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Analysis of Instantaneous Profile Test Data from Soils Near the Mixed Waste Landfill, Technical Area 3, Sandia National Laboratories/New Mexico

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Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-94AL85000

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Abstract

This paper presents the results of an instantaneous profile test conducted near the Mixed Waste Landfill at Sandia National Laboratories/New Mexico. The purpose of the test was to measure the unsaturated hydraulic properties of soils near the Mixed Waste Landfill, including the relations between hydraulic conductivity, moisture content, and soil water tension. A 4.7 meter by 4.7 meter plot was saturated with water to a depth of 2 meters, and the wetting and drying responses of the vertical profile were observed. These data were analyzed to obtain *in situ* measurements of the unsaturated hydraulic properties.

Acknowledgments

The authors wish to thank Jack Onsurez (GRAM, Inc.) and Stephen Bayliss (DanShar, Inc.) for assisting with the Time Domain Reflectometry (TDR) and collecting field measurements during the test; Randy Roberts (CDM-Federal Programs Center) for servicing the tensiometers and collecting field measurements; and Mike Fort (INTERA, Inc.) for automating the instrumentation. The authors also wish to thank Dr. Robert Knowlton (SNL/NM, Department 6603) and Jeff Havlena (Daniel B. Stephens & Associates) for their helpful suggestions on conducting the instantaneous profile test.

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Nomenclature

bgs	below ground surface
cm	centimeters
ft	feet
IP	instantaneous profile
$K(\theta)$	hydraulic conductivity as a function of moisture content
m	meters
MWL	Mixed Waste Landfill
PC	personal computer
SNL/NM	Sandia National Laboratories/New Mexico
TA-III	Technical Area 3
TDR	time domain reflectometry
θ	theta (volumetric moisture content)

Analysis of Instantaneous Profile Test Data from Soils Near the Mixed Waste Landfill, Technical Area 3, Sandia National Laboratories/New Mexico

1.0 Introduction

An instantaneous profile (IP) test was conducted on a field plot 150 meters (m) west of the Mixed Waste Landfill (MWL) at Sandia National Laboratories/New Mexico (SNL/NM) to measure the unsaturated hydraulic parameters of near-surface soils. The test was conducted as part of a RCRA Facility Investigation (RFI) of the MWL (SNL, 1993).

This paper presents the results of the IP test, including the relations between unsaturated hydraulic conductivity, volumetric moisture content, and soil water tension in soils near the MWL. The IP test data will be used to assess the potential for contaminant migration from the landfill through the vadose zone. The IP test methodology is discussed in Section 1.1.

Section 2.0 describes the MWL IP test, and presents graphs of the soil moisture tension and volumetric moisture content data collected during the test. Laboratory data from the field samples collected during this study will be published at a later date.

The IP test results are presented graphically in Section 3.0, and are summarized in Section 4.0. The implications of the IP test results concerning recharge in the vicinity of the MWL are also discussed in Section 4.0.

1.1 Background

The MWL is underlain by a vertically-extensive vadose zone, with groundwater nearly 140 meters (m) below ground surface (bgs). Consequently, most of the water movement (and potential contaminant migration) beneath the landfill occurs as unsaturated flow in the vadose zone. This unsaturated flow is controlled by the unsaturated hydraulic conductivities of the vadose zone.

The IP test was conducted near the MWL to obtain *in situ* field measurements of the unsaturated hydraulic conductivity relations and soil moisture characteristics of near-surface soils in the area. These field measurements of unsaturated hydraulic conductivity ($K(\theta)$) are essential for accurately characterizing unsaturated flow, including recharge to the aquifer; the migration of contaminants through the vadose zone, and the impacts of

rainfall infiltration and runoff. These data also provide information on soil structure and the effects of macroporosity.

The IP test could not be conducted at the MWL due to potential contamination in the soils; hence it was conducted approximately 150 m west of the MWL in the same type of soil.

IP Test Methodology

The IP test methodology was proposed by Richards and Weeks (1953), Ogata and Richards (1957), and Watson (1966) to measure the relation between soil water tension and hydraulic conductivity. The method is based upon saturating a vertical profile of soil, and then monitoring the transient drainage within that profile. The unsaturated hydraulic conductivity relations are determined for specific depths in the profile by simultaneously measuring soil water tensions and volumetric moisture contents at each depth. These data are then used to calculate the potential gradients and fluxes operating within the profile. Finally, a form of Richards equation is solved to obtain the unsaturated hydraulic conductivity as a function of soil water tension.

Although IP tests are time and labor intensive, they provide the most valid measurements of the $K(\theta)$ relationships (Marion et al., 1994). The IP test is considered the standard against which other methods are compared. Advantages of the IP test include the following:

- The IP test provides *in situ* measurements of the unsaturated hydraulic parameters, and is noninvasive; hence, it eliminates the disturbance of soil structure, and the resultant changes in soil hydraulic parameters due to invasive sampling.
- A relatively large volume of soil is sampled when measuring the parameters. For example, the MWL IP test was conducted on a test plot of approximately 44 m³. This reduces the variability of the measurements, and provides better estimates of the larger-scale hydraulic properties.
- The relations between saturated hydraulic conductivity, volumetric moisture content, and soil moisture tension can be measured simultaneously at multiple depths within the soil profile.

2.0 The MWL IP Test

This chapter describes the actual IP test conducted near the MWL, and presents graphs of the data collected during the test. Additional details of the IP test and complete tables of the moisture content and soil water tension data are presented in Bayliss et al. (1996).

2.1 MWL IP Test Description

The MWL IP test plot is located in an uncontaminated area approximately 150 meters west of the MWL in Technical Area III (Figure 1). The IP test consisted of flooding a 4.7 meter by 4.7 meter (15 ft by 15 ft) plot with 20,300 liters (5,494 gallons) of water over 47.3 hours, and monitoring movement of the wetting front and drainage from the test plot. Infiltration was limited to one-dimensional vertical flow using perimeter trenches filled with a 12 % bentonite/soil mixture. The trenches were 0.3 m (13 inches) wide and 2 m (6 ft) deep. A 30 cm (1 ft) high concrete berm was built around the perimeter of the test plot to allow water to be ponded during the test.

During the IP test, the wetting front and subsequent drainage were monitored using a neutron moisture meter, tensiometers, frequency domain probes, and time domain reflectometry (TDR) probes. Data collection was automated as much as possible to reduce costs and minimize errors.

2.2 Instrumentation

Figure 2 shows the instrument locations in the IP test plot. Three neutron access tubes were installed inside the test plot to a depth of 3 m (9 ft) each, and moisture contents were monitored with a CPN Model 503DR neutron moisture meter and a Sentry 200 Frequency Domain probe. Two additional neutron access tubes were installed outside the test plot to monitor potential leakage from the test plot, and to observe meteoric influences on the soil moisture profile.

Within the IP test plot, three instrument clusters (A, B, and C) containing six tensiometers and TDR probes each, were installed (Figure 2). Each instrument cluster contained pairs of tensiometers and TDR probes installed at depths of 30 cm, 60 cm, 90 cm, 120 cm, 150 cm, and 180 cm.

Figure 1. Instantaneous profile test plot location.

Figure 2. Instrument locations in the IP test plot.

2.3 IP Test Data

2.3.1 IP Test: Wetting Phase

The IP test plot was flooded with 20,300 liters (5,494 gallons) of water over 47.3 hrs., until the upper 2 m (6 ft) of soil were saturated. Flow to the test plot was monitored electronically using an EG&G Flow Technology meter with a magnetic induction pickup, and logged on a PC. Figure 3 shows the cumulative flow applied to the test plot, and Figure 4 shows head levels in the plot during the test. A constant head of 5.2 cm (2 in) was maintained in the center of the test plot until the upper 2 m (6 ft) of the soil profile reached field saturation, at which time flooding of the plot was discontinued.

Wetting Front Movement:

The wetting front moved relatively rapidly through the IP test plot, saturating the upper 2 m (6 ft) of soil within 1.5 days. Figure 5 shows the advance of the wetting front through the center and southeast corner of the test plot, measured with the neutron moisture meter. Each curve on the graphs represents the moisture content at a given depth. Time is shown as negative, because T_0 corresponds to the time when flooding was discontinued and drainage was initiated (December 16, 1993 at 10:00 AM).

As Figure 5 clearly indicates, the wetting front is initially sharp, and rapidly moves through the upper levels of the test plot, saturating (or nearly saturating) the upper 90 cm (3 ft) within a few hours. As hydrodynamic dispersion occurs, the wetting front spreads out, and the lower levels of the test plot saturate more slowly. The readings taken at depths of 210, 240, and 270 cm (7, 8, and 9 ft) were collected below the maximum depth of the perimeter trenches (filled with the bentonite/soil mixture) and are represented by dashed lines. The wetting front at these depths is more diffuse, due to both hydrodynamic dispersion and lateral flow.

Figure 6 shows changes in the vertical moisture profiles in the center and SE corner of the test plot as the wetting front moves downward. Each curve represents the moisture content profile at a specific time. At the start of the test, prior to flooding, the volumetric moisture contents averaged approximately 10 percent, as shown by the curves in the lower part of the graph. As the wetting front moved downward, the curves shifted to the upper part of the graph, representing wetter conditions.

Figure 3. Cumulative flow applied to the IP test plot.

Figure 4. Head levels during the flooding of the IP test plot.

Figure 5. Wetting front movement with time.

Figure 6. Wetting front movement with depth.

2.3.2 IP Test: Drainage Phase

Moisture Content:

Figure 7 presents the moisture content in the center and the southeast corner of the IP test plot during the first 400 days of the test. Each curve on the graph represents the moisture content at a given depth.

The graphs indicate that the moisture content throughout the vertical profile decreases rapidly at the start of the drainage phase of the test, but the rate of decrease tapers off after the first month. The rapid initial drainage reflects the greater hydraulic conductivities of the soil at saturated, or near-saturated, conditions. As the profile drains, the moisture content decreases and the unsaturated hydraulic conductivities (and resulting drainage rate) diminish. By January 1995, the average moisture content in the center of the test plot was decreasing by only one percent every 100 days.

As drainage from the IP test plot continued, the moisture content gradually decreased from the 30 to 35 percent range (field saturation) to the 15 to 20 percent range. Figure 8 shows this gradual shift in moisture content for the center, southeast corner, and southwest corner of the test plot, with each curve representing the vertical moisture content profile at a given time.

Several trends in Figure 8 are apparent:

- The shapes of the vertical moisture profiles are stable with time, and are gradually shifting to the drier (lower) region of the graphs.
- Most of the changes in moisture content occurred during the first 25 days of the test, with the greatest changes during the first five days. The lower graph on Figure 8 shows the minimal change in moisture contents that has occurred over the last 200 days (since the southwest access tube was installed). The SW access tube was installed four and 1/2 months after the start of the IP test.

Moisture content varies with depth and reflects variation in lithology. Two relatively wetter zones occur around depths of 120 cm and 210 cm. These zones of higher moisture content correspond to zones of finer-grained materials. Figure 9 shows the correlation between the laboratory-measured volumetric moisture content of samples, collected during installation of the southwest access tube, and the percent of soil fines passing the #200 sieve (the break between sand and silt/clay fractions).

Figure 7. Moisture content data over the duration of the IP test.

Figure 8. Vertical moisture content profiles.

Figure 9. Correlation between moisture content and lithology (SW Borehole).

Soil Moisture Tension:

Figures 10 and 11 present the first 50 days of soil moisture tension data at depths of 30, 60, 90, 120, 150, and 180 cm (1 ft through 6 ft). Tensiometer data were collected during the first year of the IP test, and the complete data set is presented in Bayliss et al. (1996).

The following observations can be made concerning the tensiometer data:

- At the start of the drainage phase of the IP test (after the test plot had been flooded for two days), soil moisture tensions at all depths, except 180 cm, were negative. These negative tensions are the equivalent of positive pressure, and indicate that the test plot had reached field saturation to a depth of at least 150 cm.
- Soil tensions at each depth increased rapidly during the first few days of the drainage phase of the IP test, as unsaturated conditions were reached. The rate of increase in tensions gradually leveled out as drainage from the test plot slowed.
- Diurnal fluctuations in tension were observed at each depth, particularly as the IP test progressed. These fluctuations are believed due to daily temperature changes, and increased in magnitude as seasonal temperatures increased.

The tensiometers were problematic, and some failed as the IP test progressed. For example, note that all three tensiometers completed at the 60 cm depth began to fail after the first two weeks of the test (Figure 10). These tensiometers were later replaced.

Figure 10. Soil moisture tensions at 30, 60, and 90 cm bgs.

Figure 11. Soil moisture tensions at 120, 150, and 180 cm bgs.

3.0 Results

This section presents the results of the IP test, including the unsaturated hydraulic conductivity data and the soil moisture characteristic data.

3.1. *Unsaturated Hydraulic Conductivity*

Soil moisture tension and volumetric moisture content data from the IP test were analyzed using the method discussed by Hillel et al. (1972) to determine the relations between $K(\theta)$ and volumetric moisture content (θ). These relations were calculated along 30 cm (1 ft) depth intervals from 30 cm to 180 cm bgs for both the center and the SE corner of the IP test plot.

Volumetric moisture content data from the center and SE corner neutron access tube (Figure 7) were paired with tensiometer data from Instrument Clusters A, B, and C (Figures 10 and 11) to calculate these relations. Data from days 1, 2, 4.83, 10, 12, 26, 29, and 195 were analyzed to obtain specific points on the $K(\theta)$ versus θ curves.

Hydraulic head profiles (Figure 12) were determined by adding soil water tension heads to elevation heads. The distinct change in slope of the hydraulic head profiles at the 120 cm depth is believed to be due to the variation in lithology at this depth (see Figure 9), and suggests that the finer-grained materials at this depth control vertical infiltration.

A unit gradient ($\delta H/\delta z = 1$) is plotted on Figure 12 as a dashed line. Although the hydraulic gradients throughout the vertical profile could have been approximated by a unit gradient to calculate the unsaturated hydraulic conductivities, the hydraulic gradients were instead determined graphically at each depth to more accurately calculate $K(\theta)$.

The resulting relations between hydraulic conductivity and volumetric moisture content for the center and southeast corner of the test plot are shown in Figure 13. The unsaturated hydraulic conductivity data measured from the IP test are summarized in Table 1.

Figure 12. Hydraulic head profile changes with time.

Figure 13. Unsaturated hydraulic conductivity as a function of moisture content.

Table 1. Unsaturated hydraulic conductivity data from the IP test.

Depth	CENTER		Depth	SE CORNER	
	K (Cm/S)	Theta (% Vol)		K (Cm/S)	Theta (% Vol)
15-45 cm	4.49E-05	24.67	15-45 cm	2.20E-05	24.94
	1.88E-05	22.96		4.52E-06	23.07
	7.02E-06	21.08		2.03E-06	22.02
	2.45E-06	19.49		1.15E-06	20.28
	5.98E-07	17.91		1.79E-07	19.06
	1.48E-07	15.70			
45-75 cm	1.18E-04	29.44	45-75 cm	5.80E-05	28.00
	4.68E-05	26.33		1.14E-05	25.97
	1.38E-05	23.80		4.60E-06	23.94
	6.30E-06	21.82		2.42E-06	22.49
	1.55E-06	19.86		4.92E-07	20.23
	2.28E-07	16.79			
75-105 cm	1.52E-04	33.93	75-105 cm	7.64E-05	30.87
	7.29E-05	31.07		1.72E-05	29.32
	1.89E-05	29.95		7.55E-06	26.78
	9.99E-06	27.70		4.26E-06	24.62
	2.28E-06	26.06		9.69E-07	21.94
	4.60E-07	22.40			
105-135 cm	6.51E-05	31.27	105-135 cm	2.13E-05	31.19
	3.85E-05	30.27		8.82E-06	31.26
	1.36E-05	29.30		3.26E-06	30.06
	7.06E-06	27.99		2.20E-06	29.12
	1.83E-06	26.50		6.68E-07	27.77
	9.41E-07	24.08			
135-165 cm	4.40E-05	28.34	135-165 cm	2.21E-05	28.70
	2.89E-05	26.91		9.88E-06	27.57
	1.17E-05	24.83		3.78E-06	26.46
	5.78E-06	24.75		2.52E-06	26.14
	1.93E-06	22.07		7.79E-07	23.67
	1.08E-06	19.72			
165-195 cm	5.76E-05	26.24	165-195 cm	2.66E-05	27.24
	3.10E-05	24.47		1.35E-05	24.45
	1.40E-05	22.37		4.74E-06	22.73
	6.62E-06	21.51		3.11E-06	21.17
	2.18E-06	19.26		9.41E-07	19.20
	1.15E-06	16.80			

The following observations can be made about the relations between unsaturated hydraulic conductivity and volumetric moisture content, shown in Figure 13:

- The unsaturated hydraulic conductivity is approximately log-normally proportional to the volumetric moisture content, within the range of moisture contents observed during the IP test. This relation is exponential, and can be described by the equation $K = ae^{\theta}$, where K is hydraulic conductivity, θ is volumetric moisture content, and a and b are empirical coefficients characterizing the soil (Hillel et. al, 1972).
- The field moisture contents measured during the IP test were limited to the range between saturation (30 to 35 percent by volume) and 15 percent by volume, due to the slow rate of drainage from the test plot. Hence, the unsaturated hydraulic conductivities could only be measured for this range of moisture contents. Nevertheless, unsaturated hydraulic conductivities varied by 3 orders of magnitude over this range (Figure 13).
- The unsaturated hydraulic conductivities vary by more than one order of magnitude between depths for a given moisture content. For example, Figure 13 shows that the hydraulic conductivity in the center of the test plot is significantly lower at the 75-105 cm and 105-135 cm depth intervals for a given moisture content.
- Lateral heterogeneities are also present. For example, the unsaturated hydraulic conductivities of the 75 to 105 cm depth interval are relatively lower in the center of the test plot than in the southeast corner of the test plot. Thus, hydraulic conductivities vary both laterally and vertically across the test plot.
- The variations in hydraulic conductivity reflect changes in soil texture. For instance, the soil textural profile in Figure 9 indicates that the 105 to 135 cm depth interval has a greater percentage of fines than the other depth intervals. Hence, it is not surprising that this depth interval has lower hydraulic conductivities than the other intervals.

3.2 Soil Moisture Characteristics

Soil moisture characteristics (soil water tension versus volumetric moisture content) were determined for each 30 cm depth interval at Instrument Clusters A, B, and C. The soil moisture characteristics were calculated by pairing simultaneous volumetric moisture content data (measured by TDR) with soil water tension data. The soil moisture characteristics were not determined for the 180 cm depths due to instrumentation problems at this depth.

Figure 14 presents the soil moisture characteristics measured at depths of 30, 60, 90, 120 and 150 cm bgs. Figure 15 presents a composite graph, showing all soil moisture characteristic data plotted on one graph. The labels correspond to instrument locations and depths, in ft. For example, "A2" corresponds to the tensiometer located in Instrument Cluster A, completed at a depth of 2 ft (60 cm).

The following observations can be made from the soil moisture characteristic plots:

- The field-measured soil moisture characteristics were limited to a tension range of between 0 and 400 cm, the tension range observed during the first year of the IP test. Soil moisture characteristics were measured for a much greater tension range in the laboratory (Strong et al., 1995).
- The soil moisture characteristics plotted in these figures represent *desorption* curves, rather than *sorption* curves, because these measurements were collected while the test plot was drying. Soil moisture characteristic curves during sorption (wetting) would show less tension at a given moisture content, due to hysteresis. Although tension and moisture content data were collected during the wetting phase of the IP test, the sorption curves could not be determined because the tensiometers were not equilibrated with the soils during the wetting phase of the IP test.
- The soil moisture characteristics demonstrate significant vertical and horizontal spatial variability, as indicated by Figure 15. Soil moisture tensions vary by up to several hundred cm for a given moisture content.

Figure 14. Soil moisture characteristics for 30, 60, 90, 120, and 150 cm bgs.

Figure 15. Soil moisture characteristics from all depths and locations within the IP plot.

4.0 Conclusions

The IP test conducted near the MWL provided high quality data on the relations between unsaturated hydraulic conductivity, volumetric moisture content, and soil moisture tension. These parameters were measured at multiple depth intervals in the upper 2 m of Madurez Fine Sandy Loam 150 m west of the MWL.

Results of the MWL IP test clearly demonstrate the influence of heterogeneities within the soil profile. The effects of these heterogeneities were observed both vertically and horizontally in the test plot.

The unsaturated hydraulic properties of soils determined from this test will be used for modeling unsaturated flow and contaminant transport from the MWL, and for reducing uncertainties in the risk assessment of the MWL. This information will better allow SNL/NM's MWL Environmental Restoration team to understand the potential for contaminant migration from the MWL to groundwater, and the resulting risk to human health and the environment.

Data from the IP test also provides information on natural recharge rates in the vicinity of the MWL. Although volumetric moisture contents in the soil profile are highly variable, they are generally in the 10% range below the zone of meteoric influence. Although hydraulic conductivities in this moisture range were not measured during the IP test, extrapolation of the existing unsaturated hydraulic conductivity curves suggest that hydraulic conductivities at the 10% moisture content will be in the 10^{-7} cm/s to 10^{-8} cm/s range. Assuming a unit gradient (a reasonable assumption below the zone of meteoric influence), natural recharge rates would be on the order of 10^{-7} to 10^{-8} cm/s. These extremely low values indicate that regional recharge in the vicinity of the MWL is negligible.

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