UCRL-ID-111733

Hydrologic Properties of the Vadose Zone at B292

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September 1992

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ABSTRACT

A formula for the unsaturated hydraulic conductivity was derived for the vadose zone down to the 45-foot depth by analysis of data from 5 wells near B292. The formula gives the median hydraulic conductivity as a function of depth and soil-water content, and was obtained by parameterization of saturated hydraulic conductivity and the water-retention characteristics to the median particle diameter of soil samples. It was noted that the variation of median particle diameter among soil samples at the same depth, taken from 5 wells in close proximity to B292, would have a great effect on saturated hydraulic conductivity. The coefficient of variation of median particle diameter was estimated to be 1.23 at any depth, based on apparent log-normal frequency distribution. The coefficient of variation of measured and predicted saturated hydraulic conductivity was estimated to be 7.9; large values are found in the literature as well.

BACKGROUND

Analysis of the soil-property measurements near B292 enables us to construct a vertical-profile representation of hydrologic properties down to 45-feet depth below grade. The primary objective is to obtain the best estimate for the vertical variation of hydraulic conductivity at B292, and a secondary objective is to estimate the effect of soil heterogeneity on the hydraulic conductivity. The hydraulic conductivity (k) is a function of the saturated hydraulic conductivity (k_S), and the soil-water content (θ). Both k_S and θ vary with depth, but k_S is a soil coefficient derivable from other soil parameters, while θ is a variable, which may either be measured or output from a calculational model. Following Campbell (1974):

$$k = k_S (\theta/\theta_S)m \tag{1}$$

where $m = 2b + 3$, θ_S is the saturated water content, and b is a soil parameter derived from the drying cycle of the water retention relation:

$$\varphi = \varphi'(\theta_S)^{-b} \tag{2}$$

θ is the soil-water potential, and φ' is "air-entry" water potential. The values of φ are given negative sign to indicate the energy (J/kg) that must be overcome to remove water from the soil matrix (analogous to "suction", 1 J/kg = 0.01 bars). Equation (2) holds for $\varphi < \varphi'$ only, since the curve changes greatly at saturation. θ_S is the soil-water content at φ.

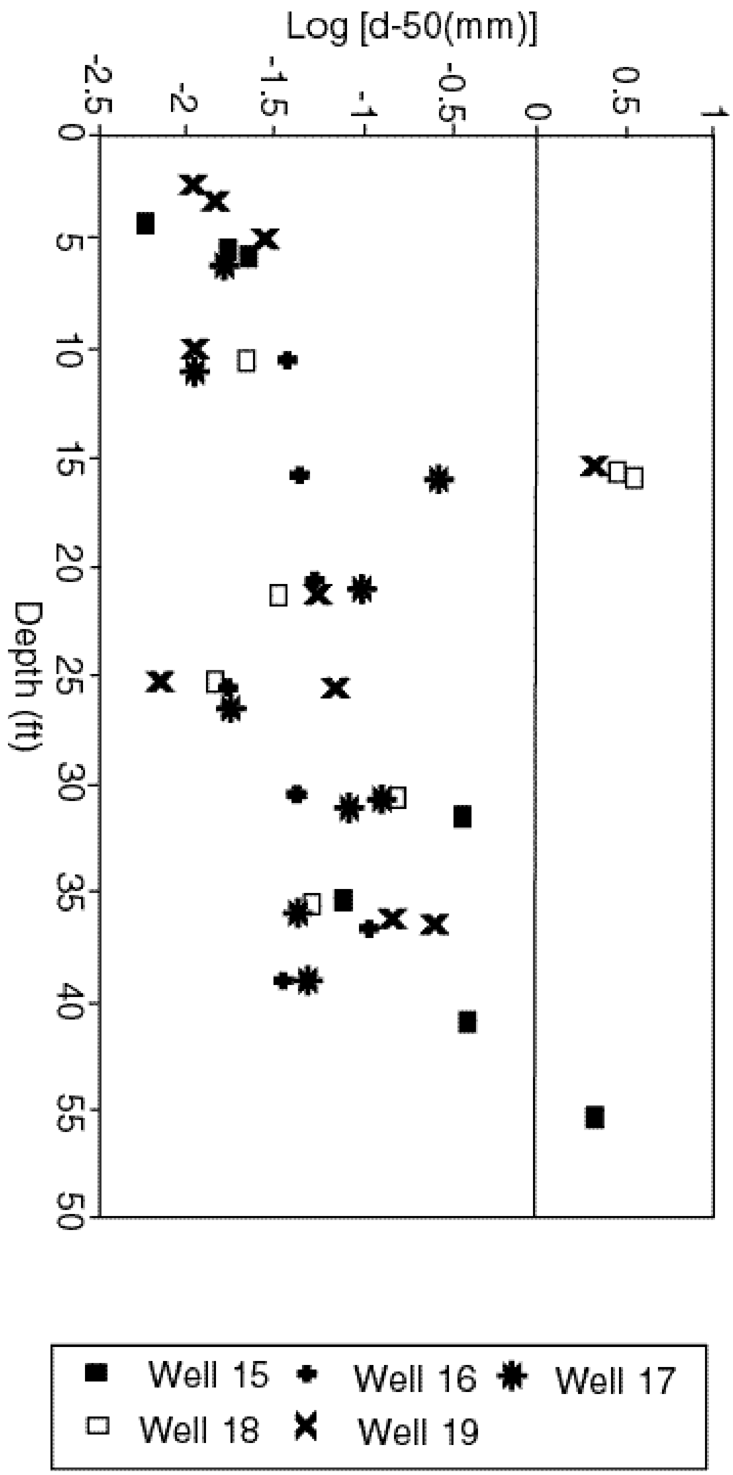

Figure 1. Median particle diameter (d-50, mm) on logarithmic (base 10) scale versus depth (ft) for five wells near B292.

Our approach is to relate measurements of k_s, and derived values of b, φ', and θ_s to the median particle diameter, d, of soil samples taken from Well 15 at B292 to derive predictive functions of d in the conventional manner of soil physics. These functions will be used to predict the median and coefficient of variation of k_s as a function of depth in Wells 15, 16, 17, 18, and 19 at B292, where d was measured extensively.

METHODS

Measurements of median particle diameter, d, and the diameter of the 84th percentile, d_{84}, for soil samples from Well 15 were made by Daniel B. Stephens & Associates (1992). From these data we determined the geometric standard deviation of the soil-particle sizes, s_g, estimated from the ratio, d_{84}/d. Measurements were also made of k_s, and retention curves φ (θ) on the same samples. The range of the median diameters was from 0.0057 mm to 2.2 mm in soil samples from 4.3 to 45.3 feet depth. We also determined interpolation formulas for k, b, and θ_s as a function of median diameter, d, by least squares regression.

Soil samples from Wells 16, 17, 18, and 19 were analyzed by Woodward-Clyde Consultants, to obtain continuous curves of particle-size distributions. From these curves we obtained median diameter, d, and 84th percentile diameter, d_{84}, and calculated the geometric standard deviation, s_g. The combination of data from the five wells allows us to estimate the variability of the derived parameters from the variability of measured diameters among samples from the same depths.

RESULTS

The median soil-particle diameter of the 42 samples from all five wells combined shows a general increase with depth beginning at a diameter of about 0.01 mm at the surface and increasing exponentially (correlation coefficient 0.75 for 6 outliers removed), doubling about every 3 meters (10 feet). See Figure 1. The variation about the general trend, however, reflects the local horizontal heterogeneity in soil stratigraphy. The CV (coefficient of variation, ratio of standard deviation/mean) of median diameter is about 1.23 at any depth. Individual samples show extremes of variation, for example at a depth of 15 feet, where sandy particles predominated in 3 out of 5 samples analyzed. In this case of an assumed log-normal variate, the CV is estimated by reorganizing Equation 13.12 from Gilbert (1987).

For application to problems of migration of tritium at B292, and for general migration and infiltration studies, a formula with spatially-averaged exponential increase with depth may be most important. The geometric standard deviation of particle size did not have an apparent systematic variation with depth. The median value of s_g was 7.4 with CV of 0.57, estimated from the distribution of values.

We derived the following interpolation formulas from Well 15. The slope of log φ vs. log θ curve was obtained for $100 < \varphi < 700$ J/kg. By least squares regression on the log-transformed d values:

$$b = (36957/d)^{0.2052} \qquad (3)$$

where d is in mm. The correlation coefficient was 0.94, CV = 0.45.

A formula for the drying water-retention curves, Equation (2), as dependent on median diameter, d, can be obtained from interpolation equations derived from Well 15 data as follows:

$$\varphi' = 36.5 \text{J/kg} \qquad (\text{CV} = 0.24) \qquad (4a)$$

$$\theta_S = 9.9\,(1 - 0.5 \log d) \qquad (4b)$$

again, where d is in mm and θ is in percent. The correlation coefficient for Equation (4b) was 0.88 and the standard error was 6.4. There was no significant variation in φ' with d, so a constant value is used tentatively in (4a), until more information is known.

The saturated hydraulic conductivity, k_S, was found to follow an interpolation formula following the Scheidegger (1960) hypothesis, proportional to d^2, from the data of Well 15, as follows (see Figure 2):

$$k_S = d^2/1249 \qquad (5)$$

where d is the median particle diameter in mm, and k_S has values given in conventional units, cm/sec. The correlation coefficient of the formula was 0.94 with a CV of 2.57. The variation in k_S can be linked to the variation in structural and textural characteristics (Warrick and Nielsen, 1980). We therefore calculated the saturated hydraulic conductivity as a function of all available d values from Wells 16, 17, 18, and 19. The k_S calculated values are shown in Figure 3, along with the measured k_S values from Well 15. As expected, the variation in d between wells at the same depth is reflected in Figure 3, along with a general profile with exponential increase of k_S with depth:

$$k_S = k_{SO} \exp (z/h) \qquad (6)$$

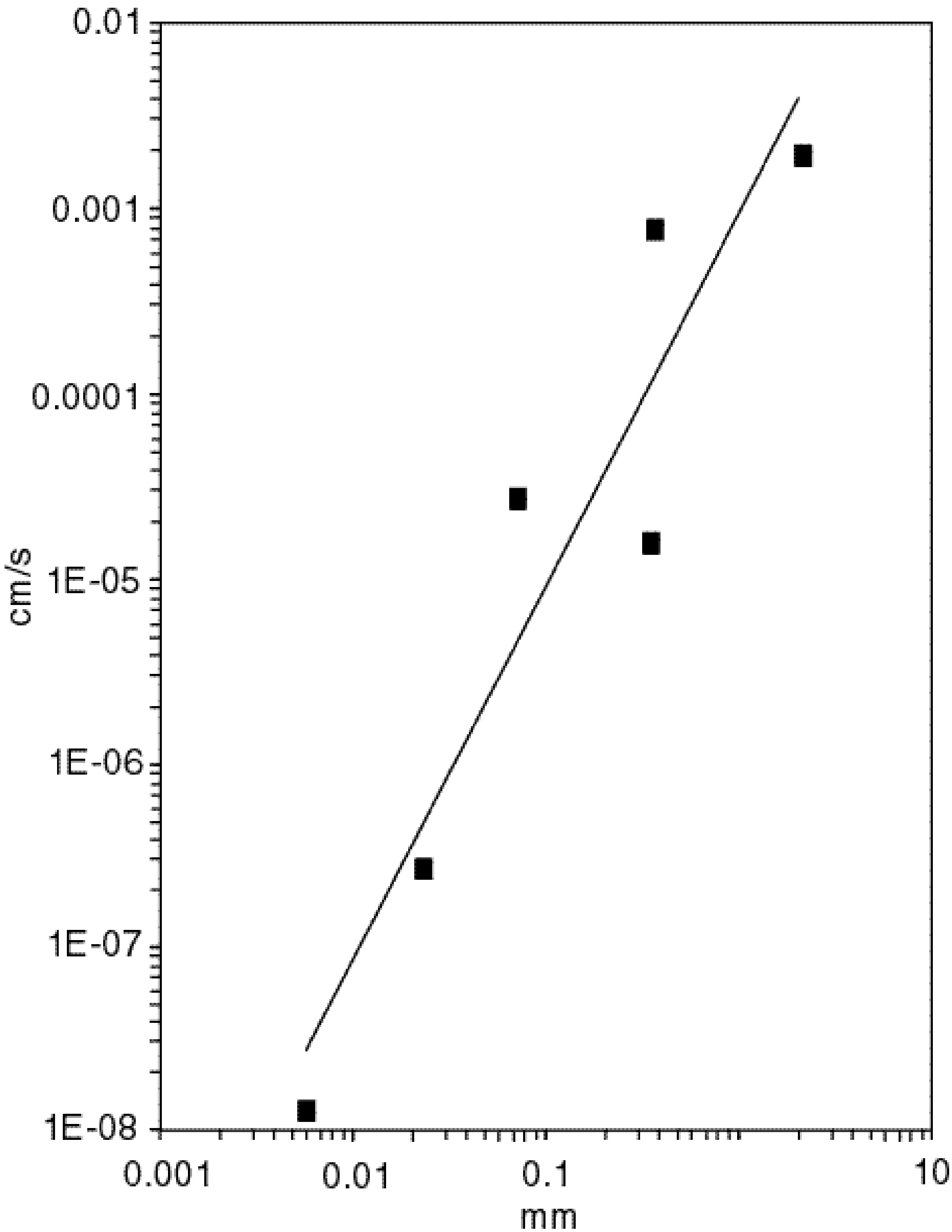

Figure 2. The saturated hydraulic conductivity (cm/s) measured on soil cores from Well 15 as a function of median soil-particle diameter (mm). The solid line is fitted Equation 5.

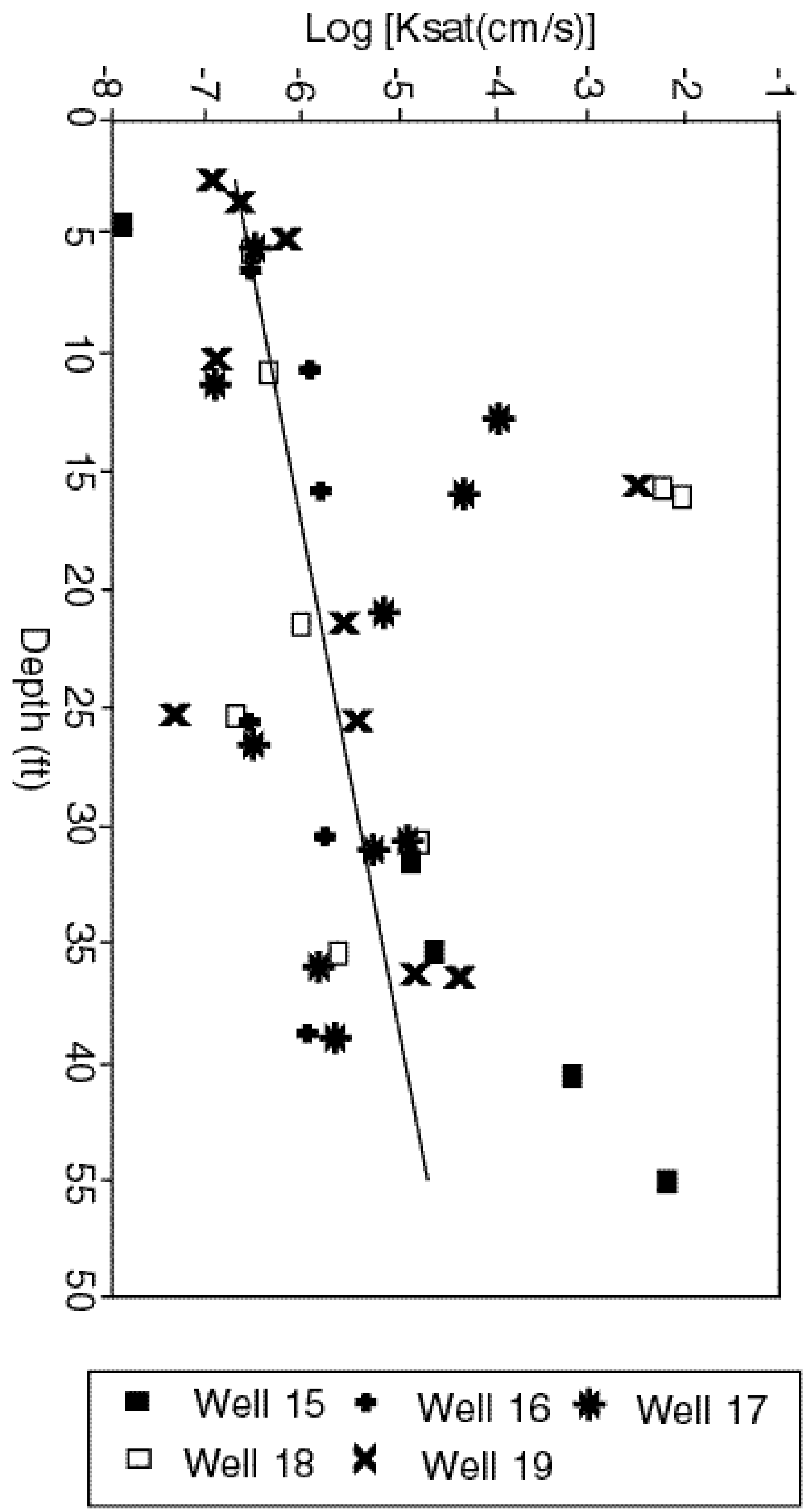

Figure 3. Saturated hydraulic conductivity (Ksat) on a logarithmic (base 10) scale versus depth (ft) near B292. Well 15 data are measured, while other well data are calculated. Solid line is fitted Equation 6.

where k_S 1.27 x 10-'7 cm/sec, is the median saturated hydraulic conductivity at the surface, z is the depth below grade, and h = 2.664m (8.74 ft) is the integral depth scale. This formula shows that the median saturated hydraulic conductivity doubles every 1.85m (6.06 ft). Equation (6) fits the data from all five wells with a correlation coefficient of 0.68 with 5 outliers removed, and has a CV b of 7.9. The CV was calculated assuming that the variate was log-normally distributed. The variation about the median k_S predicted by Equation (6) is quite large, and is what would be expected due to horizontal heterogeneity of the stratigraphy between wells. The 98th percentile of k_S values at any depth would be about 6.3 times the median value at that depth, (likewise the 1.7th percentile of k_S values would be the inverse, or 0.016 times the median value) based on the approximate log-normal distribution. This kind of variation was also the experience of Warrick and Nielsen (1980).

A predictive formula for unsaturated hydraulic conductivity, k, can be obtained from Equation (1), and application of the derived interpolation Equations (3), (4b), and (6), along with measured values of the water content, θ. The calculated values should be expected to approximate the median values of k, but with a high CV.

ACKNOWLEDGMENTS

This effort was undertaken in support of the Environmental Restoration Division, Environmental Protection Department at LLNL.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract # W-7405-ENG-48.

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