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Determination of Hydraulic Conductivity in Crushed Bandelier Tuff

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DETERMINATION OF HYDRAULIC CONDUCTIVITY IN CRUSHED BANDELIER TUFF

by

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ABSTRACT

The unsaturated hydraulic conductivity in a sample of crushed Bandelier Tuff was evaluated using volumetric pressure plate extractors. The total impedance of the tuff sample is determined from the experimental outflow data for each pressure step applied. The determination of the membrane impedance is not compulsory and the varying contact impedances are taken into account at each different pressure step. The results show that predictions of saturation ratios can be made based on knowledge of matric potentials just as predictions of hydraulic conductivities can be made based on knowledge of either matric potentials or saturation ratios. They are highly significant at the equivalent of a matric potential lower than −10 kPa. These results are then compared to those obtained by means of the predictive methods promoted by Campbell and Millington-Quirk using moisture retention data.

INTRODUCTION

The knowledge of unsaturated hydraulic conductivity values in the tuff would be of paramount importance for the estimation of radionuclide movement in the tuff surrounding waste pits.

Several methods have been used for the determination of unsaturated conductivity (Bruce and Klute, 1956; Miller and Elrick, 1958; Rijtema, 1959). The above methods were used to calculate the unsaturated hydraulic conductivity on a sample of crushed Bandelier Tuff from a radioactive waste disposal site at the Los Alamos Scientific Laboratory.

METHOD

The essential parts of the apparatus included a volumetric pressure plate extractor with a cell pressure control system accurate to 0.25%. The porous plate had a bubbling pressure of 200 kPa. The outflow measurement system consisted of a sealed Erlenmeyer flask into which the water was released. The flask was placed on a Mettler balance which allowed for continuous weighing of the outflow. A burette was used for air removal from beneath the porous plate.

PROCEDURE

The simplest technique, described by Klute (1965), was first used for the purpose of determining the unsaturated hydraulic conductivity. Although the experimental technique itself seemed to be flawless, no matching of Klute's theoretical diffusion equation plotted as the overlay or theoretical curve and the experimentally determined volume-outflow curve, could be obtained without translation of the plots. An overlay was drawn for each applied Matric Potential. The conclusion was consequently reached that the assumption of a negligible head loss through the porous plate was not valid.

A series of corrective outflow overlays were drawn in accordance with the method suggested by Miller and Elrick for the determination of hydraulic conductivity extended to cases with non-negligible plate impedance. The corrective translation needed to obtain the matching of any of the overlays and the experimental curves turned out to be near an order of magnitude larger than what Miller and Elrick assumed! Rijtema pointed out that unless good contact is established between the plate and the soil, an unknown flow impedance may prevail, which could far outweigh the plate impedance itself. The plate impedance permitted a flow rate of 3.8×10^{-8} m^3 s^{-1} m^{-2} kPa^{-1} or 1.37 cc hr^{-1} cm^{-2} bar^{-1} at saturation. The possible contact impedance could appear and grow as the matric potential or the saturation ratio was decreasing. Using Rijtema's method the total impedance of the tuff sample is determined from the experimental outflow data for each applied matric potential (or pressure step). Data for $1 - Q_t/Q\infty$ are computed from the experimental values of the outflow Q_t at time t and the equilibrium yield $Q\infty$ obtained for a particular pressure step. Values of $1 - Q_t/Q\infty$ are plotted on a logarithmic scale against tL^{-2}, where t is the time elapsed for a particular outflow quantity Q_t and L is the thickness of the sample. Rijtema devised a method to calculate the diffusivity based on the ratio of the slope of the straight line drawn through the experimental points and a value derived directly from the intercept of that straight line and the $1 - Q_t/Q\infty$ axis. The hydraulic conductivity K at that particular pressure step can now be calculated by finding the product of the diffusivity D and the specific water capacity c.

RESULTS

The equation for the time required for 0.99 of the outflow to occur is

$t_{0.99} = 1.68\ L^2\ D^{-1}$ (Klute, 1965)

This equation was used to check what the magnitude of D would have to be if the equilibrium time were chosen as one day. Computations show that D should be 2.5×10^{-8} m^2 s^{-1}. From past experiments, it was known that the diffusivity of Bandelier tuff normally exceeded that value at matric potentials higher than −200 kPa. Consequently, the time for equilibrium was set at one day. Upon completion of the experiment, the sample was oven-dried, yielding an additional 41 grams of water. The total amount of water present at saturation was calculated to be 185 grams. The dry weight of the tuff equals 597 grams. It can be deducted that saturation is equivalent to 31% of water by weight. Table I shows how matric potential outflow, water ratio by mass, degree of saturation, specific water capacity, water diffusivity and hydraulic conductivity correspond.

If matric potential vs saturation ratio, hydraulic conductivity vs saturation ratio and hydraulic conductivity vs matric potential are plotted on a log-log graph, a straight line is obtained in every case corresponding to matric potentials lower than −11 kPa.

TABLE I

HYDRAULIC CHARACTERISTICS OF BANDELIER TUFF AS A FUNCTION OF MATRIC POTENTIAL (Spec. H_2O Capacity, H_2O Diff. and Hydraulic Conduct. was only measured at pressure steps <10%)

Matric Potential (−kPa)	Outflow (g)	Water Ratio by Volume	Specific Water Capacity (m^{-1})	Water Diffusivity (m^2s^{-1})	Hydraulic Conductivity (ms^{-1})
0	0.000	0.400			
10	20.082	0.356			
11	24.320	0.347	8.98×10^{-2}	1.02×10^{-7}	9.18×10^{-9}
30	108.128	0.166			
33	110.261	0.162	1.58×10^{-2}	2.15×10^{-7}	3.38×10^{-9}
42	117.407	0.147			
46	120.241	0.140	1.50×10^{-2}	1.38×10^{-7}	2.07×10^{-9}
60	126.241	0.127			
66	127.841	0.124	5.64×10^{-3}	1.33×10^{-7}	7.51×10^{-10}
80	131.589	0.116			
88	132.749	0.113	3.07×10^{-3}	1.40×10^{-7}	4.30×10^{-10}
96	134.437	0.109	2.98×10^{-3}	1.21×10^{-7}	3.60×10^{-10}
120	136.949	0.104			
132	137.949	0.102	1.76×10^{-3}	9.3×10^{-8}	1.64×10^{-10}
146	139.315	0.099	2.06×10^{-3}	4.8×10^{-8}	9.91×10^{-11}
161	140.543	0.096	1.73×10^{-3}	4.62×10^{-8}	8.01×10^{-11}
177	142.643	0.092	2.78×10^{-3}	1.88×10^{-8}	5.22×10^{-11}
195	144.057	0.089	1.66×10^{-3}	3.08×10^{-8}	5.13×10^{-11}

If θ_v represents the water-filled porosity, θ the saturation ratio, ψ the matric potential in kPa, K_s the saturated hydraulic conductivity (9.2×10^{-7} m s^{-1}) and r the coefficient of correlation, the following equations are obtained:

1) $\psi = 1.93\ \theta^{-3.056}$ $\quad$ r = 0.9964

2) $\theta = 1.21\ \psi^{-0.321}$ $\quad$ r = 0.9964

3) $k = 2.43 \times 10^{-2}\ \psi^{-2.475}$ $\quad$ r = 0.9948

4) $k = 5.44 \times 10^{-3}\ \theta_v^{7.623}$ $\quad$ r = 0.9865

As can be seen from the high values obtained for the coefficient of correlation, the above equations, if plotted on a log-log graph, will very closely match a straight line.

The range of matric potentials was limited to those below −11 kPa, because the hydraulic conductivity in the −10 to −11 kPa range, based on the amount of water released at that decrease in matric potential, was below what could have been expected from a lack of fit to the rest of the line. Inclusion of this point would have destroyed the linearity of the log-log plot. This point was included, though, in the matric potential—water content function $\psi(\theta_v)$ used in the prediction of the hydraulic conductivity according to the Millington-Quirk method, the description of which is to follow.

PREDICTIVE METHODS

Since the hydraulic conductivity-water content relationship $K(\theta)$ is comparatively difficult to compute, the possibility of predicting the hydraulic conductivity from the matric potential-water content relationship has been widely explored. Millington-Quirk (1961) and Campbell (1973), among others, developed equations for this purpose. Several authors treated a variety of predictive methods against experimental data and indicated the superiority of a "corrected" Millington-Quirk (MQ) method. A correction coefficient is introduced to match the observed versus the computed saturated conductivity. Jackson et al. (1965) and Kunze et al. (1968) modified the MQ formula by introducing a "matching factor" to improve the predictability of the equation. The MQ method uses the equation

$$K = 3.14 \times 10^{-2}\ \theta_v^{4/3}\ n^{-2}\ [h_1^{-2} + 3h_2^{-2} + ... + (2n-1)\ h_n^{-2}] \cdot K_s/K_{sc}\ (\text{in ms}^{-1})$$

The water-filled porosity θ_v in $cm^3\ cm^{-3}$, the pressure potential h in kPa and the total number of pore intervals n give the hydraulic conductivity units of ms^{-1}. In portions of the curve where data were scarce, curve fitting through regression analysis was applied to enhance the validity of the moisture characteristic curve. The constant is valid for laboratory experiments conducted at a temperature of 300°K · K_s/K_{sc} is the matching factor (measured saturated conductivity/ calculated saturated conductivity).

If the obtained conductivity data is fitted to the water filled porosity, a power function is obtained where, for θ_v ranging from 0.02 to saturation (0.40)

$$K = 7.96 \times 10^{-4}\ \theta_v^{7.379} \text{ with } r = 0.9994 \quad .$$

As can be seen through comparison with the laboratory method using Rijtema's technique, the slopes are almost identical, the $K(\theta_v)$ function being somewhat steeper when measured (Rijtema). This is counterbalanced by the fact that the coefficient used in Rijtema's equation is almost 7 times higher than in the MQ equation. Consequently, *at any point*, will the measured hydraulic conductivity be *less* than 7 times higher than the predicted one using the MQ method. The inclusion of pressure potentials less than 11 kPa had the effect to change the slope of the curve slightly. This procedure was necessary, however, to obtain a sufficient number of water content increments and corresponding pressure potentials on the $\psi - \theta_v$ curve described above.

Campbell's method for determining unsaturated conductivity from moisture retention data is simpler but agrees less with the Laboratory method when applied to the Bandelier Tuff. An empirical expression relating water potential to water content for limited ranges of water content is, below matric potentials of −11 kPa,

$$\psi = \psi e\ (\theta/\theta_s)^{-b}$$

where ψe is the air entry water potential and θ_s the saturated water content. The slope b can be determined out of the above relationship and the unsaturated hydraulic conductivity is subsequently determined out of the equation

$$k = k_s\ (\theta/\theta_s)^{2b+2} \quad .$$

Through regression analysis, using the moisture retention data, $\psi/\psi_s = 0.0097(\theta/\theta_s)^{-3.0563}$, fixing the value of b at 3.0563. The unsaturated hydraulic conductivity is subsequently expressed as

$$k = 1.56 \times 10^{-3} \theta_v^{8.113} \text{ (in ms}^{-1}\text{)}$$

Higher exponents in the three alternative regressions mean lower hydraulic conductivity while higher coefficients mean higher values. Since the formula with the highest exponent is also the one with highest coefficient, the three methods never result in hydraulic conductivities exceeding one order of magnitude in difference. The superiority of the Millington-Quirk method seems to be confirmed when matched with the measured values. Campbell's predictive method retains the advantage of being the easiest one to compute.

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