LONG-TERM STABILITY OF TIME DOMAIN REFLECTOMETRY MEASUREMENTS IN A MULTI-YEAR FIELD EXPERIMENT

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ABSTRACT

Time Domain Reflectometry (TDR) measurements from a field demonstration of landfill covers at Los Alamos, New Mexico, USA were analyzed in an attempt to determine the long-term stability of the TDR system. The demonstration was comprised of four landfill cover designs: Conventional, EPA, Loam Capillary Barrier and Clay Loam Capillary Barrier with each design replicated at slopes of 5%, 10%, 15%, and 25% for a total of 16 plots. A total of 212 locations in the plots were instrumented with 2 rod TDR pairs and each location was interrogated at 7 hour intervals for seven years using an automated and multiplexed measurement system. The TDRs were located in a variety of soil types and at differing depths from the soil surface. Measurements from differing soil types were considered separately and seasonal changes in soil water content due to precipitation were minimized by annual averaging. Statistical and graphical analyses were performed to assess the stability of the measurements over the life of the demonstration.

INTRODUCTION

Federal and state regulations governing landfill closures specify long-term monitoring (30 years or more) of the performance of the landfill cover. Time Domain Reflectometry (TDR) measurements are a likely candidate for fulfilling this requirement since they are easily automated and a proven technology. Soil moisture content of the cover will be an important variable because it affects seepage through the cover to the waste and surface runoff. Regulators will request data that demonstrates the stability of the measurement technique over the long post closure monitoring period. Without such evidence, regulators are unlikely to accept a monitoring method. The objective of this presentation is to develop the basis for accepting TDR as a long-term monitoring technique for soil water content at Los Alamos.

Seven years of TDR measurements from a field experiment evaluating the performance of various landfill covers were analyzed in an attempt to identify any long-term degradation in performance by the TDR system. Data from 212 locations in the experimental design were taken at approximately 7-hour intervals from January 1992 through December 1998 at the Protective Barrier Landfill Cover Demonstration at Los Alamos National Laboratory, Los Alamos, New Mexico (Nyhan, et al., 1997).

The TDRs in this field experiment were installed at various depths and in different soil types for purposes of evaluating the landfill cover performance. For the purposes of this analysis the TDR data from differing soil types were segregated to identify performance effects caused by soil characteristics and because the environmental conditions presented to each soil type varied widely due to positioning in the cover profile.

An analysis of each TDR in a soil type was performed in which the mean annual soil water content was determined for each year to minimize seasonal water content fluctuations. The mean for each year was compared to the mean soil water content for all the years (Grand Mean). A preliminary analysis using the time stability concept proposed by Vauchaud, et al. 1985, was performed to compare TDR data from two different soil types.
MATERIALS AND METHODS

The purpose of the Protective Barrier Landfill Cover Demonstration was to monitor and compare water balance for the conventional landfill cover design, similar to that used in Los Alamos and the waste management industry for waste disposal, with that of three other designs containing engineered barriers. The performance of all four designs was evaluated at dominant downhill slopes of 5, 10, 15 and 25%, giving a total of 16 plots. Each of the 16 plots consist of 4 metal pans in the bottom for seepage collection overlain by layers of soil which vary in type and thickness depending on the cover design. The plot profiles are seen in Figures 1a through 1d and detail the soil type used for each layer and the layer’s thickness. The experiment used six different soil types in all. A full description of the plot construction has been previously provided by Nyhan, et al., (1994).

Volumetric water content was measured with a pair of stainless steel wave guides (60-cm long, 3-mm diam soil moisture probes; Campbell Scientific, Logan, UT) which are buried parallel and 5 cm apart in the soil. One set of wave guides was emplaced vertically in every soil layer above the bottom center of each metal pan in the seepage collection system; these wave guides allowed us to determine soil water inventory in four locations in each field plot. A second set of wave guides was emplaced horizontally in several soil layers to provide us with a more detailed picture of soil water dynamics close to the interfaces of certain key soil layers. Positioning of the TDRs in the cover profile are shown in Figures 1a through 1d. These figures are for the four different cover types with a 5% slope but are representative of the positioning in corresponding cover types with higher slopes.

Figure 1a. Plot profile of Conventional Cover Design

Figure 1b. Plot profile of EPA Cover Design
Each set of wave guides was connected to 4.6-m of shielded twin-lead antenna cable that was connected to a molded balun connected to a 26-m length of RG-8/U coaxial cable. An instrument trailer housed a 256-to-1 coaxial switch that connected one set of wave guides at a time to a TDR cable tester (model 1502B, Tektronix Inc., Beaverton, OR) through a system of 37 8-to-1 coaxial switches (model 610-007A, Autek Systems Corp., Santa Clara, CA). The computerized TDR system captured and stored the information from each pair of wave guides as a 220-point waveform (which represented an average of 16
waveform determinations). A personal computer (model 386-20, Compaq Computer Co., Austin TX) stored the waveform data on a hard disk, which was then used to determine the water content of the soils using the calibration described by Topp, et al., (1980).

**APPROACH**

The TDR data were segregated by soil type to see if any observable effects were related to a soil type and because each soil type experienced very different soil water content levels and fluctuations due to their physical location within the plots.

Two approaches were used for this analysis. In the first, data from each TDR was compared only to data from the same TDR for each of the years. Annual averaging of the measurements for each TDR was performed which contributed to smoothing variations from seasonal changes in soil water content. While year to year variations in soil water content will still have an effect on the annual means, the mean for any one year can be compared to the mean of all the years (Grand Mean). The comparison of the final year’s mean to the grand mean should be in the same range as the comparison of the other years means to the grand mean if there has been no appreciable degradation of the measurement system.

The first technique used thus becomes:

1. segregate TDR measurements by soil type
2. determine failure rate of TDRs in each soil type and overall failure rate
3. determine the annual mean for each TDR in a soil type for all years
4. compare each TDR annual mean for a particular year to the Grand mean.
5. compare annual means from year to year for each TDR to determine if the final year indicates any trend that is noticeably different from the other years. The final year of the experiment should be the strongest indicator of a system that is degrading over time.

The second approach is based on the time stability concept described by Vachaud, et al., (1985), in which the difference $\Delta_{ij}$ between individual determinations of soil water content $S_{ij}$ at location $i$ ($i=1-L$) at time $j$ ($j=1-2486$) and the mean soil water content $S_j$ at the same sampling time is calculated:

$$\Delta_{ij} = S_{ij} - \overline{S}_j$$

with

$$\overline{S}_j = (1/L) \sum_{i=1}^{i=L} S_{ij}$$

where

$L$= number of locations for a soil type

This corresponds to a relative difference:

$$Rd = ?_{ij}/\overline{S}_j$$

Our multiple daily measurements were averaged on a daily basis to provide a uniform sampling interval for this analysis. By determining the annual mean of these daily differences any large spread in the grouping around the mean should be apparent which would indicate that some of the TDRs are behaving abnormally. We employed this approach on two of the soil types. The medium sand was chosen because it was impacted very little by precipitation, and clay loam topsoil was chosen because it was used as a topsoil and experienced large fluctuations in water content.

**ANALYSIS**

The failure rate of the TDRs was determined for each soil type as well as for the experiment overall. Out of the 212 TDRs in the experiment 10 had failed by the time data collection had stopped, giving an overall failure rate of 4.7%. Table 1 shows
the total number of TDRs in each soil type and failure rates for each. There has been no post mortem performed to identify the exact failure mechanism.

Table 1. TDR Failure Rates By Soil Type

<table>
<thead>
<tr>
<th>SOIL TYPE</th>
<th>TOTAL</th>
<th>FAILED</th>
<th>FAILURE RATE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium Sand</td>
<td>16</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>64</td>
<td>2</td>
<td>3.1%</td>
</tr>
<tr>
<td>Tuff</td>
<td>32</td>
<td>3</td>
<td>9.4%</td>
</tr>
<tr>
<td>Clay Loam</td>
<td>16</td>
<td>1</td>
<td>6.3%</td>
</tr>
<tr>
<td>Loam</td>
<td>48</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Clay/Tuff</td>
<td>36</td>
<td>4</td>
<td>11.1%</td>
</tr>
</tbody>
</table>

Analyses were performed on five (medium sand, fine sand, tuff, clay loam, loam) of the six soil types in the experiment. The clay/tuff soil was not included due to this soil’s high electrical conductivity, which made soil water content determinations difficult. Regulatory requirements for long-term monitoring of covers with a clay layer of this type may require use of alternative monitoring technologies. Since the aim of our efforts is an attempt to determine stability it was decided to only consider data from soils that are good candidates for TDR measurements. Figures 2 through 6 show representative examples of soil water content over time for TDRs in each of the soil types. These plots demonstrate the wide range of soil water content regimes between soil types. Also plotted are the annual means and the grand mean for that probe. As the degradation of a system should be most apparent over longer periods of time it is instructive to compare the data from the last year of the experiment to data from earlier years. Time series plots for all the TDRs show no obvious differences for 1998 as compared to the other years.

Figure 2. Typical TDR in Medium Sand
Figure 3. Typical TDR in Fine Sand

Figure 4. Typical TDR in Tuff

Figure 5. Typical TDR in Clay Loam
The annual mean water content for every probe was calculated and plotted by soil type (Figures 7 through 11). Considering the spread of the data points for each year it is seen that the 1998 data falls within the range of the data from the earlier years. The medium sand layer (Figure 7) maintained very stable water contents for the length of the experiment. Response to precipitation can be seen in the time series plot for this probe (Figure 2) but the change in values were on the order of less than half of a per cent volumetric water content. While this change is certainly caused by precipitation it shows that if there is any trend to instability in the system it is not observable even on a water content scale this fine.
Figure 8. Fine Sand Annual Means By Probe

Figure 9. Tuff Annual Means By Probe

Figure 10. Clay Loam Annual Means By Probe
The mean relative difference calculation of the medium sand data, which is presented by year, is shown in Figure 12. While there is slightly more spread in the values around the mean in the 1998 data, the maximum mean relative difference for any of the TDRs is less than 4% and the 1998 data are not largely different than the previous years. The results of the same calculation of the clay loam data are shown in Figure 13. The spread around the mean is on the order of $\pm$ 15% reflecting the greater fluctuations in water content seen by these TDRs. However, the overall spread of the data around the mean is basically the same for all years.
CONCLUSIONS

Preliminary analysis of seven years of data from 212 TDR locations emplaced in various soil materials at Los Alamos showed no discernable evidence of drift in water content measurements. Changes in soil water content due to precipitation make an analysis of signal stability difficult. Even in a soil that has very little change in water content over long time periods and changes by only small increments, no discernable trend in the data could be identified. Comparing annual averages from year to year for each TDR showed no large difference in the final year of data compared to previous years which should have given an indication of overall signal drift. Also, comparing the relative mean difference of each TDR compared to all other TDRs at any one sampling time showed no evidence that there was a trend in the data from one year to the next. This leaves us with only two possible conclusions. Either there is no stability problem with this technology in the time frame involved in this experiment or any trend to instability is of such a small value that it was not evident even in our most stable
soil. The robustness of the TDR system is evident in the low failure rate we experienced over the seven years of data collection.

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REFERENCES


