Scale Characteristics of the Different Methods of Measuring Soil Permeability

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The various air permeability and hydraulic conductivity field measurement techniques range from small scale probe methods to very large scale hydraulic drawdown measurements. Different methods are distinguished by their measurement scale and varying sensitivity to heterogeneity and anisotropy. Several case studies will be presented, in which varying scale methods have been compared. One is a cone penetrometer (CPT) hydraulic conductivity measurement compared with a large scale drawdown test at the Savannah River Site. The other is a suite of three different scale measurements of air permeability: straddle packers, open borehole anemometry, and total well vapor extraction, performed at Los Alamos National Laboratory in Bandelier tuff. The utility of the different measurement methods is dependent on the application. Large scale measurements are needed to develop production characteristics for remedial design, whereas small scale, detailed profiles are needed to delineate discrete sources to optimize production.

Field scale measurements can be generally grouped into small scale, large scale, and hybrid techniques that use a mix of scales. Examples of *small scale* measurement techniques are straddle packer borehole tests, slug tests and cone penetrometer-based measurements. The scales of these measurements are typically in the range of centimeters to large fractions of a meter. Characteristics of this family of measurements are:

- Localized measurement, because the technique influences a relatively small volume and cannot reach distant media
- Potentially high spatial resolution (the measurement can usually be located at whatever vertical spacing is desired by the end-user)
- Can be performed in a single well, borehole, or CPT push (the techniques do not typically require an observation measurement at a distance)
- Relatively fast to implement (minutes)
- Because of the potential for high spatial resolution, the methods can quantify heterogeneity and macroscopic anisotropy (due to layering on the geometric scale of the measurement range of influence)

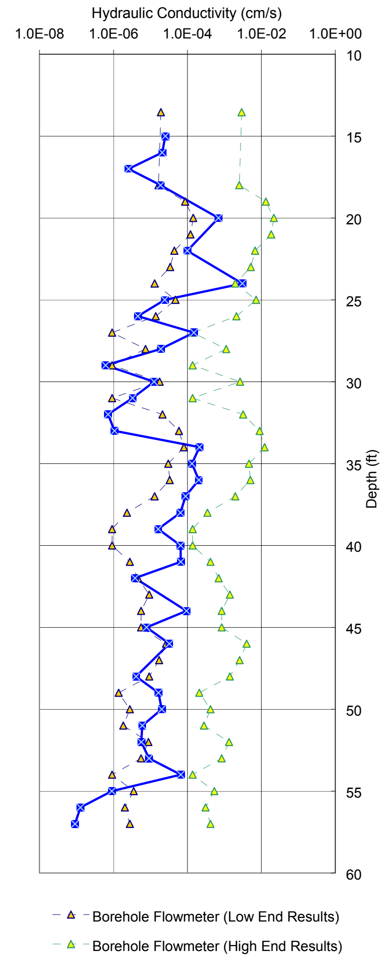
Large scale methods have evolved from the traditional methods used to quantify water production in wells. They include a family of techniques based on total-well drawdown methods, and can be applied to both saturated conductivity and vapor extraction tests. These tests usually require an observation well a distance from the test well to interpret the data. They are characterized by:

- A relatively large region of influence, on the order of meters (although they are still influenced most heavily by the hydraulic properties immediately adjacent to the well)

- Little or no spatial resolution, either vertically or horizontally, unless multiple observation wells are used to quantify horizontal or vertical spatial variability. These methods typically yield one bulk value of the hydraulic conductivity or permeability of the region under test.

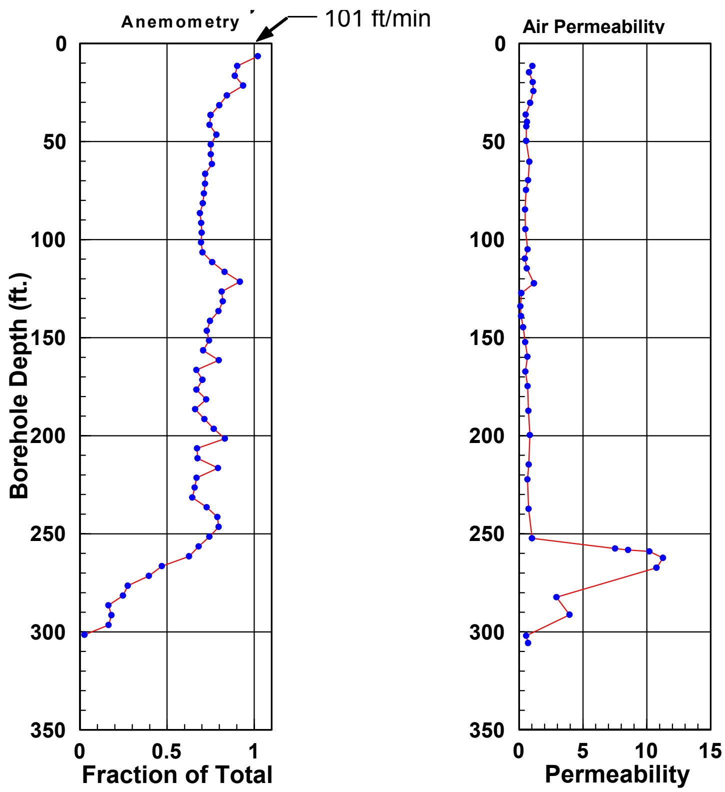
An example of a *hybrid* technique is the integration of a water well spinner survey with total hole drawdown test results. In this approach, which can be implemented in vapor extraction measurements as well, a spinner survey logs the well during production. The survey develops a vertical velocity profile in the well, which can be differentiated with depth to quantify production zones. When coupled with the total borehole bulk hydraulic conductivity, this method can produce a vertical conductivity profile. Two case studies are presented to compare the methods.

Case I: Savannah River Site saturated hydraulic conductivity measurements with total well extraction and CPT measurements. In April 1998, the Cone Permeameter™ measurement system was fielded at the Savannah River Site D Area Coal Pile Runoff Basin. This area had been characterized prior to installation and testing of a barrier system and interceptor well ("Interim Report, D-Area Interceptor Well, DIW-1 Water Table Aquifer (U)," M.A. Phifer et al., Westinghouse Savannah River Company, Sept. 1996). The area is underlain by a series of interbedded sand, silt, and clay layers. These CPT measurements extended from the water table (at approximately 4.8 ft. depth) into the top of the confining layer, with the deepest permeameter measurements at approximately 60 ft. The Cone Permeameter™ was integrated with a standard CPT cone tip and deployed by Applied Research Associates using a 30-ton truck loaded to 26 tons. Measurements required 3 to 10 minutes per location. On the second day of testing 35 measurements were obtained in a five-hour period. The Cone Permeameter™ data is compared with previous borehole flowmeter and total flow saturated conductivity measurements taken in well DCB-25, approximately 15-ft. distant. Drawdown measurements resulted in bulk saturated hydraulic conductivities ranging from 5.9E-5 to 1.1E-3 cm/s, depending on which of the three observation wells was used. The bulk conductivity data was combined with borehole flowmeter data to develop a profile of the conductivity vs. depth on 1-ft. intervals. The Cone Permeameter™ data is plotted in the adjacent figure, compared with the previous borehole flowmeter tests in DCB-25. Borehole flowmeter data for both the high (1.1E-3 cm/s) and low (5.9E-5 cm/s) bulk conductivity cases are plotted, indicating the range of uncertainty in the borehole flowmeter data. The Cone Permeameter™ data generally falls between the high and low conductivity values.



Saturated hydraulic conductivity measurements at the Savannah River Site D Area Coal Pile Runoff Basin

Case II: Pilot Vapor Extraction Test, Los Alamos TA-54. In preparation for implementation of a vapor extraction test in Bandelier tuff, extensive air flow measurements were



Air flow measurements conducted in Bandelier tuff at LANL TA-54

conducted in an array of uncased holes augered in the volcanic tuff. Open borehole anemometry measurements were initially conducted in each hole to indicate relative production profiles in the hole. This was accomplished by drawing a steady flowrate of air from the well, while simultaneously logging the air velocity distribution in the well with a hot film anemometer. Following that, discrete straddle packer measurements were conducted to quantify the permeability. Data from borehole 54-1018 is shown at the right. The anemometry measurements indicate that almost 80% of the total flowing volume is produced in the region between the 250 and 300 feet depth, which is consistent with the relatively high permeability measured in that zone by the packer system. Very near to this borehole, an extraction well was constructed. Surface casing was run to 75 ft., and the remaining 75 ft. of the borehole was left open as the extraction zone. An extraction blower was mounted at the top of the casing, which produced an average extraction flow rate of 0.87 kg/min under a differential vacuum of 18.4 kPa. To evaluate the effectiveness of the air permeability measurements, a 3D air flow model (AIR3D) was applied using the measured permeability distribution. The permeability varied with depth, but was modeled as uniform in its horizontal distribution (within a horizontal layer the permeability was homogeneous and isotropic). The extraction vacuum was specified in the model, and the code calculated the resultant flow into the well. The modeled extraction flow and measured average flow vary by only 24% (the modeled flow being lower than the measured). This is very good agreement given that the model did not consider deviations from homogeneous and isotropic conditions.

These case studies show two instances in which detailed permeability measurements provided a level of precision unattainable with traditional methods. In the case of the SRS measurements with a CPT tool, highly detailed data was obtained at a small fraction of the time and cost of the standard drawdown well method, with much lower overall uncertainty in the results. At Los Alamos, discrete straddle packer measurements produced a permeability distribution that allowed accurate prediction of extraction system performance, with the added benefit of knowing exactly what zones were dominating the production. As more tools are available for rapid characterization of the media to greater detail, our ability to predict the large scale processes improves.