

CONE PERMEAMETER™ – IN-SITU PERMEABILITY MEASUREMENTS WITH DIRECT PUSH TECHNIQUES

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ABSTRACT

Soil permeability, which defines the magnitude of fluid flow (gas or liquid) under imposed pressure gradients, is one of the most important hydrologic parameters to measure when predicting fluid or contaminant movement in the subsurface, designing environmental remediation systems, or simply characterizing a geologic site. Science and Engineering Associates, Inc. (SEA), has developed the Cone Permeameter™, a cone penetrometer technology that measures the in-situ air permeability or hydraulic conductivity in unconsolidated media. The cone permeameter rod incorporates a well-defined injection zone and multiple pressure ports placed at discrete locations from the injection zone. A permeability value is obtained by injecting a known flowrate of air or water, measuring the pressure response along the permeameter rod, and then applying a one-dimensional, spherical, steady-state Darcy flow model to the measured injection rate and pressure profile. Near to the injection point the pressure field is distorted by a combination of the cylindrical injection zone and the compacted soil near the rod surface. A fundamental premise of the measurement is that, as the distance from the injection point is increased, the resulting pressure distribution will become spherical. This method measures the pressure gradient far enough from the injection point to avoid the distorted field.

The Cone Permeameter™ measurement system has the following benefits over existing in-situ permeability methods:

- All the advantages of direct push: minimal waste, risk reduction, fast emplacement, low unit measurement cost
- 3 to 10 minute measurement time per elevation
- Rapid mobilization and minimal site disturbance
- Complements standard CPT geophysical measurements
- Higher spatial resolution possible than borehole techniques (<10 vs. 50+ cm.)
- Potentially more accurate and quantified permeability measurements
- Compared to the pore pressure dissipation technique, which can only measure in low permeability water saturated media, the Cone Permeameter™ system can measure five orders of magnitude in both saturated and unsaturated environments

The initial research and feasibility assessment of this system was completed in early 1997 as the first phase of a contract supported by the DOE Characterization,

Monitoring, and Sensor Technology (CMST) program through the Federal Energy Technology Center. In the second phase of this same study the Cone Permeameter™ system was successfully employed in the unsaturated zone and below the water table at the Savannah River Site in two separate demonstrations in April and June of 1998. A third deployment took place in November 1998 at the Hanford site, and a fourth at Cape Canaveral in December 1998 and January 1999. This presentation will detail the measurement approach and review field measurement results.

THE NEED FOR PERMEABILITY DATA

Soil permeability defines the magnitude of fluid flow (gas or liquid) under imposed pressure gradients. It is one of the most important parameters to measure when predicting fluid or contaminant movement in the subsurface, designing environmental remediation systems, or simply characterizing a site. In the case of saturated geologic media, natural pressure gradients exist due to changes in slope (hydraulic gradients). For unsaturated geologic media, changes in barometric pressure impose natural pressure gradients on soil gas. Unnatural pressure gradients are imposed by soil vapor extraction, active venting, pump-and-treat, air sparging, in-situ vitrification, and other remediation processes requiring the active movement of fluids through geologic media. The design of these processes requires knowledge of the flow characteristics of the soil. The most important is its permeability. Soil permeability can vary by several orders of magnitude in a given geologic or hydrogeologic setting. The variability of permeability is illustrated by the range of values shown in the table below for different media.

Table 1. Typical permeability values for various media (1 Darcy equals $9.87 \times 10^{-9} \text{ cm}^2$).

Media	Sat. Hydraulic Conductivity K (cm/s)	Permeability k (Darcy)
Clay	4.6e-7	4.8e-4
Sand	4.7e-2	49
Gravel	4.7	4900
Gravel/Sand Mixture	0.47	490
Sandstone	4.7	4900
Limestone/Shale	4.7e-5	4.9e-2
Granite	4.6e-7	4.8e-4

CURRENT METHODS

In-situ permeability measurements are typically conducted in open or screened holes formed by conventional drilling techniques. In saturated geologic media, the permeability is obtained with borehole flowmeters, drawdown tests, or isolated packer

measurements. Soil gas permeability measurements are obtained either with total borehole flow or isolated packer measurements in uncased or screened wells. Obtaining permeability data in conventionally drilled boreholes can be expensive, primarily due to the cost of borehole installation.

If it is possible to measure permeability with direct push techniques like cone penetrometers, sonic emplacements, or smaller manual or truck-mounted equipment (such as Geoprobos), significant savings can be realized through reduced time, increased safety, minimal secondary waste generation, and integration with the other measurements obtained during the process (such as the geophysical data obtained during instrumented cone penetrometer emplacements).

THE CHALLENGE OF PERMEABILITY MEASUREMENTS WITH DIRECT PUSH TECHNIQUES

Direct push emplacements pose difficult measurement problems for permeability determinations. Typically, the rods are relatively small, restricting the size of instrument hardware that can be used for the measurement. In cone penetrometer applications (CPT), for example, the rod outside diameter may be 2" and the inside diameter only 0.75". The major issue, however, is the reduction in permeability adjacent to the rod surface due to the compaction of the soil caused by the rod emplacement. This alteration of the soil flow characteristics can be significant and would result in artificially low permeability data with conventional techniques. A method called the pore pressure dissipation technique has been used with cone penetrometers to obtain hydraulic conductivity in saturated soils, and actually capitalizes on the compaction to obtain permeability data. This method uses the pore pressure instrumentation in the cone penetrometer tip to sense the buildup and decay of pore pressure due to the emplacement of the rod and the resulting compaction of the soil adjacent to the rod. The approach requires some understanding of soil type to infer permeability, but its major limitation is that if the soil permeability is too high the pore pressure will increase only slightly and decay too quickly to measure. Consequently, this technique is typically applied in soils with permeability below 10^{-4} Darcies (10^{-7} cm/s hydraulic conductivity) in water saturated conditions.

THE THEORY

Darcy's law is the classical representation for low Reynolds number flow in porous media. It predicts volumetric flow as being proportional to the fluid pressure gradient. Hydrogeologists frequently use permeability to specifically describe water flow through soil, incorporating the fluid viscosity in the term. This term is also frequently referred to as the *saturated hydraulic conductivity*, K .

Air permeability is the permeability of the soil media to air flow in its existing condition, wherein the moisture saturation of the soil is not necessarily known and is considered part of the soil matrix. It is commonly used in the form independent of fluid properties, k . The air permeability of a soil sample will change as the degree of water saturation changes, and is equal to the intrinsic permeability when the soil is at its lowest achievable water saturation.

The basic premise of the Cone PermeameterTM approach is that as fluid is injected (or extracted) from a discrete section of the penetrometer string, it will tend to result in a spherical flow field as the fluid moves outward from the rod. The flow field will become essentially spherical, even if the soil adjacent to the rod is of a much lower permeability (due to compaction). Eventually, for a given injection rate, the radial pressure profile along the axis of the penetrometer rod is identical to that which would occur if the rod (and compacted soil) did not exist. Measurement of the pressure gradient at a distance from the injection point produces adequate information to accurately infer the permeability.

The spherical flow model evolves from the classic Darcy porous flow relation. The injection or extraction source is represented as a spherical volume with radius r_o . Fluid is added to (or removed from) the zone at a known rate. The medium has a permeability, k , which is assumed homogeneous. At some distance r_{inf} the pore fluid pressure is at ambient conditions (P_A).

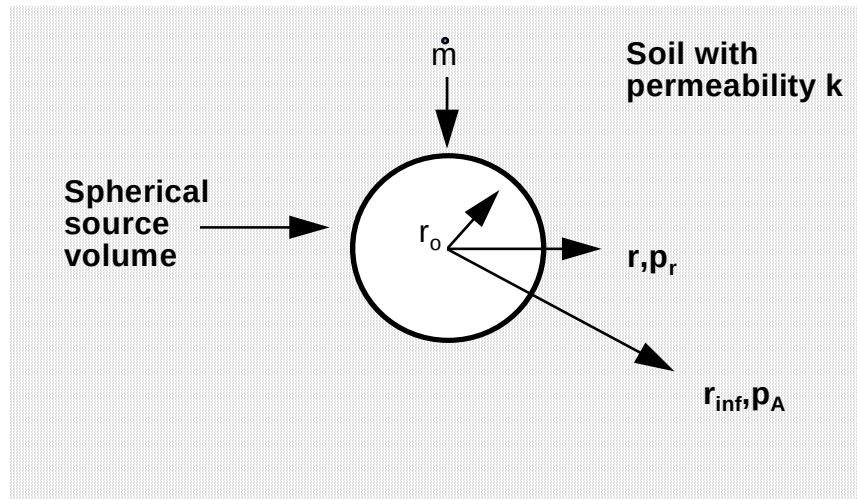


Fig. 1. One-dimensional spherical flow geometry.

Darcy's law defines the steady state volumetric flow rate per unit area (u , also known as the Darcy velocity) in a one-dimensional geometry as

$$u = \frac{-k}{\mu} \frac{dp}{dx} \quad (\text{Eq.1})$$

where dp/dx is the applied pressure gradient causing the flow, k is the permeability of the medium, and μ is the dynamic viscosity of the fluid. For one-dimensional flow, the volumetric flow rate Q over the entire area of interest is

$$Q = \int_A u \cdot dA = - \int_A \frac{k}{\mu} \cdot \frac{dp}{dx} \cdot dA \quad (\text{Eq.2})$$

The mass flow rate can then be determined as

$$\dot{m} = - \int_A \rho \cdot \frac{k}{\mu} \cdot \frac{dp}{dx} \cdot dA \quad (\text{Eq.3})$$

To apply this in the measurement of effective soil gas permeability, the derivation considers gas flow in the accessible porosity of the soil. For an ideal compressible gas the equation of state can be written as

$$\rho = \frac{P}{RT} \quad (\text{Eq.4})$$

where R is the gas constant (the universal gas constant divided by the gas molecular weight), and T is the absolute temperature. Substitution of the ideal compressible gas equation into the mass flow rate equation, replacing dp/dx by dp/dr , and integrating over the area of a sphere gives

$$\dot{m} \left(\frac{1}{r_0} - \frac{1}{r} \right) = \frac{-2\pi k}{\mu RT} \cdot (P^2 - P_0^2) \quad (\text{Eq.5})$$

where P_0 is the pressure at the source location r_0 , and P is the pressure at some distance r. Solving for k yields the flow model used in the Cone PermeameterTM air permeability method:

$$k = \frac{\mu RT \dot{m}}{2\pi(P_0^2 - P^2)} \cdot \left(\frac{1}{r_0} - \frac{1}{r} \right) \quad (\text{Eq.6})$$

A similar derivation is used for saturated hydraulic conductivity measurements with the spherical geometry. The only difference in this case is that the fluid density ρ is constant, instead of pressure dependent. Solving for k under these conditions produces an equivalent relationship for incompressible flow:

$$k = \frac{\mu \dot{m} \left(\frac{1}{r_0} - \frac{1}{r} \right)}{4\pi\rho(P - P_0)} \quad (\text{Eq.7})$$

These models are readily incorporated in the field measurement system to produce results while the measurement is being conducted.

THE CONE PERMEAMETERTM FIELD SYSTEM

A penetrometer rod section is fabricated to allow air or water injection through a screened region. The radial pressure profile is measured with multiple pressure measurement ports distributed above or below the extraction zone. These points are filtered penetrations into the probe that allow pressure communication to sensors embedded in the rod. The permeameter is fabricated in a standard 2" diameter rod, with five pressure ports ranging from 0.02 m to 0.7 m from the injection zone. At the surface a fluid pumping system controls the injection flowrate. The data system collects the flow rate and resulting pressure profiles, then calculates in real time the inferred permeability.

The field system is shown in fig. 2. The Cone PermeameterTM rod, designed and fabricated by Applied Research Associates, Inc., incorporates a proven fluid injection design and highly accurate pressure sensing elements embedded in the rod. The design allows the permeability measurements to be conducted simultaneously with standard CPT

cone measurements (pore pressure, tip, and sleeve pressure), which results in real time, complementary data sets of soil type and hydrogeologic properties. The data system provides detailed analyses of pressure profiles and process histories for real-time display.



Fig. 2. Pump box, data-acquisition system, and permeameter rod.

Results of lab-scale tests in a cubic meter test cell are depicted in the plot below. Using a mixture of silica flour and sand to achieve a 1 Darcy medium, the Cone PermeameterTM measured an air permeability of 0.68 Darcy. The pressure profile was spherical from less than 0.1 m to the outer measurement port location at 0.7 m (fig. 3).

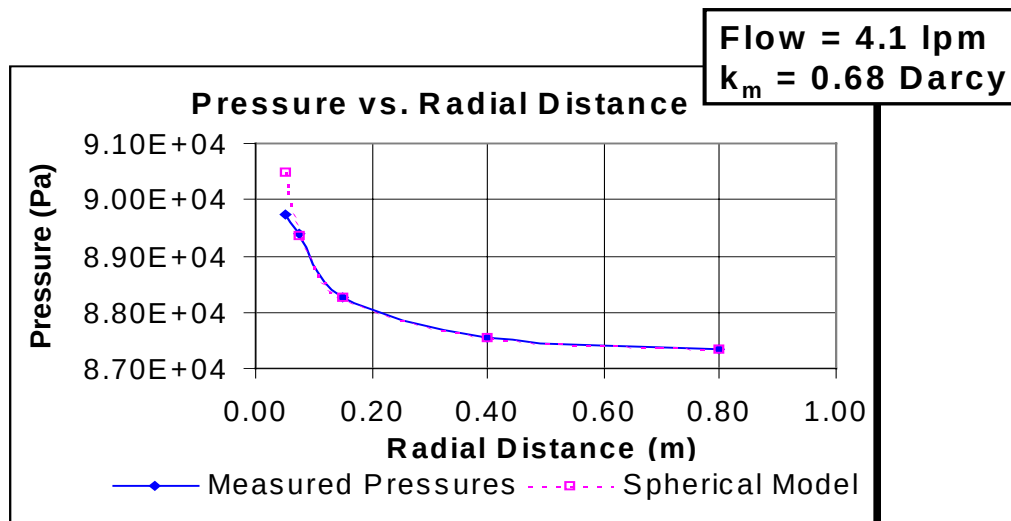


Fig 3. Laboratory pressure profile and inferred permeability in 1 Darcy soil.

CASE STUDY: SATURATED HYDRAULIC CONDUCTIVITY TESTING AT THE SAVANNAH RIVER SITE D AREA COAL PILE RUNOFF BASIN

The first demonstration of the Cone PermeameterTM measurement system was conducted 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 (1). The area is underlain by a series of interbedded sand, silt, and clay layers. The groundwater beneath the site is divided into two aquifer systems. The shallow system contains a water table aquifer and a semi-confined aquifer. The water table and semi-confined aquifers are separated by a dark silty clay semi-confining unit that is 10 to 15 feet thick. The top of the semi-confining unit is 50 to 60 ft. deep.

These tests 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 PermeameterTM was integrated with a standard CPT cone tip and deployed by Applied Research Associates using a 30-ton truck loaded to 26 tons. CPT data (pore pressure, sleeve stress, tip stress) was obtained simultaneously with the permeameter measurements. The permeameter measurements typically required pushing the rod to the desired depth, starting water injection, and observing flow and pressure histories until a relatively steady condition was attained. This required from 3 to 10 minutes per measurement station. On the second day of testing 35 measurements were obtained in a five-hour period.

The Cone PermeameterTM data can be compared with borehole flowmeter and total flow saturated conductivity measurements taken in well DCB-25, approximately 15-ft. distant. Drawdown measurements taken in 1996 resulted in saturated hydraulic conductivities (horizontal) ranging from $5.9\text{E-}5$ to $1.1\text{E-}3$ cm/s, depending on the monitor well 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 PermeameterTM data is plotted in fig. 4, compared with the previous borehole flowmeter tests in DCB-25. Borehole flowmeter data for both the high ($1.1\text{E-}3$ cm/s) and low ($5.9\text{E-}5$ cm/s) bulk conductivity cases are plotted, indicating the range of uncertainty in the borehole flowmeter data. The Cone PermeameterTM data generally falls between the high and low conductivity values.

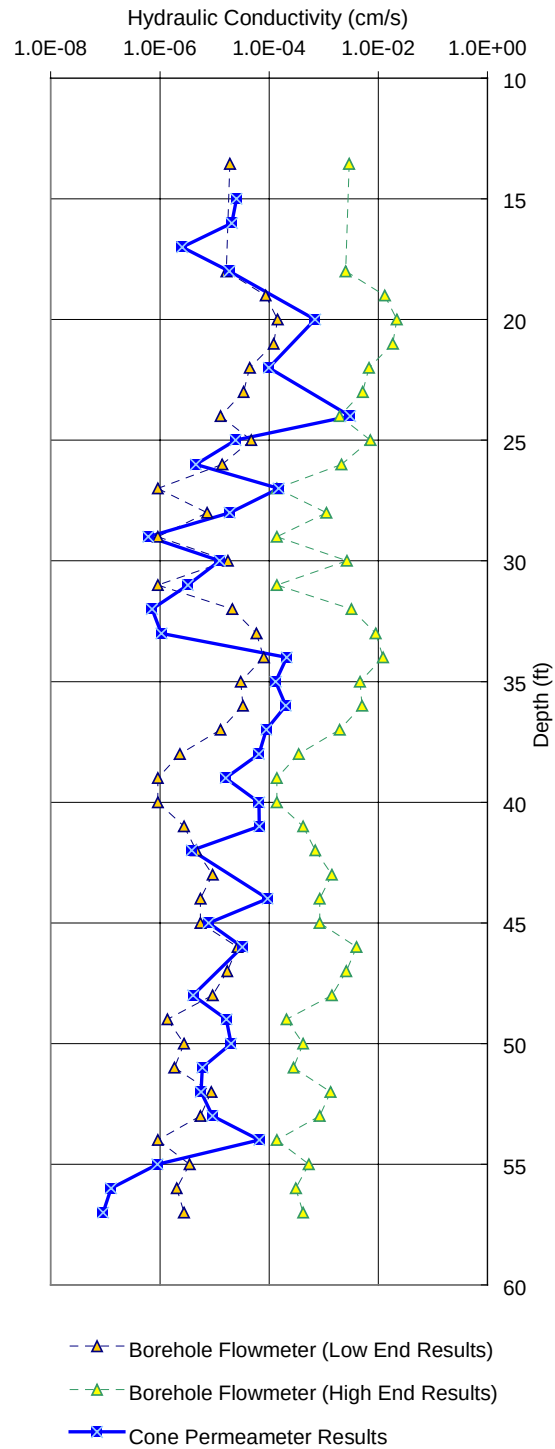


Fig. 4. Cone PermeameterTM saturated hydraulic conductivity data (near DCB-25) from the Savannah River Site.

STATUS OF THE CONE PERMEAMETER™ SYSTEM

The initial research and feasibility assessment of this system was completed in early 1997 for a contract supported by the DOE Characterization, Monitoring, and Sensor Technology (CMST) program through the Federal Energy Technology Center. Numerical modeling and laboratory tests demonstrated that the basic premise of the system's operation was credible. The pressure fields resulting from injection of air and water into a mockup probe were spherical, and they could be measured in such a fashion that the near field compaction resulting from the penetrometer emplacement could be avoided. Results from this study are documented in a topical project report (2).

Given the positive results of the initial feasibility assessment, an engineering prototype of the measurement system was successfully employed both in the vadose zone and below the water table in three different areas at the Savannah River Site (SRS). Results from this effort showed excellent agreement with previous permeability testing done at the site. The data also had a positive correlation with other cone penetrometer physical measurements taken concurrently during the testing sequence (i.e., the permeability was higher in layers identified as sands and lower in areas composed of clay). A final field test of the Cone Permeameter™ for the CMST contract was completed in December 1998 and January 1999 at Launch Complex 34, of the Cape Canaveral Air Station, Florida. This data is under review.

The technology was also successfully fielded in the vadose zone at two additional sites in 1998. With sponsorship from Westinghouse Savannah River Company in June 1998, the Cone Permeameter™ was used to characterize the air permeability of the existing clay liner at the Area E Burial Grounds at SRS. Over a two-day period, measurements were conducted at 10 different locations. Most recently (November, 1998), the Cone Permeameter™ was employed at the 200 East Area of the Hanford Site, where air permeability measurements were performed in the Hanford Formation. Permeability results from this test are currently under review and have not been released.

Once the field demonstrations are completed, and minor modifications have been incorporated into the rod design, the Cone Permeameter™ system will be available for sale to support cone penetrometer operations. Adaptation of the design to smaller emplacement systems, such as Geoprobe units, is anticipated.

REFERENCES

1. M.A. PHIFER ET AL., "Interim Report, D-Area Interceptor Well, DIW-1 Water Table Aquifer (U)," Westinghouse Savannah River Company (September 1996)
2. WILLIAM LOWRY, NEVA MASON, and DAN MEREWETHER, "In-situ Permeability Measurements with Direct Push Techniques: Phase I Topical Report," SEASF-96-147, Science & Engineering Associates (November 1997)