Appendix D
Recommended Estimation Methods for Air Permeability

D-1. Introduction

Various methods used to estimate the air permeability of a given soil are summarized below. Air permeability estimates are required to predict or evaluate system performance using the available analytical and numerical models. Indirect, laboratory, and field methods for estimating air permeability are presented.

D-2. Indirect Method

Air permeability can be estimated as a function of saturated hydraulic conductivity. Intrinsic permeability can be obtained from the definition of saturated hydraulic conductivity as

$$k_i = \frac{K\,\mu}{\rho\,g} \qquad \text{D-1}$$

where

k_i = intrinsic permeability, $[L^2]$

K = saturated hydraulic conductivity, [L/T]

μ = dynamic viscosity of water, [M/L-T]

ρ = density of water, $[M/L^3]$

g = gravitational constant, $[L/T^2]$

a. The relationship between air permeability and intrinsic permeability is typically expressed as

$$k = k_i * k_{ra} \qquad \text{D-2}$$

where

k = air permeability

k_i = intrinsic permeability

k_{ra} = relative permeability to air

b. Burdine (1953) and Mualem (1976) have developed closed-form analytic solutions expressing relative permeability as a function of water content. Corey (1986b) used Burdine's solution in conjunction with the Brooks-Corey pressure-saturation relation (Brooks and Corey 1964) to develop the following expression for relative permeability to air

$$k_{ra} = (1 - S_e)^2 \left(1 - S_e^{\frac{2+\lambda}{\lambda}} \right) \quad \text{D-3}$$

where

S_e = effective water saturation

λ = Brooks-Corey pore size distribution index

c. Effective water saturation S_e is further defined as

$$S_e = \frac{S_w - S_r}{1 - S_r} \quad \text{D-4}$$

where

S_w = water saturation

S_r = residual water saturation

Figure 4-2 shows the relationship between relative permeability to air and water content based on Equation D-3.

d. Thus, with estimates of the water content, residual water saturation, capillary pressure head-saturation relationship and saturated hydraulic conductivity, air permeability can be calculated as

$$k = (1 - S_e)^2 \left(1 - S_e^{\frac{2+\lambda}{\lambda}} \right) \frac{K\mu}{\rho g} \quad \text{D-5}$$

D-3. Laboratory Methods

a. Grain size distribution. Air permeability as a function of the average pore radius can be estimated very roughly from grain size analyses performed on soil samples using the following relationship (Massmann 1989)

$$k_i = 0.125\, r^2 \qquad \text{D-6}$$

where

k_i = intrinsic permeability, darcies

r = characteristic pore radius (mm), defined as

$$r = c\, D_{15} \qquad \text{D-7}$$

where

c = empirical constant approximately equal to 0.1 for sand and gravel

D_{15} = grain size for which 15 percent by weight of particles are smaller (mm)

Combining Equations D-6 and D-7

$$k = 1{,}250\, D_{15}^2 \qquad \text{D-8}$$

b.Column tests (e.g., permeameters). Permeameters subjected to a pressure gradient may be used to estimate the air permeability of a given soil sample.

D-4. Limitations of Indirect and Laboratory Methods

In general, indirect and laboratory methods yield air permeabilities which may be suspect. This is due primarily to the following:

a. Samples collected from discrete depths may not be representative of the unsaturated zone as a whole. This is especially true when attempting to predict pore size distribution from grain size distribution (e.g., by the method above). Grain size data reveal little as the presence of structural features such as macropores, cracks, or thin lenses are paths of least resistance for airflow.

b. Laboratory studies such as column tests may be limited by scale dependency, and thus the results may not be readily extrapolated to a field-scale design. Similarly, column tests performed on fine grain soils such as silt and clay generally suggest that little or no airflow is possible under a variety of vacuums. However, field studies conducted on these soil types may reveal that significant airflow may be achieved due to macropores, secondary permeability zones such as fractures, and heterogeneities.

c. The presence of NAPL, which competes with water and air for pore space, may not be factored into the air permeability calculation.

d. Spatial variability in the moisture content and soil types (i.e., heterogeneities) may not adequately be accounted for in a small number of discrete samples.

e. Air permeability measurements are a function of the soil's dry bulk density, which may be altered by sample collection and repacking of soils. To the extent that adequate numbers of samples are collected and measures are taken to account for the above factors, indirect and laboratory methods can provide useful supplemental data encompassing spatial variability over a larger portion of a site than is typically possible using field methods performed at a more limited number of locations.

D-5. Field Methods

a. Pneumatic pump tests (air permeability tests). Pneumatic pump tests offer an alternative to indirect and laboratory methods for calculating air permeability. These tests tend to provide more realistic estimates of air permeability and are capable of characterizing a larger portion of the unsaturated zone at each test location. A number of investigators (e.g., Johnson, Kemblowski, and Colthart 1990b; McWhorter 1990; and Massmann 1989) have developed transient and steady-state solutions for airflow, which can be used for analysis of pneumatic pump test data. These solutions are described further below.

(1) Pneumatic pump tests can be conducted using extraction wells in the same manner as groundwater pump tests. Since flow equations are also available for point sinks and horizontal line sinks, extraction points or trenches can also be used. Monitoring probes are installed adjacent to the extraction vent to collect pressure data as a function of distance and time. The effects of layered heterogeneities and vertical anisotropy can be extremely important, and it is strongly recommended that they be evaluated using vertically spaced monitoring probes (multidepth probe clusters). Likewise, lateral heterogeneities and horizontal anisotropy can be evaluated using horizontally spaced monitoring probes. Ideally, horizontally spaced monitoring probes should be installed in two perpendicular directions, with spacing increasing logarithmically with distance from the vent (e.g., 0.2 m, 2 m, 20 m, etc.). The perpendicular orientation allows evaluation of anisotropy within the horizontal plane, and the logarithmic spacing allows preparation of distance-drawdown plots for evaluation of well efficiency.

(2) Although pressure measurements should be recorded at the extraction vent to evaluate well efficiency, these measurements should *not* be used for air permeability calculations. Fitting the compressible flow solution to radial distance drawdown data typically predicts measured vacuums at the extraction vent that are two to five times lower than the actual measurements at the extraction vent. This is probably the result of water buildup near the extraction vent. If the vent is screened near the water table, or if the soil moisture content exceeds residual saturation, the increase in capillary pressure caused by the induced vacuum will tend to increase water saturations. Increased water saturations will be greatest

immediately adjacent to the vent. Figure 4-2 shows that for predominantly air-filled soils, even a slight increase in water saturation significantly reduces the air permeability. As a result, the pressure gradient and measured vacuum near the extraction well will be much higher than that predicted assuming a constant water content (McWhorter 1990).

b. Transient solutions. Transient solutions may be used for evaluation of low-permeability soils, or for determination of air permeability prior to redistribution of soil moisture as a result of the induced vacuum (or pressure). Rapid pressure measurements should be recorded upon startup, with measurement intervals increasing with time (e.g., 10-second intervals for the first 2 minutes, 30-second intervals for the next 8 minutes, 1-minute intervals for the next 20 minutes, and so on).

(1) The solution method should be selected based on the geometry of the vadose zone and the vent being tested. One-dimensional radial solutions should be used for fully penetrating wells in vadose zones with upper and lower impermeable boundaries (e.g., Massmann 1989; McWhorter 1990, Johnson, Kemblowski, and Colthart 1990b). These solutions can also be used for partially penetrating wells, provided that measurement points are located at least 1- times the vadose zone thickness from the extraction well.

(2) McWhorter (1990) developed an exact, quasi-analytic solution for transient one-dimensional radial flow. Although the solution has the capability to incorporate gas slippage, the analysis method outlined below assumes that the Klinkenberg factor (a measure of gas slippage) has been set equal to zero. Accordingly, McWhorter (1990) refers to air permeability as the apparent gas permeability.

(3) McWhorter's solution is applied by preparing a graph of $(P/P_{atm})^2$ versus ln (r^2/t), where P is the absolute pressue measured at distance r, P_{atm} is atmospheric pressure, and t is time since the start of the test. The slope of the line is then used to calculate the apparent gas permeability using the equation

$$k_a = - \frac{R\,T\,\mu\,Q_m}{2\,\pi\,b\,M\;P_{atm}^2\,slope} \qquad \text{D-9}$$

where

k_a = apparent gas permeability reflecting the air-filled and not the water-filled pore space

R = gas constant

T = absolute temperature

Q_m = mass flow rate

b = unsaturated zone thickness

M = molecular weight

(4) Johnson, Kemblowski, and Colthart (1990b) developed an approximate solution for transient radial two-dimensional flow by linearizing the partial differential equation (PDE) for transient flow (see paragraph 2-4*d*).

(5) As described in paragraph 2-4*c*, the solution to the linearized PDE for a constant sink at $r = 0$, with $P = P_{atm}$ at $r = 4$, is (Johnson et al. 1990b):

$$P - P_{atm} = \frac{Q_v \mu}{4 \pi b k_a} \int_u^\infty \frac{e^{-x}}{x} dx \qquad \text{D-10}$$

where

P = absolute pressure [M/LT^2]

P_{atm} = atmospheric pressure [M/LT^2]

Q_v = volumetric flow rate [L^3/T]

μ = dynamic viscosity [M/LT^2]

b = the thickness of the vadose zone or stratum of interest [L]

x = a dummy variable of integration, and

$$u = \frac{r^2 n_a \mu}{4 k_a P_{atm} t} \qquad \text{D-11}$$

where

r = radial distance [L]

n_a = air-filled porosity [L^3/L^3]

t = time

(6) Equation D-10 is sometimes written as

$$P - P_{atm} = \frac{Q_v \mu}{4 \pi b k_a} W(u) \qquad \text{D-12}$$

where $W(u)$ is the Theis well function. Equation D-12 can be solved for air permeability as:

$$k_a = \frac{Q_v \, \mu \, W(u\ )}{4 \pi \, b \, k_a (P - P_{atm})} \tag{D-13}$$

and Equation D-11 can be solved for air-filled porosity as:

$$n_a = \frac{4 \, k_a \, P_{atm} \, t}{r^2 \, \mu} u \tag{D-14}$$

(7) By fitting a log-log plot of $P - P_{atm}$ versus time to the Theis "type curve" ($W(u)$ vs. $1/u$), a point along the type curve can be selected where values of $P - P_{atm}$ and t correspond to a particular u and $W(u)$. These values can be subsituted into Equations D-13 and D-14 to obtain values of air permeability and air-filled porosity.

(8) In a similar manner, plots of $P - P_{atm}$ versus time can be fitted to type curves for the leaky well function (paragraph 2-4*c*) to obtain values of air permeability, air-filled porosity, and the vertical air permeability of a leaky confining layer.

(9) The Cooper-Jacob approximation offers a somewhat simpler method for analysis of transient air permeability test data (paragraph 2-4*c*). The Cooper-Jacob approximation applies when $u \leq 0.01$ (i.e., small radial distances or large values of time), and is written as:

$$P - P_{atm} = \frac{Q_v \, \mu}{4 \pi \, b \, k_a} \left(\ln \frac{4 \, k_a \, P_{atm} \, t}{r^2 \, n_a \, \mu} - 0.5772 \right) \tag{D-15}$$

(10)When u # 0.01, a plot of pressure vs $ln(t)$ should show a straight line with slope:

$$m = \frac{Q_v \, \mu}{4 \pi \, b \, k_a} \tag{D-16}$$

where

m = the change in pressure over one log cycle

(11)The time intercept when $P - P_{atm} = 0$ should occur is:

$$\ln \frac{4 \, k_a \, P_{atm} \, t_o}{r^2 \, n_a \, \mu} = 0.5772 \tag{D-17}$$

where

t_o = the time intercept when P - P_{atm} = 0

(12)Equation D-16 can be rearranged in terms of air permeability:

$$k_a = \frac{Q_v \, \mu}{4 \, \pi \, b \, m} \qquad \text{D-18}$$

(13)Likewise, equation D-17 can be solved for the air-filled porosity:

$$n_a = 2.25 \, \frac{k_a \, P_{atm} \, t_o}{r^2 \, \mu} \qquad \text{D-19}$$

c. Steady state solutions. Steady state solutions can be used for air permeability tests, provided that sufficient time is allowed for flow to stabilize. Estimates of the length of time necessary to reach steady-state for one-dimensional radial flow can be developed by noting that the slope of the Theis type curve is small for u # 0.01, indicating that there is little change in P - P_{atm} over time. By choosing a point on the Theis type curve (or leaky type curves, if used) where further changes in W(u) are considered negligible, the time to reach steady state can be calculated according to:

$$t = \frac{r^2 \, n_a \, \mu}{4 \, k_a \, P_{atm} \, \varepsilon} \qquad \text{D-20}$$

where

ε = the value of *u* for which further changes in *W*(*u*) are considered negligible

(1) For some conditions, steady state solutions may provide a better estimate of air permeability than transient methods. These conditions include sites with an unsealed ground surface, or where applied vaccums (or pressures) are greater than 0.2 atmospheres. Although transient test data from sites with leaky surface covers can be evaluated using the leaky well function, this analysis treats air as an incompressible fluid. In contrast, steady state solutions treat air as a compressible fluid. As shown by Massmann (1989), these effects are significant for applied vacuums greater than 0.2 atmospheres, gauge.

(2) For the case of one-dimensional radial flow, steady state solutions can also be used to analyze transient permeability test data, provided that *u* # 0.01. This condition is known as the pseudo-steady state (McWhorter and Sunada 1977), and is described in paragraph 2-4*d*.

(3) For one-dimensional radial flow, the steady state solution is given by Equation 2-20. This equation can be written for two discrete measurement points as:

$$k_a = \frac{Q_v P^* \mu}{\pi b} \frac{\ln(r_2 / r_1)}{P_1^2 - P_2^2} \qquad \text{D-21}$$

where

Q_v = volumetric flow rate [L^3/T] (extraction flow is considered to be negative)

P^* = pressure at the point of flow measurement [M/LT^2]

r_1, r_2 = radial distance to observation points [L]

P_1, P_2 = absolute pressures at observation points [M/LT^2]

(4) Since the vacuums measured at extraction wells are commonly exaggerated by reduced well efficiency, these data should not be used for determination of air permeability. However, in conjunction with wellbore vacuums calculated using Equation 2-20, these data can be used to calculate well efficiency via Equation 4-6.

(5) A steady state solution for two-dimensional radial flow is given in Equation D-22 below (see paragraph 2-4*c*).

(6) Equation D-22 can be used to determine the horizontal and vertical air permeability using methods outlined by Shan, Falta, and Javandel (1992), or computer programs can be used to fit field data to Equation D-22 as a function of horizontal and vertical air permeability. The vertical air permeability can be determined by scaling the horizontal coordinate axis (r) using Equation E-8 until the best fit of field data is obtained. The vertical air permeability can then be determined from the horizontal air permeability and the appropriate scaling factor. An example of field data fitted to Equation D-22 is shown in Figures D-1 and D-2.

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2\pi k_a (L - l)} \left[\begin{array}{c} \ln\left(\dfrac{z - l + \sqrt{r^2 + (z - l)^2}}{z - L + \sqrt{r^2 + (z - L)^2}} \bullet \dfrac{z + L + \sqrt{r^2 + (z + L)^2}}{z + l + \sqrt{r^2 + (z + l)^2}} \right) \\ - \displaystyle\sum_{n=1}^{\infty} (-1)^n \ln \left(\begin{array}{c} \dfrac{z - 2nb + L + \sqrt{r^2 + (z - 2nb + L)^2}}{z - 2nb + l + \sqrt{r^2 + (z - 2nb + l)^2}} \bullet \dfrac{z - 2nb - L + \sqrt{r^2 + (z - 2nb - L)^2}}{z - 2nb - l + \sqrt{r^2 + (z - 2nb - l)^2}} \bullet \\ \dfrac{z + 2nb - L + \sqrt{r^2 + (z + 2nb - L)^2}}{z + 2nb - l + \sqrt{r^2 + (z + 2nb - l)^2}} \bullet \dfrac{z + 2nb + L + \sqrt{r^2 + (z + 2nb + L)^2}}{z + 2nb + l + \sqrt{r^2 + (z + 2nb + l)^2}} \end{array} \right) \end{array} \right] \qquad \text{D-22}$$

d. Automated Permeability Analysis Tools. Falta (1996) presents software, GASSOLVE, that analyzes soil air permeability using transient or steady-state pressure/vacuum data collected during a field test. The software implements solutions for compressible airflow to a partially (or fully) penetrating well. A multi-dimensional non-linear optimization routine inverts the pressure data from multiple observation wells to determine air permeability. The software allows the user to specify the surface boundary condition as open (uncovered and allowing a direct communication between the atmosphere and the subsurface), leaky (surface covering or shallow strata that inhibits, but does not prevent, the communication with the atmosphere), or fully covered (no communication due to a tight seal such as a geomembrane). The software is a simple DOS program that uses ASCII text input files. When preparing the input file, the user can import well/time/vacuum data from another ASCII file or can enter the data manually. The software output includes the horizontal air permeability and, if a open site is assumed, and the vertical permeability of the soil. If a leaky surface is assumed, the program also computes a leakage value. The program also compares the predicted vacuum/pressure at each monitoring point to the observed values and computes the residual sum of squares and a total average error as a measure of the goodness of fit. The GASSOLVE software is available from the USACE HTRW CX (DoD staff and contractors only) or Dr. Falta at Clemson University.

e. Soil gas tracer studies.

(1) Soil gas tracer studies rely on the use of conservative gases which are injected into the subsurface through wells. The tests provide a method to calculate the breakthrough of a given gas as a function of the subsurface conditions (i.e., air permeability). The tests can be performed either under a natural or forced gradient. The selection of a suitable gas for a tracer study is dependent upon the properties of the gas and the availability of instrumentation for detecting the injected gas. A number of potential tracers have been cited in the literature, including sulfur hexafluoride, helium, methane, and argon.

(2) Tracer studies provide not only an estimate of the air permeability, but also provide empirical data on the pore volume exchange rate which is used to optimize the SVE/BV operation. The apparent vapor velocity can be calculated by dividing the distance between the tracer gas injection and detection points by the elapsed time from injection of the tracer gas to the appearance of the center of mass of the tracer slug at the detection point. By injecting tracer gas at one monitoring point at a time and detecting the arrival of the tracer at the test vent, an assessment of the anisotropy of a site can be made (Marley 1993).

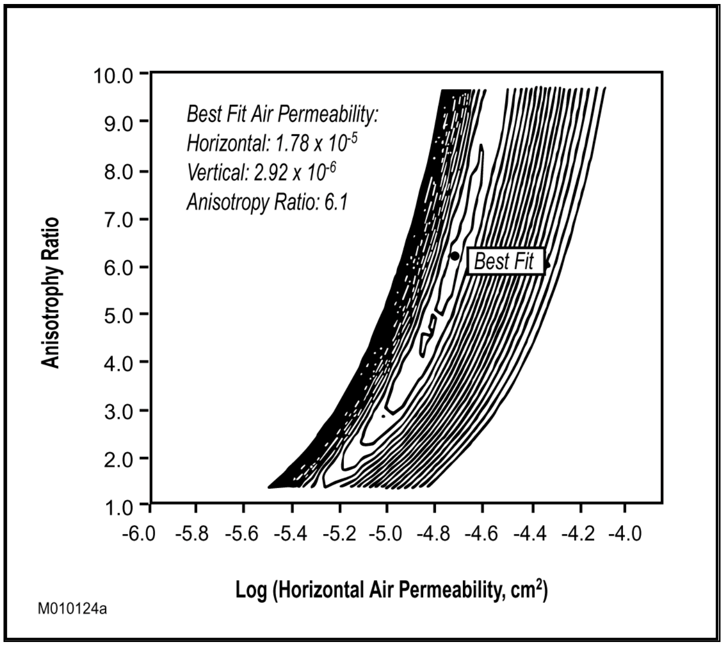

Figure D-1 Best fit of field data using Equation D-22

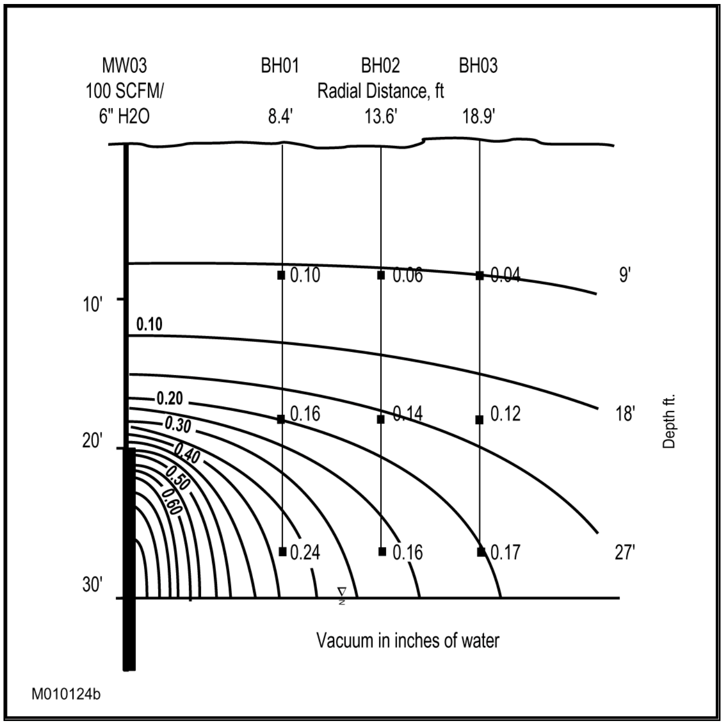

Figure D-2. Pressure isobars calculated using Equation D-22 and best-fit air permeabilities from Figure D-1.