the sounds increases as the turbulent flow rate increases. For example, at a flow rate of 0.3 cm/sec (4 gpm through the 30-cm-diameter test column), the amplitude of acoustic signals through coarse-grained soils is about equal to the background noise likely to exist at liquid impoundment sites. But at an increased flow rate of 1 cm/sec (10 gpm in the 30-cm column), the amplitude is 100 times greater.
4. At a flow rate of 0.3 cm/sec, the sound amplitude increases with increasing variation in soil grain size.
5. At a flow rate of 0.3 cm/sec, the sound amplitude decreases with increasing soil density.
6. The sounds emitted when water flows through soils have significant amplitude at frequencies up to 500 Hz, and they have a peak amplitude between 100 and 200 Hz.
7. The attenuation of sounds between 100 and 500 Hz is 10 dB/m near the surface of a lake.
8. No significant sounds were detected when water flowed at rates up to 1 cm/sec through either a 5- or 15-cm rip in a 1-mm-thick PVC liner material.

Recommendations

1. Determine the spectral response for background sounds emitted at existing waste impoundment sites at frequencies up to 500 Hz.
2. Determine the attenuation of sounds at frequencies from 20 to 500 Hz in a typical waste impoundment site environment.
3. Determine the advantage of different arrays of acoustic sensors for detecting leaks at waste disposal sites.
4. Determine the spectral characteristics for acoustic signals emitted from leaks with known flow rates at a field model of a liquid impoundment site.
5. Determine the spectral response of sounds emitted when plastic liner materials creep.
6. Determine whether AE occurs when water flows through a silt or clay soil.

Time Domain Reflectometry

TDR is a wide-frequency bandwidth, short-pulse-length measurement technique that is sensitive to the high-frequency electrical properties of the material in and around conductors of a transmission line. The high-frequency (10^6 to 10^9 Hz) dielectric properties of water in its liquid state are about 20 times greater than the high-frequency dielectric properties of dry geologic materials: thus TDR is primarily sensitive to changes of water content in geologic materials and relatively insensitive to changes in soil type and density, temperature, and pore liquid salt content.* In materials with a relatively uniform water content, TDR is sensitive to changes of soil and rock type. This method is also sensitive to changes in the phase of the water molecule, and thus frozen or unfrozen wet soils. In addition, TDR can detect either water- or air-filled fractures and voids in the materials along the transmission line.

Leaks from liners of waste impoundments into the soil below are likely to have different electrical properties from those of the host material: thus TDR can measure leachates in the soil material along a transmission line. The TDR technique, using transmission lines placed under a liner offers the significant potential of being a practical method for detecting small leaks from waste dump sites.

The electrical measurements in soils are carried out by placing a transmission line consisting of two electrical conductors in the soils to be tested. Commercial high-frequency transmission line conductors are usually up to 1 cm apart, but it is intended to design and use transmission lines whose conductors are as far apart as possible — on the order of meters. Before a practical TDR system can be developed for detecting leaks under waste impoundment liners, tests are needed to determine the practical problems of increasing the spacing between the conductors.

The objective of this study was to determine the size of an anomaly (simulating a leachate) that could be detected as the spacing for the transmission line conductor was varied.

Background

TDR has been applied to measurements of geologic materials for fewer than 10 years, and therefore much of the work to date has been carried out to determine the practical applications and limitations of the technique. The main application of TDR for more than 30 years has been for testing transmission line cables such as those used in radio and telephone communications and in high-voltage transmission lines.

The electrical properties of geologic materials, especially soils, are very complicated at first glance. But over the frequency range we are interested in (10^6 to 10^9 Hz), the dielectric constant is primarily sensitive to changes in water content and has a relatively weak sensitivity to changes in soil type and density, temperature, and soluble salt content. TDR has shown excellent potential for carrying out useful electrical property measurements of geologic materials.

The TDR equipment is coupled to the geologic medium by a transmission line. A transverse electromagnetic (TEM) wave propagates along the transmission line in the dielectric material between and around the conductors, which act as guides for the waves. The propagation velocity and attenuation characteristics of the TDR signal in the transmission line are dependent on the electrical properties of the material in the transmission line.

Methods and Equipment

Experiments were first conducted in the laboratory to determine how the TDR signal pulse rise time response varied as the conductor spacing of the transmission line increased. Next, experiments were carried out to determine the physical size of the anomaly in the transmission line that could be detected by the TDR system as the conductor spacing was varied. Finally, tests were con-

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*Topp, G.C., J.L. Davis, and A.P. Annan, "Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines," Water Resources Research, Vol. 16, No. 3, June 1980.

ducted to determine the change of TDR response as the position of the anomaly was moved in the transmission line.

The equipment consisted of a TDR unit, an X-Y plotter, a parallel transmission line, an electrical connector to connect the TDR unit to the transmission line, and boxes filled with dry sand to simulate an anomaly. The TDR instrument used for these experiments was a Tektronics Model 1502 cable tester, a portable field unit with pulser, receiver, and display units in one package. The transmission line was a parallel wire transmission line. The two conductors of the line were made of 6-m-long aluminum tubes with a 5-cm outside diameter. These tubes were supported on a wooden frame so that the spacings between the tubes could be varied (10, 20, 40, 60, 80, 100, 120, 150, and 200 cm). A special electrical connector was designed and built to connect the TDR unit to the conductors at the different spacings. The connector consisted of a 50- to 200-ohm Balun transformer and two sheets of metal to connect the transformer to the aluminum tubes. Figure 3 is a schematic diagram of the TDR unit, the connector, and the parallel transmission line.

The anomalies that might be found in the field were simulated in the laboratory by boxes (15-cm^3) filled with dry sand and placed side by side and on top of each other when the size of the overall anomaly needed to be increased. The sand had a dielectric constant of 3.5. The boxes of sand were the equivalent of a water-saturated soil in a soil host material with a volumetric water content of about 20 percent. The electrical losses in the air and sand were negligible to the TDR pulse used. This arrangement provided a satisfactory initial model of an actual field setup under a waste impoundment liner.

Results and Conclusions

Findings of the project were as follows:

1. The TDR pulse signal rise time increases with the spacing between the conductors of a transmission line. The attenuation to the higher frequencies in the pulse increases with the frequency, and thus the TDR system resolution decreases as the spacing increases. In other words, the size of the anomaly in the transmission line must increase with the transmission line spacing to produce the same TDR-reflected signal amplitude.
2. The TDR signal amplitude does not vary when the TDR signal travel time in the anomaly is less than or equal to the total travel time necessary for the signal to propagate through the anomaly. As the electrical length of the anomaly decreases below the pulse travel time in the anomaly, the signal amplitude decreases.
3. The TDR signal amplitude varies slightly with the height of the anomaly (i.e., the dimension whose axis is perpendicular to the plane of the conductors in the transmission line varies as long as the height of the anomaly is at least three times greater than the diameter of the conductors).
4. The amplitude of the TDR signal is greatest when the anomaly touches both conductors of the transmission line. The signal amplitude decreases significantly as the width of the anomaly decreases relative to the spacing of the conductors. The signal amplitude decreases less rapidly if the anomaly is in contact with either of the conductors.

These findings lead to the conclusion that a cube-shaped anomaly whose sides are equal to at least half the spacing between the conductors will have a TDR signal amplitude of about one-fifth the maximum signal amplitude that would occur if the transmission line penetrated an anomaly that was very large relative to the spacing of the transmission line conductors. This generalization will be affected by a number of factors not included in the studies. The electrical loss properties of the materials likely to be found in the field will reduce the TDR signal amplitude. Thus the size of the anomaly will have to be increased to increase the reflected TDR signal amplitude. The electrical property contrast of the leachate-saturated soil relative to that of the host soil under the waste impoundment may not be as great as the electrical property contrast used in the model. Thus the reflected signal amplitude may not be as large in the waste site environment.

The model used in these experiments only tested the TDR response in transmission lines whose maximum spacing between the conductors was 2 m. Larger spacings between the conductors are practical using the same TDR unit, but experiments to determine the maximum spacing of the conductors still need to be carried out.

The TDR technique appears to be a practical method for detecting and determining the position and extent of a leachate under a small waste impoundment liner. A cube-shaped leak with dimensions on the order of one-half the space between the conductors of the transmission line is about the minimum practical size that can be detected using the TDR technique.

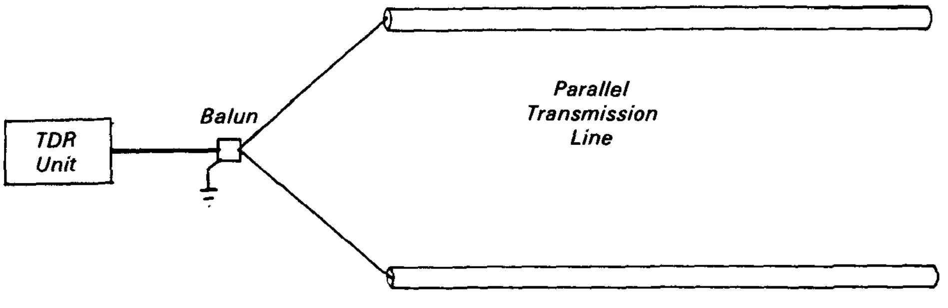

Figure 3. *Schematic diagram of the TDR system.*

Recommendations

The following recommendations should be followed before a TDR system is placed in the field under a waste impoundment liner:

1. Carry out experiments using simulated leaks over transmission lines at different conductor spacings placed in a sandy soil about 1 m thick.
2. Based on the results of the above experiments, design a series of transmission lines with different spacings between the conductors and placed in a sandy soil under a lined pond filled with water. Vary the lengths of the transmission lines up to about 30 m. Use controlled leaks in the liner to test the ability of the TDR system to detect leaks of different sizes and positions around the transmission lines.
3. Carry out a TDR system field design configuration and cost analysis after the above tests have been made.
4. Design TDR equipment specifically for detecting leaks at actual waste impoundment sites. Possibly a higher-power pulse of longer duration would make the TDR system more economical for detecting leaks at large waste impoundment sites.
5. Determine the best materials for transmission line conductors to minimize corrosion in a waste dump environment.
6. Determine the high-frequency (1 to 1000 MHz) electrical properties of some leachate-saturated soils and of soils typically found under waste sites.

The results of the recommended research will help define the usefulness of the TDR technique for detecting leaks and for determining the extent of leaks from a waste impoundment liner. Such studies will also aid in the design of a practical TDR system for monitoring leaks from waste dump sites.

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***Carlton Wiles** is the EPA Project Officer (see below).*

The complete report, entitled "Innovative Concepts for Detecting and Locating Leaks in Waste Impoundment Liner Systems: Acoustic Emission Monitoring and Time Domain Reflectometry," (Order No. PB 84-161 819; Cost: $13.00, subject to change) will be available only from:

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