FIELD VS. LABORATORY PERMEABILITY ESTIMATES

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INTRODUCTION

Estimates of subsurface fluid flow and solute transport parameters are used to model the migration of contaminants, as well as to predict the efficiency of proposed remediation strategies. Important parameters can be measured using laboratory analyses conducted on cores, or using field tests. To compare the representativeness of field vs. laboratory procedures, both laboratory and field estimates of hydraulic conductivity and air permeability were collected from an unsaturated fractured rock. Measured parameters were obtained from a large sample of 105 core segments collected at 3-m intervals. Field borehole tests were also conducted over 3-m intervals centered at the location where the core segments were collected.

The Apache Leap Tuff Site is the focus of the current investigation due to geologic, structural and environmental conditions which are similar to conditions at many waste disposal sites. The Apache Leap Tuff Site is located near Superior, Arizona, approximately 160 km north of Tucson, Arizona, (Longitude 111° 04'W, Latitude 33° 18'N, Elevation 1,200 m). The site lies in the uppermost part of an approximately 20-million-year old tuff formation which varies from a slightly welded unit on top (where the Apache Leap Tuff Site is situated) through a moderately welded unit below, to a densely welded unit near the base of the formation. The field site selected for study is in the White Unit of the Apache Leap Tuff which consists of a tuff matrix porosity of approximately 17.5 percent and fractures averaging 0.77 fractures per meter.

To obtain parameters for the rock matrix and the fractures at the site, nine boreholes were installed at a 45° angle from the vertical (Figure 1). This novel arrangement of the borehole cluster was necessary due to the existence of both near-vertical and horizontal fractures at the site. The inclined boreholes allowed for the sampling of vertical fractures.

PROCEDURES

Laboratory analyses of unfractured rock-core segments and field testing of borehole intervals were used to determine the water and air permeabilities of the uppermost unit of the

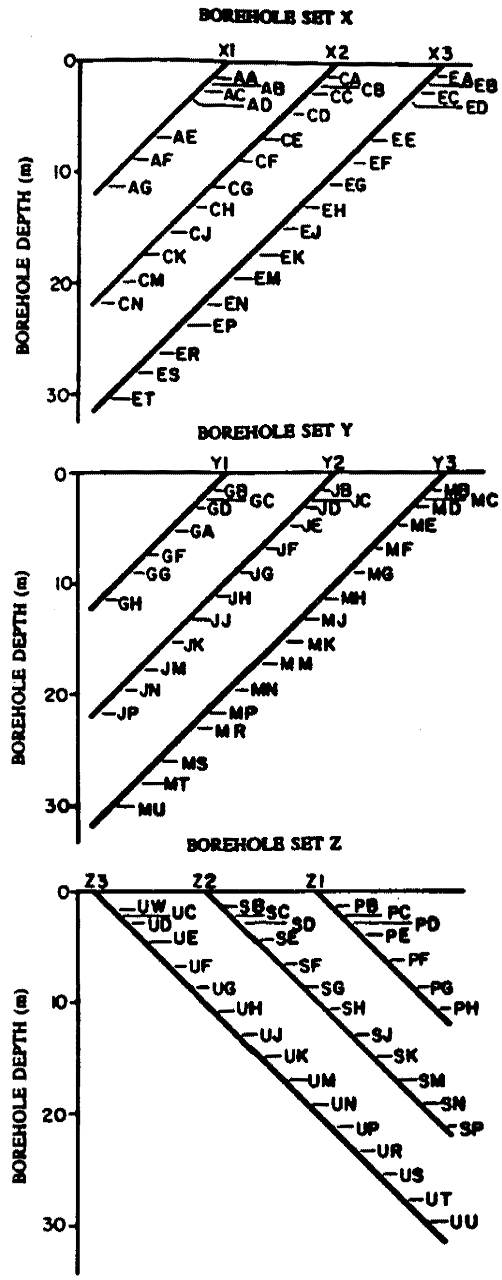

Figure 1: Field measurements and core sample locations showing identification labels. The borehole sets lie in parallel vertical planes offset by 5 m perpendicular to the planes.

Apache Leap Tuff. Approximately 270 m of 6.4-cm diameter oriented core were obtained from the nine inclined boreholes. Data for the tuff matrix were obtained from the oriented cores using 5-cm long sections cut from the core at approximately 3-m intervals at 105 locations free of visible fractures. Saturated water permeabilities of rock cores were obtained using a permeameter consisting of an inflatable packer to seal the annulus between the rock segment and an outer brass collar. Air permeabilities for both oven-dried and partially saturated unfractured rock core segments were obtained using a permeameter.

Borehole saturated water permeabilities were determined using a modified falling-head borehole test as described by Tidwell et al. (1988). A single packer was placed at the top of an uncased borehole interval and the rate of water injection to the open borehole below the packer was monitored in response to a constant water level maintained near the top of the borehole. After the flow rate stabilized, the packer was lowered 3 m to the top of the next interval and the injection rate for the intervening interval was calculated by subtracting the two flow rates. The borehole saturated water permeability was obtained from the calculated injection rate using an equation presented by Tidwell et al. (1988) to incorporate the geometry of the inclined boreholes.

Once the rock water contents surrounding the boreholes had stabilized as determined by neutron probe methods (approximately 1 yr), field borehole estimates of air permeabilities were obtained using single-hole air injection tests for the same 3-m intervals used for the water tests. In the air tests, two inflatable packers were positioned at either end of the test interval and a constant-mass air flow rate was injected into the interval while monitoring the air pressure within the injection interval. The injection continued until a steady pressure in the injection interval was observed, a matter of minutes for most intervals. Air permeabilities were calculated using an equation developed by Dachler (1936) adapted for steady, isothermal air flow.

RESULTS AND DISCUSSION

Table 1 presents summary statistical data for core and borehole water and air permeabilities in units of 10^{-15} m^2 (10^{-15} m^2 $\approx$ 1 millidarcy). Histograms of core saturated water permeabilities, core oven-dry air permeabilities, borehole saturated water permeabilities, and borehole ambient air permeabilities are presented as Figure 2(a-d), respectively. Also presented are the geometric means and horizontal bars indicating the sample standard deviation. The geometric mean of core oven-dry air permeabilities is higher than the geometric mean of saturated water permeabilities (1.77 and 0.56 x 10^{-15} m^2, respectively).

Core saturated water permeabilities vary across a range of approximately three orders of magnitude (0.07 to 44.6 x 10^{-15} m^2), while borehole-estimated saturated water permeabilities range across approximately five orders of magnitude (0.042 to 1820 x 10^{-15} m^2). Like the water permeabilities, core oven-dry air permeabilities vary across three orders of magnitude (0.38 to 101 x 10^{-15} m^2) and borehole air permeabilities range across at least five orders of magnitude ($<$0.044 to $>$1340 x 10^{-15} m^2).

TABLE 1: Apache Leap Tuff Core and Borehole Air and Water Permeability Data (units of 10^{-15} m^2)

	------ WATER ------		------- AIR ------	
	Core	Borehole	Core	Borehole
Minimum	.07	.042	.38	<.044
Median	.43	1.05	1.21	.36
Maximum	44.6	1,820.	101.	>1,340.
Arithmetic				
Mean	2.17	30.7	5.71	43.1
Std. Dev.	6.55	205.	15.6	215.
Coef. Var.[1]	3.02	6.66	2.73	5.00
Skew Coef.[1]	4.95	8.47	4.84	5.58
Geometric				
Mean	.56	1.38	1.77	.82
Std. Dev.	3.57	5.92	3.41	10.1
Coef. Var.[1]	2.22	5.46	2.15	11.9
Skew Coef.[1]	1.56	1.18	1.44	1.16

[1] Dimensionless

No direct correlation between enhanced permeability and the number of fractures was observed, yet all of the intervals which lacked fractures were associated with intervals of lower borehole permeability. It is inferred that the influence of fractures is complicated by the large permeability variation of individual fractures.

Figure 3 presents scatterdiagrams of core and borehole permeabilities for both water and air. Also presented are lines of equal permeability along with the simple correlation coefficient between corresponding data points at the same sampling location. Figure 3(a) further illustrates that the core saturated water permeabilities are significantly less than observed oven-dry air permeabilities at the α=0.05-level but are highly correlated (r=0.923). This artifact can be explained by the Klinkenberg effect, as discussed later.

Figure 3(b) demonstrates a good correlation between borehole air tests and borehole water tests (r=0.876). The test statistics indicate that the geometric means of the two data sets are not significantly different in part because fractures, neglected in core analyses, are included in both air and water borehole tests.

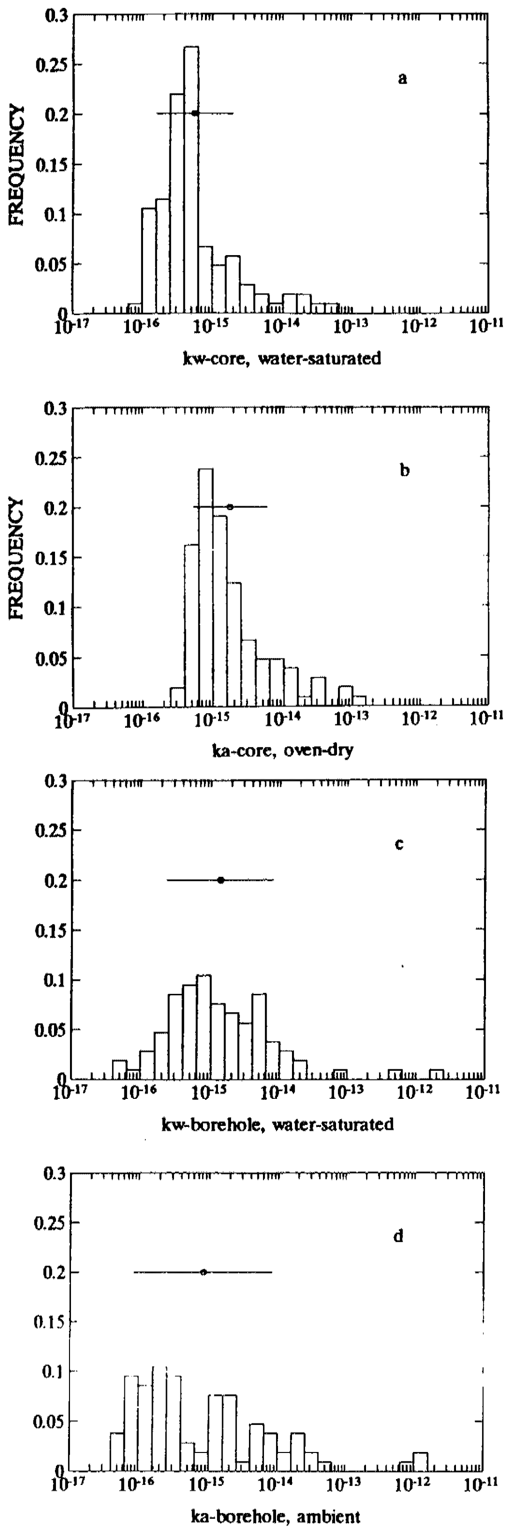

Figure 2: Permeability histograms including geometric means (o) and mean ± standard deviation (horizontal bars): (a) water permeability for water saturated cores, (b) air permeability for oven-dried cores, (c) water permeability for saturated boreholes, and (d) air permeability at ambient conditions.

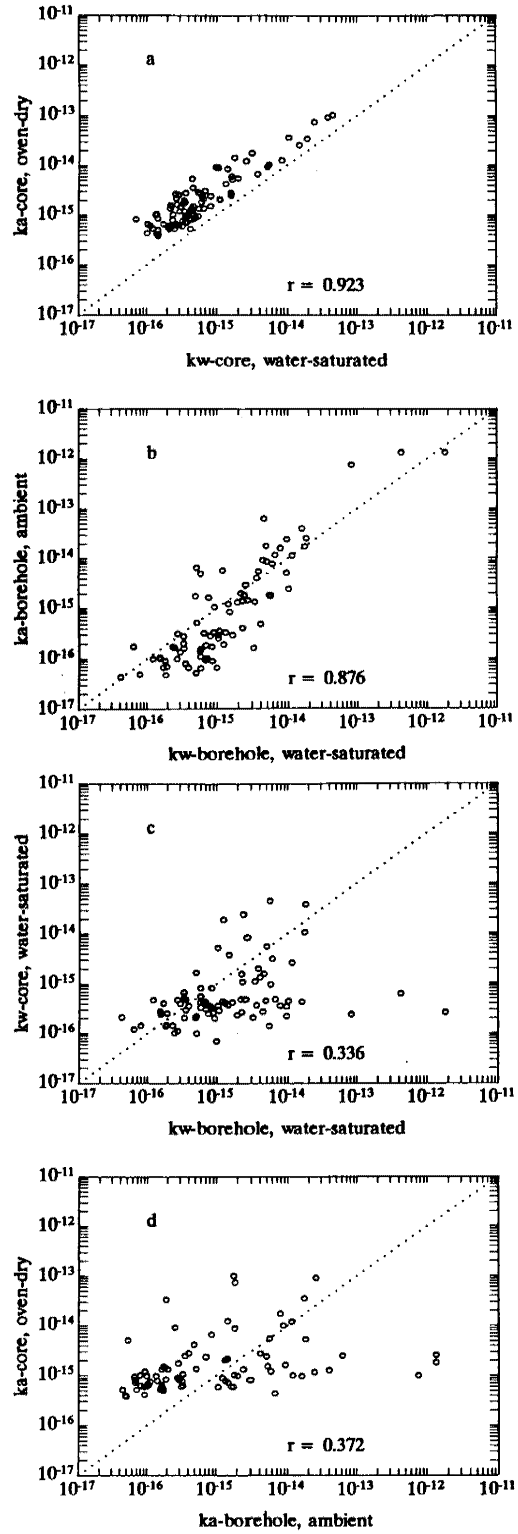

Figure 3: Permeability scatterdiagrams including simple correlation coefficients and lines of equal permeabilities for the core and borehole data.

Oven-dry air permeabilities are highly correlated to saturated water permeabilities for the same core, yet the oven-dry air permeabilities are consistently higher than the saturated water permeabilities. Klinkenberg (1941) specified a relationship between saturated water and oven-dry air permeabilities which included slip flow of air along the walls of pores. The ratio of the permeabilities is a function of the ambient air pressure used to conduct the air test, which is related to the mean free path of the air molecules, and the pore diameter.

Core saturated water permeabilities are compared to borehole saturated water permeabilities in Figure 3(c). The relationship is poorly correlated (r=0.336), with many intervals lying either far above or far below the line of equal values. Again, the data sets are not significantly different.

Like the water test data, core oven-dry air data is poorly correlated to borehole air permeability (r=0.372), shown as Figure 3(d), but the geometric means of the data sets are not significantly different. The best overall correlation exists between borehole data and air permeabilities obtained for oven-dry samples, but the least significant difference is observed between borehole data and core data at 500 kPa. For the core oven-dry air data the geometric mean permeabilities are higher for the core data than for the borehole data. The difference in means can be attributed to variable rock matrix and fracture matric suctions.

SUMMARY AND CONCLUSIONS

Field-scale permeability tests are often required to provide characterization data for evaluating the suitability of a waste disposal site, for predicting the fate of contaminants, or for establishing remediation programs. Methods for obtaining data in unsaturated fractured rock using borehole water injection tests are restricted by slow water flow, by the desire to avoid injecting water at the site, or by the complexity associated with water pressure gradients induced by gravity and matric suctions. Laboratory core water permeability data are often used as surrogates for borehole permeability data.

Also shown in this paper is the poor correlation between core and borehole permeabilities for air and water. The core permeabilities poorly predict individual borehole permeabilities due, in part, to the exclusion of fractures in core samples, as well as to the substantially larger rock volumes examined using borehole compared to laboratory core experiments. Statistically significant differences in variances were demonstrated between core and borehole permeabilities. Notwithstanding the inability to predict individual borehole permeabilities at specific locations, no significant differences between laboratory core and field borehole mean water and air permeability data was shown.

The most promising method for predicting borehole saturated water permeabilities for specific locations is the use of borehole air injection tests. Air injection tests are attractive because the influence of gravity can be neglected, no water is injected at the borehole site which might alter ambient hydraulic and chemical conditions, and tests conducted using air reach steady state conditions much earlier than water tests.

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