August 19, 2008

Note To: Eugene Peters

From: Randall Fedors /**RA/**

Subject: Soil Hydraulic Properties Measured During Site Visits to Yucca Mountain, Nevada

This intra-office note briefly describes the methodologies and summarizes the measurements completed to estimate in situ soil hydraulic properties on the ridges, hillslopes, and washes of Yucca Mountain near the potential repository footprint. Estimates are included for hydraulic conductivity and unsaturated zone parameters using sorptivity and the Gardner (1958) relation for effective conductivity. In addition, several measurements of drainage on bedrock with soil- or caliche-filled fractures are included.

The measurements were performed during three visits to Yucca Mountain in 1997 and 1998 by staff from the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC). The measurements were made during field visits by Randall Fedors (CNWRA, now at NRC), Stuart Stothoff (CNWRA), James Winterle (CNWRA), Dani Or (CNWRA contractor), and David Groeneveld (CNWRA contractor). The results are taken directly or derived from entries in CNWRA scientific notebooks 175, 217, 255, 432, and a trip report (Stothoff and Winterle, 1997). In addition, a compilation of observations from 10 site visits (Stothoff, 2008) includes descriptions of the three site visits of interest, including some of the hydraulic data presented here.

Different in situ techniques were used during the site visits. The different techniques for estimating soil hydraulic properties range from simple to complex. Results from the in situ measurements should be viewed with levels of confidence commensurate with the technical sophistication of the technique used for measurement. Simple ponding, Guelph permeameter, disk permeameter, and tension infiltrometer approaches were utilized. The first technique neglects the multi-dimensionality of flow and assumes steady state behavior was reached. The last several techniques, depending on the actual implementation, can account for the multi-dimensionality of flow, and can be used to estimate unsaturated zone properties. The generated data were intended to provide staff with site-specific information that could support conceptual models and provide preliminary information on hydraulic properties. Stated otherwise, the data are not intended to be used as the sole basis for direct inputs to net infiltration models or licensing decisions.

Most of the soil covering Yucca Mountain ridges and hillslopes appears to be relatively uniform texturally, as expected given its eolian origin. The soil can be classified as a silt or fine sand loam. Based on field observations, in situ development of soil profiles has generally not occurred on ridges and hillslopes, with the exception of buried erosional remnants of (apparent) Pleistocene soil found locally in protected pockets on the crest and ridgetops. Pleistocene soils also may occur at depth in thick colluvial or alluvial environments. The soils with in situ-developed profiles are believed to be Pleistocene age because chemical alteration rates of soils in the current Holocene semi-arid climate are slow, and the wetter climate in the Pleistocene promoted more rapid soil profile development. No in situ measurements were made on the small buried pockets of Pleistocene sediments. The percent rock fragments (size >2 mm [0.08 in.]) in the soil is one readily observable difference between locations. Another difference between locations is noted between hillslope and wash (channel) sediments, with the latter reflecting redistribution by fluvial processes. Colluvial processes are also evident in deposits at the toes of slopes. During site visits in 1997 and 1998, measurements were performed in a range of environments: (i) on the soil on ridges and hillslopes, (ii) on terrace deposits adjacent to channels, (iii) on alluvium in streambeds, (iv) on bedrock with soil-filled fractures, and (v) on soil at the bottom of a talus pile.

Coordinates are provided for many of the locations where tests were performed. For the coordinates listed in the scientific notebooks, hand-held global positioning system (GPS) units were used to collect location data in the Universal Transverse Mercator North American Datum 1927 (UTM NAD27) geographic coordinate system. At the time of the field visit, the satellite transmissions were still being scrambled, thus reducing accuracy. A differential GPS system was not utilized. For locations where GPS readings were not recorded in the field notebooks, and field descriptions were used to estimate coordinates at a later time, the coordinates should similarly be considered approximate. The accuracy of the coordinates is consistent with the intent of obtaining measurements for soils in different geomorphic environments. The particular wash or ridge, and the approximate location within that wash or ridge, are provided in all cases.

This Note is organized chronologically by visit, with a short description of the measurement methodology for each visit followed by a table of the results.

<u>March 26-28, 1997</u>

Measurements of flux rates from water injection test were performed at two areas during a site visit March 26-28, 1997: the alluvial sediments of Solitario Canyon, and the sediments near the crest of Yucca Mountain. Different equipment was used at the two areas, which is briefly described in the two subsections below. Information was recorded in scientific notebooks 175 (pages 16-24), 217 (pages 1-31), and 432 (volume VI pages 20-34). In addition, Stothoff and Winterle (1997) and Stothoff (2008) provide details of the site visit and summaries of the hydraulic conductivity estimates.

Alluvial Sediments in Solitario Canyon

A Guelph permeameter was used at 13 locations in stream beds of Solitario Canyon and side canyons to estimate hydraulic conductivity of alluvial sediments. The technique involves augering a small hole and recording the supply rate of water to needed maintain a set water height in the hole. The depths of augered holes ranged from 20 to 40 cm. Flux rate readings for two water depths (5 and 10 cm) were recorded at each site. The saturated hydraulic conductivity is estimated as (Soilmoisture Equipment Corporation, 1986)

$$K_s = 0.145\, R_2 + 0.191\, R_1 \qquad \textbf{Eqn (1)}$$

where R_1 and R_2 are the flux rates in the reservoir for the different steady water depths of 5 and 10 cm. The coefficients in Eqn(1) incorporate the shape factors accounting for injection shape and flow in the subsurface (Reynolds and Elrick, 1986), and a reservoir constant calibrated by the equipment manufacturer (Soilmoisture Equipment Corporation, 1986).

Table 1 lists the saturated hydraulic conductivity estimates at the 13 locations. Unsaturated zone parameters were not estimated. The data in Table 1 are taken from the trip report (Stothoff and Winterle, 1997), though the hydraulic conductivity estimates have been converted to units of cm/hr. It was noted in the trip report that augering was difficult due to the presence of large cobbles. Also noted in the trip report was the upper limit of the technique (approximately 10^{-2} cm/s [36 cm/hr]), which was exceeded in over half the sites.

Table 1. Results of Guelph Permeameter Measurement in Alluvial Sediments. Locations in UTM NAD27 Projection

Site	Easting, m	Northing, m	Hydraulic Conductivity (cm/hr)	Material Description
1	546,637	4,077,467	150	Silty coarse gravels with many large cobbles.
2	546,517	4,077,632	80	Coarse gravel with fine silty sand
3	546,794	4,077,389	240	Sandy coarse gravel
4	546,826	4,077,651	180	Well-sorted, pea-sized gravel
5	546,772	4,077,250	8	Silty, sandy gravel with large cobbles
6	546,667	4,077,103	24	Silty, sandy gravel with a few large cobbles
7	546,612	4,076,972	9	Silty coarse gravel
8	546,593	4,076,710	41	Sandy gravel with a few large cobbles
9	546,597	4,076,410	79	Sandy gravel
10	547,186	4,079,275	360	Coarse sand and gravel
11	547,135	4,078,848	140	Well-sorted pea-gravel with coarse sand
12	547,121	4,078,681	33	Well-sorted pea-gravel with coarse sand
13	547,021	4,078,283	7	Silty overbank sediments (stream channel is well sorted pea-gravel)

Hillslope and Ridge Sediments Near Yucca Mountain Crest

Disc permeameter and tension infiltrometer instruments were used on hillslope and crest soils to estimate hydraulic properties. The permeameter uses ponded conditions (head conditions slightly greater than zero). Whereas, the tension infiltrometer supplies water to the soil at tension (small negative values of head) that may exclude macropore flow, but would more directly lead to estimates of effective conductivity under unsaturated conditions. Temporal data of flux supplied to the soil was collected in both cases. The water supply area at the soil surface for both the permeameter and the infiltrometer was 314 cm^2; both had a 20-cm diameter base. Hydraulic conductivity, sorptivity, and the effective conductivity were estimated using the Gardner relation.

Relations accounting for the geometry of the apparatus and the dimensionality of water entering the soil from a circular supply area are needed to analyze the field data. Following the approach described in White, et al. (1988), the effective conductivity at some tension head is

$$K(h) = Q - \frac{4bS^2}{(\Delta\theta)\pi\, r_{base}} \qquad \textbf{Eqn (2)}$$

where h is the tension head, Q is some average flux at late times, $\Delta\theta$ is change in the water content, r_{base} is the radius of the permeameter base in contact with the soil, S is the sorptivity, and b is a shape factor that is taken as 0.55 in these analyses. The parameter b is constrained to a range of 1/2 to $\pi/4$, for which b=0.55 is representative (White and Sully, 1987). The value of 0.55 generally yields small errors and is therefore widely used (Everett, et al., 1999). For the ponded permeameter, h=0 cm, thus a saturated conductivity is obtained using the same equation above. Sorptivity reflects early time behavior of water entering the soils when capillarity is assumed to dominate gravity flow. Sorptivity is estimated as the slope of the early-time cumulative infiltration (I) data as a function of the square root of time (t) following White, et al. (1988)

$$S = \frac{I(t)}{\sqrt{t}} \qquad \textbf{Eqn (3)}$$

The Gardner equation (Gardner, 1958) for effective conductivity is

$$K(h) = K_s \exp(\alpha h) \qquad \textbf{Eqn (4)}$$

The coefficient α, also known as the sorptive length parameter, in the Gardner relation is calculated as (White, et al., 1988)

$$\alpha = \frac{\Delta\theta \, \Delta K}{b S^2} \qquad \textbf{Eqn (5)}$$

where ΔK is the change in conductivity during the test. For the analysis of the field data, the average porosity was taken as 0.42 and initial water content as 0.02. No site-specific data were collected, but these values are reasonable for the conditions at Yucca Mountain. These values for porosity and initial water content lead to a near-surface change in water content of $\Delta\theta$=0.4 m^3 m^{-3} during the infiltration process. For the change in conductivity, $\Delta K = K(h) - K_{initial}$, note that $K_{initial}$ is negligible compared to K_s or $K(h)$; thus $\Delta K \cong K(h)$ in Equation 5.

Table 2 summarizes the 10 measurements performed on soils near the southern extent of the potential repository footprint on the broad slope of Yucca Mountain crest and an adjacent hillslope.

Table 2. Hydraulic Properties of Soils for Yucca Mountain Crest and Hillslopes

<table>
<tr><th>Site</th><th>Location: Easting and Northing UTM NAD27, and Description</th><th>K(h) cm/hr</th><th>K_s cm/hr</th><th>Gardner α, cm-1</th><th>Sorptivity, cm/s1/2</th><th>Condtions</th></tr>
<tr><td rowspan="4">1</td><td rowspan="4">547,665 m and 4,074,905 m; Yucca Mountain (YM) crest south of potential repository footprint [a]</td><td>-</td><td>17.5</td><td>0.167</td><td>0.145</td><td>Ponded</td></tr>
<tr><td>-</td><td>10.5</td><td>0.371</td><td>0.076</td><td>Ponded</td></tr>
<tr><td>2.5</td><td>-</td><td>0.293</td><td rowspan="2">0.058</td><td>Tension, h=-10 cm</td></tr>
<tr><td>0.6</td><td>-</td><td>0.146</td><td>Tension, h=-4.5 cm</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">547,477 m and 4,074,256 m; YM crest, south of footprint [b]</td><td>-</td><td>4.3</td><td>0.149</td><td>0.077</td><td>Ponded</td></tr>
<tr><td>3.6</td><td>-</td><td>0.074</td><td>0.099</td><td>Tension, h=-11 cm</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">547,649 m and 4,074,367 m; YM crest, south of footprint [c]</td><td>-</td><td>16.2</td><td>0.246</td><td>0.115</td><td>Ponded</td></tr>
<tr><td>-</td><td>14.2</td><td>0.331</td><td>0.093</td><td>Ponded</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">Side slope 30 m off Highway Ridge Road</td><td>-</td><td>22.3</td><td>-</td><td>-</td><td>Ponded</td></tr>
<tr><td>-</td><td>17.6</td><td>-</td><td>-</td><td>Ponded</td></tr>
</table>

a. Site 1 approximately 310 m north-northeast of Borehole G-3
b. Site 2 approximately 365 m south-southeast of Borehole G-3
c. Site 3 was approximately 15 m north-northeast of Borehole UZ-N62

Stothoff (2008) provided a range for the saturated hydraulic conductivity results from the ponded permeameter tests. He noted the range was 1.2×10^{-3} to 4.9×10^{-3} cm/s [4.3 to 17.6 cm/hr], but that the lowest measurement came from a site where post-test excavation revealed a large rock fragment directly below the injection surface.

June 5-9, 1997

Hydraulic Properties of Soil in Hillslopes of WT-2 and Abandoned Washes

Infiltration (water-injection) rates were measured on hillslope sediments at two areas during a site visit June 5-9, 1997. Information is recorded in scientific notebooks 175 (pages 34-36) and 432 (volume VI pages 34-37). Stothoff (2008) summarizes details of the site visit and provides estimates of the water flux rates derived from scientific notebook 175 during the field visit; these rates are included in column 3 of Table 3 for traceability. The analysis of temporal data (columns 4, 5, and 6) in Table 3 summarizes calculations recorded in scientific notebook 432.

Ponded disc permeameters were used for the three measurements recorded in Table 3. The data analysis followed the approach described in the March 26-28, 1997, site visit for ponded permeameters. The exact locations for the three measurements were not recorded, just the general geomorphic position and the specific wash, WT-2 and Abandoned Washes. The GD1 and GD2 sites were directly on surficial materials. The Scree1 site was at the bottom of an excavation in a talus pile, where eolian-derived material collects.

Table 3. Hydraulic Properties of Soils on Hillslopes of WT-2 and Abandoned Washes

Site	Location	Water Loss Rate (Stothoff, 2008), Rough Estimate K_s, cm/hr	Analysis of Temporal Data		
			K_s, cm/hr	Gardner α, cm^{-1}	Sorptivity, $cm/s^{0.5}$
GD1	WT-2 Wash, upslope of Ghost Dance Fault exposure; Site GD2 is 4 m east of GD1	19	16	0.552	0.767
GD2		14	10	0.136	0.120
Scree1	N 36º 49.532, W 116º 27.515 North-facing slope in Abandoned Wash	26	22	0.510	0.093

May 16-18, 1998

The site visit May 16-18, 1998, focused on Upper Split Wash. Split Wash has 3 confluences of channels; Upper Split Wash is defined here as starting at the middle confluence extending to the crest. Measurements were performed in various locations in channels and side slopes. Information was recorded in scientific notebooks 255 (pages 84-87), 432 (volume VI pages 38-55), and 175 (page 61).

Test methods included disc permeameter measurements on soils and simple ponding experiments in channels. The former method was utilized during previous site visits. The latter method was used to qualitatively check the potential for infiltration on bare bedrock in channels that might be enhanced during periods of runoff. The fractures in the bedrock were soil- and caliche-filled, and thus are included here in a discussion of soil hydraulic properties.

Hydraulic Properties of Sediments on Slopes and Terraces of Upper Split Wash

A disc infiltrometer was used to characterize hydraulic properties of soils on various landforms in Upper Split Wash. Four measurements on hillslopes in Upper Split Wash, one measurement on the broad crest of Yucca Mountain at the top of Split Wash, and six measurements on a terrace deposit adjacent to the channel in Upper Split Wash were completed (Table 4). As used during previous site visits, the permeameter had a 20-cm diameter base (supply area for water at the soil surface). Calculations of hydraulic property values shown in Table 4 follow the approach described in the section on the March 26-28, 1997, site visit.

Relatively wet conditions caused by rainfall events prior to the site visit made it difficult to obtain transient data during the measurements of infiltration. Transient behavior is required for estimation of sorptivity (Eqn 3) and the Gardner α (Eqn 4). Soil water content measurements indicated that the gravimetric soil water content was between 0.1 and 0.15 kg/kg; or, by assuming a bulk density of 1.5 kg/m^3, the volumetric water content was between 0.135 and 0.2 m^3/m^3. Because of the relatively wet conditions, the values of the Gardner α parameter and sorptivity have an increased level of uncertainty compared to the estimation of K_s, which is less sensitive to initially wet conditions.

Table 4. Hydraulic Properties Estimated Using a Disc Infiltrometer on Hillslope Sediments in Upper Split Wash

Site	K_s, cm/hr	Gardner α, cm^{-1}	Sorptivity, cm/s$^{1/2}$
Middle Terrace #1	12.5	0.30	0.043
Middle Terrace #2	60.0	0.79	0.063
Western Terrace #1	8.7	0.12	0.070
Western Terrace #2	17.4	0.40	0.050
Western Terrace #3	15.6	0.42	0.049
Western Terrace #4	23.8	0.51	0.056
North-Facing Slope #1	20.4	0.45	0.048
North-Facing Slope #2	5.78	0.72	0.017
South-Facing Slope #1	22.5	0.68	0.057
South-Facing Slope #2	39.3	0.63	0.078
Top of Watershed #1	17.5	0.58	0.037

Drainage in Fractured Bedrock in Channels of Upper Split Wash

Portions of the channels in Upper Split Wash exhibited bare bedrock. At several locations, fracture and bedrock topology were conducive to performing infiltration tests. The bedrock at these locations is the Tiva Canyon lower lithophysal unit.

Two methods were used to estimate infiltration rate into channels, an infiltrometer and direct ponding in natural depressions of wide-aperture fractures. In the first method, the infiltrometers were containers with an area of approximately 1700 cm^2 that were sealed where in contact with bedrock. In the second method, infiltration rates were estimated from direct ponding over a fracture in natural depressions. Fractures were chosen such that the area of the fracture could be readily measured; this area was considered the water supply area. The apertures of the fractures were generally less than 10 cm. Soil, caliche, or come combination was visible within most of the fractures in the test areas.

Table 5 contains the drainage rates measured in channels. The two general locations in Split Wash were in the northern channel upslope from the middle confluence of channels (Easting 548,550 m and Northing 4,078,337 m, UTM NAD27), and near the northern-most upper confluence (Easting 548,128 m and Northing 4,078,418 m, UTM NAD27). For water ponded on matrix and fractures, the average flux in Table 5 is calculated using the entire ponded area and the fracture flux is calculated using the measured area of the fracture. All four calculations of fracture flux assume negligible contribution of the matrix for drainage.

Table 5. Drainage Into Exposed Bedrock and Fractures in Channels of Upper Split Wash

Location	Type	Average Flux, cm/hr	Fracture Flux, cm/hr	Comments
(1) North branch, near middle confluence	infiltrometer	0.12	1.2	Estimated crack area - 10%
(2) South branch near middle confluence	infiltrometer	2.6	21.2	Measured crack area - 12.4%
(3) North wash, near uppermost northern confluence	direct ponding	-	1.9	-
(4) North wash, 5 m downslope of Site 3	direct ponding	-	4.6	-

Not listed in Table 5 are three other measurements where drainage into fractured bedrock was recorded. These measurements were performed at two locations: near the upper confluence (Easting 548,128 m and Northing 4,078,418 m, UTM NAD27), and at the downslope side of the wash headwall (approximately Easting 548,020 m and Northing 4,078,450 m, UTM NAD27) of the northern-most upper wash. The flux rates for these tests were 0.43, 1.3, and 3.3 cm/hr. The fracture areas in the bedrock for these three tests were not measured because the fractures had small apertures. The water supply area for these three tests was smaller than the apparent representative volume element when the fractures were considered. Therefore, the drainage estimates cannot be converted to a fracture flux, even if the matrix contribution is considered negligible.

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