Designation: D8037/D8037M – 16

Standard Practice for Direct Push Hydraulic Logging for Profiling Variations of Permeability in Soils[1]

This standard is issued under the fixed designation D8037/D8037M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice describes a method for rapid delineation of variations in formation permeability in the subsurface using an injection logging tool. Clean water is injected from a port on the side of the probe as it is advanced at approximately 2cm/s into virgin soils. Logging with the injection tool is typically performed with direct push equipment, however other drilling machines may be modified to run the logs by direct push methods (for example, addition of a suitable hammer and/or hydraulic ram systems). Injection logs exceeding 100 ft [30m] depth have been obtained. Direct push methods are not intended to penetrate consolidated rock and may encounter refusal in very dense formations or when cobbles or boulders are encountered in the subsurface. However, injection logging has been performed in some semi-consolidated or soft formations.

1.2 This standard practice describes how to obtain a real time vertical log of injection pressure and flow rate with depth. The data obtained is indicative of the variations of permeability in the subsurface and is typically used to infer formation lithology. The person(s) responsible for review, interpretation and application of the injection logging data should be familiar with the logging technique as well as the soils, geology and hydrogeology of the area under investigation.

1.3 The injection logging system may be operated with a built in electrical conductivity sensor to provide additional real time information on stratigraphy and is essential for targeting test zones. Other sensors, such as fluorescence detectors (Practice D6187), a membrane interface probe (Practice D7352) or a cone penetration tool (Test Method D5778) may be used in conjunction with injection logging to provide additional information. The use of the injection logging tool in concert with an electrical conductivity array or cone penetration tool is highly recommended (although not mandatory) to further define hydrostratigraphic conditions, such as migration pathways, low permeability zones (for example, aquitards) and to guide confirmation sampling. The EC log and injection pressure log may be compared in some settings to identify the presence of ionic contaminants or ionic injectates used for remediation.

1.4 The injection logging system does not provide quantitative permeability or hydraulic conductivity information. However, injection pressure and flow data may be used to provide a qualitative indication of formation permeability. Semi-quantitative values of permeability may be obtained by correlation of injection logging data with other methods (**1-4**).[2] Also, a log of estimated hydraulic conductivity (**5**) may be calculated for the saturated zone using an empirical model included in some versions of the log viewing software. The data allows for estimates of hydraulic conductivity (K) at the inch-scale using the corrected injection pressure and flow rate.

1.5 This tool is to be used as a logging tool for the rapid delineation of variations in permeability, lithology and hydrostratigraphy in unconsolidated formations. Direct push soil sampling (Guide D6282) and slug testing (Practice D7242) by means of groundwater sampling devices (Guide D6001) or direct push monitoring wells (Guide D6724 and Practice D6725) may be used to validate injection log interpretation, permeability and hydraulic conductivity estimates. Other aquifer tests (Guide D4043) in larger wells can also be used to obtain additional information about permeability and hydraulic conductivity. However, correlation of results from long screened wells with the fine detail of the hydraulic injection log data may be difficult at best due to the effect of scale in measurements of transmissivity (**6**).

1.6 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026, unless superseded by this standard.

1.7 The values stated in either inch-pound units or SI units [presented in brackets] are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

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[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Groundwater and Vadose Zone Investigations.

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[2] The boldface numbers in parentheses refer to a list of references at the end of this standard.

1.8 *This practice offers a set of instructions for performing one or more specific operations. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this practice may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without the consideration of a project's many unique aspects. The word "standard" in the title means that the document has been approved through the ASTM consensus process.*

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D653 Terminology Relating to Soil, Rock, and Contained Fluids
D1587 Practice for Thin-Walled Tube Sampling of Fine-Grained Soils for Geotechnical Purposes
D2434 Test Method for Permeability of Granular Soils (Constant Head) (Withdrawn 2015)[4]
D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction
D4043 Guide for Selection of Aquifer Test Method in Determining Hydraulic Properties by Well Techniques
D5084 Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter
D5088 Practice for Decontamination of Field Equipment Used at Waste Sites
D5092 Practice for Design and Installation of Groundwater Monitoring Wells
D5299 Guide for Decommissioning of Groundwater Wells, Vadose Zone Monitoring Devices, Boreholes, and Other Devices for Environmental Activities
D5778 Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils
D5856 Test Method for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall, Compaction-Mold Permeameter
D6001 Guide for Direct-Push Groundwater Sampling for Environmental Site Characterization
D6026 Practice for Using Significant Digits in Geotechnical Data
D6067 Practice for Using the Electronic Piezocone Penetrometer Tests for Environmental Site Characterization
D6187 Practice for Cone Penetrometer Technology Characterization of Petroleum Contaminated Sites with Nitrogen Laser-Induced Fluorescence
D6282 Guide for Direct Push Soil Sampling for Environmental Site Characterizations
D6724 Guide for Installation of Direct Push Groundwater Monitoring Wells
D6725 Practice for Direct Push Installation of Prepacked Screen Monitoring Wells in Unconsolidated Aquifers
D7242 Practice for Field Pneumatic Slug (Instantaneous Change in Head) Tests to Determine Hydraulic Properties of Aquifers with Direct Push Groundwater Samplers
D7352 Practice for Direct Push Technology for Volatile Contaminant Logging with the Membrane Interface Probe (MIP)

3. Terminology

3.1 *Definitions:*

3.1.1 Definitions are in accordance with Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *atmospheric pressure (P_{atm}), n*—relative to injection logging, the atmospheric pressure is measured with the downhole pressure sensor during the reference test when no water is being pumped through the probe, the bottom valve is open on the reference tube, and the water level in the reference tube is stable.

3.2.2 *corrected injection pressure (P_c), n*—relative to injection logging, the corrected injection pressure is calculated by subtracting the measured atmospheric pressure (P_{atm}) and the piezometric pressure (P_{piezo}) from the total injection pressure (P_{tot}) at a specified depth increment (i). That is:

$$P_{c(i)} = P_{tot(i)} - \left(P_{atm(i)} + P_{piezo(i)}\right)$$

3.2.3 *dissipation test, v—relative to injection logging*, a test made by halting the advancement of the probe, shutting off injection flow, and recording the change (decay) in ambient formation pressure with time, also called a pressure dissipation test.

3.2.3.1 *Discussion*—When the excess pressure in the formation caused by water injection and probe advancement has fully dissipated then the observed pressure provides a measurement of the formation piezometric pressure (P_{piezo}) when the probe is below the water level. It is recommended to perform dissipation tests in higher permeability materials (sandy) so that dissipation occurs quickly to stability. Changing pressure in the formation (such as caused by a nearby extraction or injection well) will result in changing piezometric pressure over time. These conditions will influence the piezometric profile determined from dissipation tests.

3.2.4 *injection port, n*—relative to injection logging, a replaceable screened orifice approximately 0.4-in. [10mm] in diameter on the side of the HPT probe where water is injected into the formation as the probe is advanced into the subsurface.

3.2.5 *piezometric pressure (P_{piezo}), n*—relative to injection logging, the piezometric pressure is the stabilized pressure measured during a dissipation test when the probe is below the piezometric surface, the probe is not moving and no water is being pumped through the probe.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] The last approved version of this historical standard is referenced on www.astm.org.

3.2.6 *total injection pressure (P_{tot}), n*—relative to injection logging, the total injection pressure is the pressure observed by the down-hole sensor as the probe is being advanced while water is injected into the formation through the injection port.

3.2.7 *trigger, n*—relative to injection logging, mechanical interface between the operator and instrumentation to initiate or terminate data collection.

3.3 *Symbols:*

3.3.1 P_c—corrected injection pressure.

3.3.2 P_{tot}—total injection pressure.

3.3.3 P_{atm}—atmospheric pressure, as measured with the down-hole pressure sensor during a reference test.

3.3.4 P_{piezo}—piezometric pressure (same as Hydrostatic Pressure, μ_o, D653)

3.4 *Acronyms:*

3.4.1 *HPT, n*—Hydraulic Profiling Tool (see 6.1)

3.4.2 *MIP, n*—Membrane Interface Probe

3.4.3 *CPT, v*—Cone Penetration Test

3.4.4 *EC, adj*—Electrical Conductivity

3.4.5 *LIF, n*—laser induced fluorescence

3.4.6 *OIP, n*—Optical Image Profiler

4. Summary of Practice

4.1 This practice describes the field method for performing an injection log. A steel probe is advanced through unconsolidated soils and sediments at approximately 2cm/s while clean water is injected into the formation through a screened port on the side of the probe. An in-line pressure transducer just above the port (or at the surface) measures the pressure required to inject water into the formation while a flow meter at the surface measures the rate of water injection. Drive rods are incrementally added to the tool string as the probe is advanced to depth using direct push methods. Injection logs exceeding 100 ft [30m] depth have been obtained. Total log depth is controlled by soil and formation conditions and equipment push capacity.

4.2 The injection probe may include an electrical conductivity (EC) array. This array is used to measure the bulk formation electrical conductivity as the probe is advanced to depth and provides independent, real time stratigraphy data during the testing. Sometimes injection probes are run with a companion cone penetration test (CPT) which provides tip resistance and sleeve friction data as the probe is advanced to depth (D6067). While neither an EC array nor a CPT module is required to run the injection log the additional independent data can be very useful to confirm the HPT log result and to provide additional valuable information about the subsurface.

4.3 An electronics system with portable computer and software acquires the injection pressure, water flow rate and bulk formation EC or CPT data as the probe is advanced. The pressure, flow and EC or CPT data are plotted on screen versus depth as the log is obtained for live time viewing and interpretation. The measured injection pressure and flow rate along with the EC or CPT data provides information about formation permeability, lithology and hydrostratigraphy.

4.4 At selected depths below the water table a pressure dissipation test may be conducted. Insertion of the probe into the formation and injection of water induces excess pore pressure as the probe is advanced. To conduct a pressure dissipation test probe advancement is halted and water flow is stopped. The down-hole pressure transducer is used to monitor decay of the excess pore pressure versus time. When the pore pressure stabilizes the pressure transducer is measuring the potentiometric pressure at that depth in the formation. This data may be used to calculate the local water level and piezometric profile. Often it is useful to conduct dissipation tests at several depths during a log, especially between possible confining layers. This may help to identify confined layers with different hydraulic head or vertical hydraulic gradients across a formation.

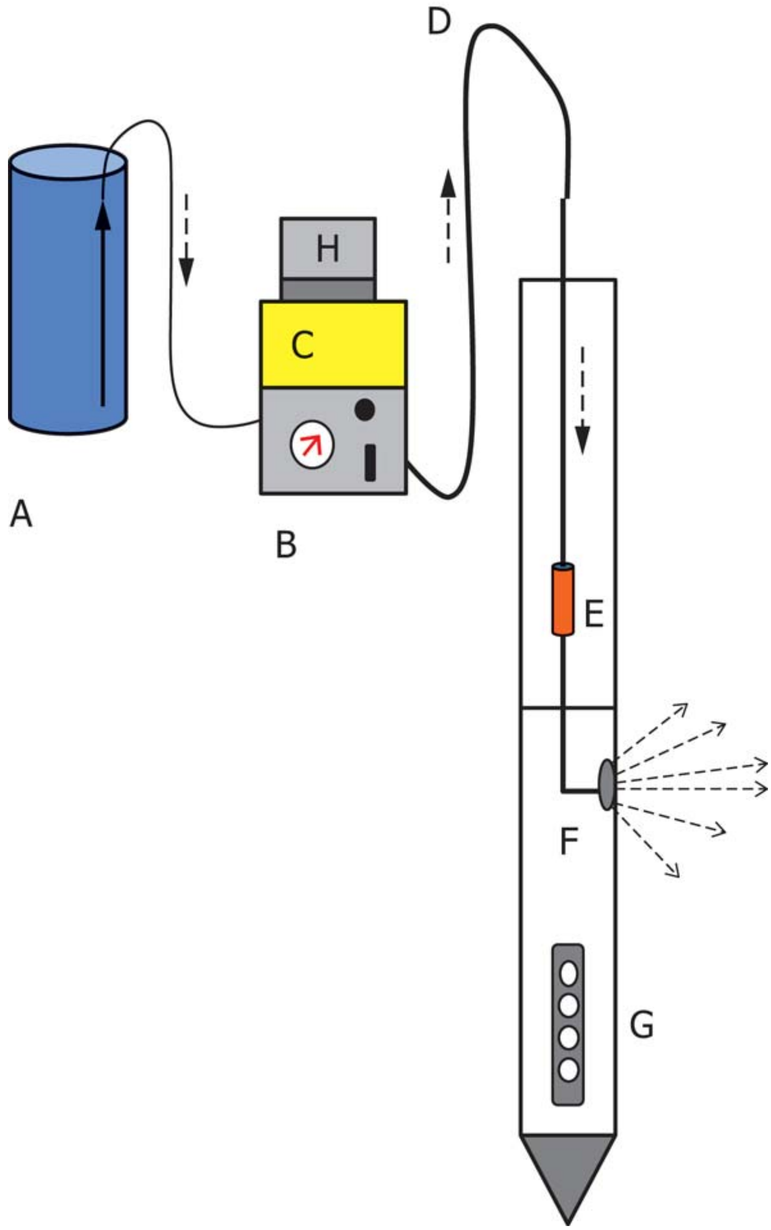
4.5 Logging is continued to the desired depth or until refusal is encountered. At that point data acquisition is stopped and the injection probe is retracted using the hydraulic system of the direct push machine.

5. Significance and Use

5.1 The injection logging system provides a rapid and efficient way to ascertain the pressure required to inject water into unconsolidated formations at the given flow rate in real time (Fig. 1) (**1-4, 7**).[5] The measured injection pressure and flow rate are then used to assess variations in formation permeability versus depth and infer changes in formation lithology and understand the local hydrostratigraphy (**1-4, 8-16**). Log interpretation should be confirmed with targeted soil coring adjacent to selected log locations or running logs adjacent to one or more previously logged borings.

5.2 The tooling system described below is one commercially available injection logging system called the Hydraulic Profiling Tool (HPT) and this standard follows the operating procedure for this system (**7**). Other permeability profiling tools have been and can be used for measuring the same or similar parameters related to formation permeability and hydraulic conductivity (**1-4, 11, 12, and 17**). Most of these tools utilize one injection port on the probe and measure the injection pressure at the surface. When the injection pressure is measured at the surface correction for frictional losses in the water supply tube are required. These corrections will need to account for the length and diameter of the supply tube, flow rate, temperature and viscosity of the fluid, and whether the flow is laminar or turbulent in the supply tube (**1**). When the pressure measurement is made down hole at the port these corrections are not required (**5, 7**). At least one type of hydraulic profiling tool uses two down-hole ports and pressure transducers to measure pressure changes induced in the formation by injection from a separate screen at discrete intervals (**17**). This system may be used to provide an injection pressure log and conduct tests to measure hydraulic conductivity at discrete intervals. At least two systems enable the operator to collect ground water samples at selected depths as the probe is advanced (**11,14**).

[5] The boldface numbers in parentheses refer to a list of references at the end of this standard.



The water container (A) provides water to the metering pump in the HPT flow module (B) and is pumped down hole via the trunkline (D) and through the inline pressure sensor (E) and out of the screened port (F) into the formation. As the probe is advanced at 2cm/s the inline pressure sensor (E) monitors the pressure required to inject water into the formation while the injection flow rate is measured with a flow meter in the flow module (B). The electrical conductivity array (G) simultaneously provides an EC log of the bulk formation as the probe is advanced. Analog signals are converted to digital output in the field instrument (C) and displayed on the computer screen (H) for live-time viewing in the field. Data is saved for later review and analysis.

FIG. 1 Schematic of an Injection Logging System, Demonstrating Principles of Operation

NOTE 1—Some early versions of the 2-port Permeameter suffered from anomalous K measurements when tests were conducted over small vertical intervals with significant changes in K over the decimeter to centimeter scale (**18**). More recent versions of the 2-port Permeameter overcome this limitation by measuring injection pressure from one port as the probe is advanced to verify homogeneity over the interval where quantitative K tests are performed (**17**). Additional work with driveable piezometers and injection logging tools has been conducted by several researchers (**19-23**).

5.3 Correlation of a series of injection logs across a site can provide 2-D and 3-D definition of variations in formation permeability, lithology and hydrostratigraphy (**2**, **8**, **9**, **13**, **14**, **15**).

5.4 Both contaminant migration pathways and low permeability zones (barriers) may be defined for environmental investigations. The injection logging system may be used to conduct water supply and groundwater resource investigations (**9**) or to evaluate sites for aquifer recharge (**14**) in appropriate geological settings. Some investigators use injection log data to assist in the development of groundwater models (**2**).

5.5 The data obtained from application of this practice may be used to guide soil (Guide D6282) and groundwater sampling (Guide D6001) or placement of long-term monitoring wells (Guide D6724, Practice D6725, and Practice D5092). The logs also may be used to select the location and screen intervals for water supply wells (**9, 14**) or dewatering wells.

5.6 The data can be used to optimize site remediation by knowing the depth and distribution of higher permeability zones and lower permeability zones. For example, the logs can guide where remediation fluids may be injected successfully or provide guidance about the required injection pressures.

5.7 The injection logging system may be configured with a soil electrical conductivity array (Fig. 1 and Fig. 2) for simultaneous logging of bulk formation electrical conductivity which also may be used to infer formation lithology or indicate changes in pore fluid ionic strength (**14, 15**). Alternately, the HPT system may be paired with a CPT probe to obtain information on soil/sediment types and strength of materials for foundation design (**24**). The HPT probe also may be coupled with a membrane interface probe for the detection of some volatile organic contaminants (Practice D7352) (**8**) or with a laser induced fluorescence (LIF) probe (D6187) or optical image profiler (OIP) (**25**) or fuel fluorescence detector probe (**26**) that uses ultraviolet light for the detection of fuels and related organic contaminants by fluorescence.

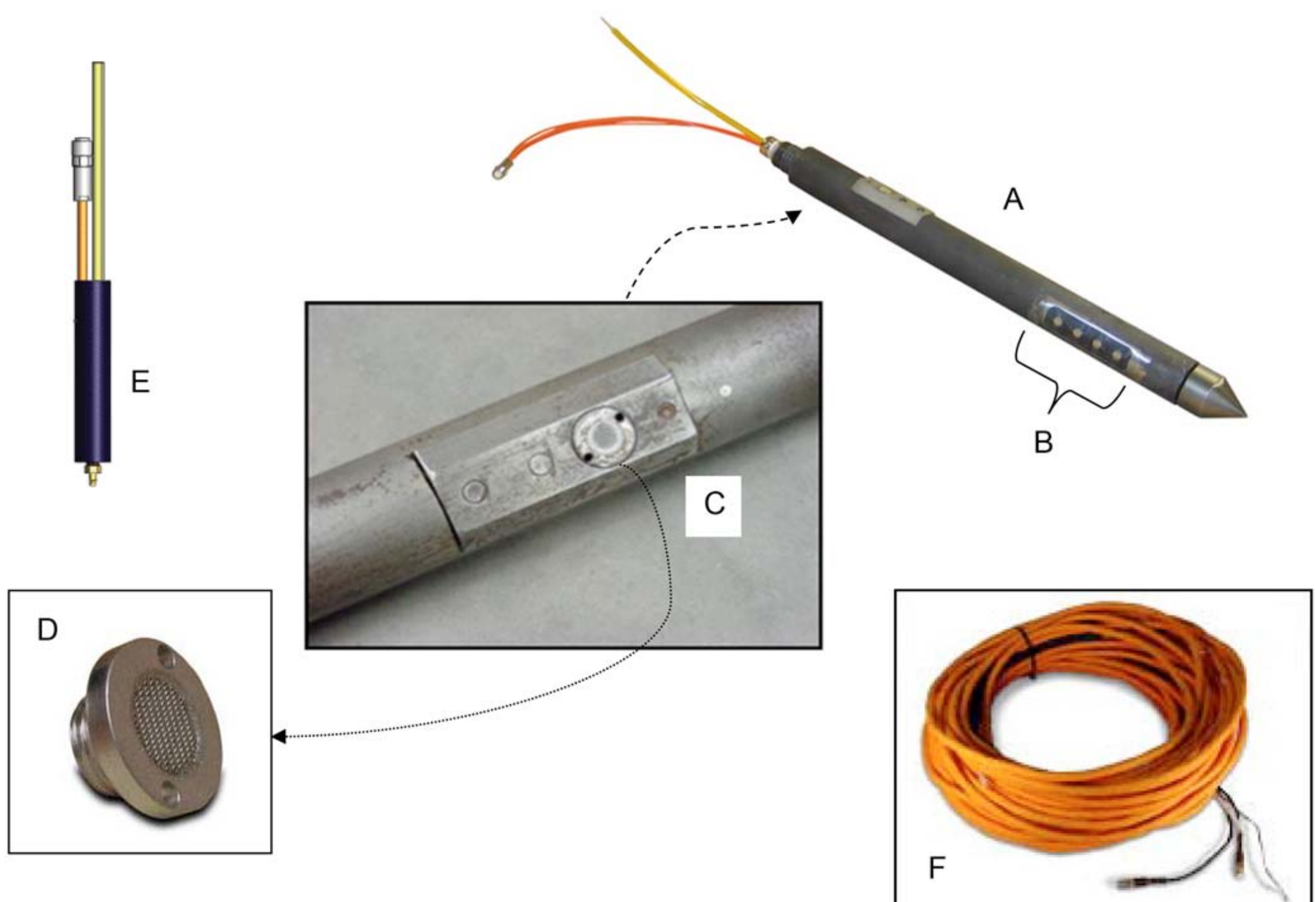
5.8 DP methods are not designed to penetrate consolidated rock (for example, granite, basalt, gneiss, schist, limestone or consolidated sandstone) and may have difficulty penetrating very dense formations (for example, highly compacted glacial tills) and heavily cemented soils (for example, caliche). Alluvial and glacial deposits with abundant cobbles and boulders usually cannot be penetrated. Other drilling methods can be used to pre-bore through surface obstructions and set surface casings.

NOTE 2—The quality of the result produced by this standard is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Practitioners that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

Practice D3740 was developed for agencies engaged in the testing and/or inspection of soils and rock. As such, it is not totally applicable to agencies performing this practice. However, users of this practice should recognize that the framework of Practice D3740 is appropriate for evaluating the quality of an agency performing this practice. Currently there is no known qualifying national authority that inspects agencies that perform this practice.

6. Apparatus

6.1 *General*—The following discussion provides descriptions and details for the Hydraulic Profiling Tool (HPT) and



A) injection logging probe, B) electrical conductivity array, C) screen mounted in probe, D) close up of removable screen, E) down-hole pressure sensor, F) trunkline

FIG. 2 Common Components of an Injection Logging Tool

system components (Fig. 1). Additional details on the HPT components and system described here are available in the manufacturer's operating procedure (7). Other injection logging systems may have different specifications and components.

6.2 *Hydraulic Profiling Tool*—A steel probe with a screened port on one side. The HPT screen allows for the injection of water into soils and unconsolidated formations as the probe is advanced steadily at a rate of approximately 2cm/s to depth. A down-hole pressure sensor monitors the total pressure required to inject water into the formation while simultaneously an up-hole flow meter measures the rate of water injection (Fig. 1).

6.2.1 The screen is set in a removable insert. It is constructed of stainless steel wire mesh and the orifice has a diameter of approximately 0.4-in. [10mm].

6.2.2 The down-hole pressure sensor operates in a pressure range of 10 psi to 100 psi [70kPa to 700kPa] with an accuracy rated at ±1 % full scale. Sensor accuracy at lower pressures generally exceeds manufacturer's specifications.

6.2.3 Plastic tubing is used to supply clean water to the screen. The tubing is usually included in the trunkline (Fig. 2).

6.3 *Trunkline*—This cable (Fig. 2) consists of electrical wires for the down hole pressure sensor, EC array and other optional probes or sensors (for example, CPT, MIP, LIF, OIP). The trunkline also contains the water supply line for the injection screen. This trunkline is packaged in a durable, protective jacketing and is pre-strung through the steel drive rods prior to logging.

6.4 *Pressure Sensor*—A replaceable pressure transducer assembly installed just above the injection probe in the tool string to measure the pressure required to inject water into unconsolidated materials while the probe is being advanced by direct push methods.

6.5 *Reference Tube*—A cylinder, closed on the bottom and open on the top, of specified height and diameter with a valve 6-in. [150mm] below the top edge of the cylinder. The injection probe is submerged under water in the reference tube to conduct a calibration check (reference test) on the down-hole pressure sensor.

6.6 *EC Test Jig and Test Load*—Devices used to perform the quality assurance test of the electrical conductivity array. Some arrays require only a test jig.

6.7 *Water Container*—A plastic or metal container, clean and free of any particulates or contaminants, used to hold at least 5 gallons [20 liters] of clean water. The water is pumped down hole to inject into the formation for injection logging.

6.8 *Flow Module*—The flow module (Fig. 3) is used to control and measure the rate of water flow delivered to the injection port. The water supply pump and flow meter are included in the module. A bypass line is included on the pump so when downhole pressure exceeds pump capacity flow bypass is permitted to prevent pump damage. An inline pressure sensor inside the module monitors the water pressure in the injection line (line pressure). A pressure gauge on the flow module allows for visual verification of the line pressure. A shut off valve on the module permits the operator to stop flow to the injection screen when desired (for example, during a pressure dissipation test).

6.9 *Field Instrument (FI)*—The primary function of this electronic component (Fig. 3) is to acquire the analog signals from the down-hole pressure sensor, flow meter, line pressure sensor, EC array and other optional down hole sensors and convert the signal to digital data for output to a laptop computer. The FI also supplies regulated voltage to the EC array for electrical conductivity logging.

6.10 *Laptop Computer*—A portable computer (Fig. 3) is used to acquire and display the digital log data on screen as the log is obtained using the data acquisition software. The data is saved for later review, plotting and reporting.

6.11 *Acquisition Software*—A software package designed to receive digitized HPT log data and plot it graphically on screen versus depth as the probe is advanced. Some software packages can display the injection pressure, water flow rate, electrical conductivity log, depth and rate of probe advancement as the log is obtained (27). The line pressure also may be displayed. Quality assurance tests also are performed with the acquisition software. Data for all of these parameters are saved in the log file.

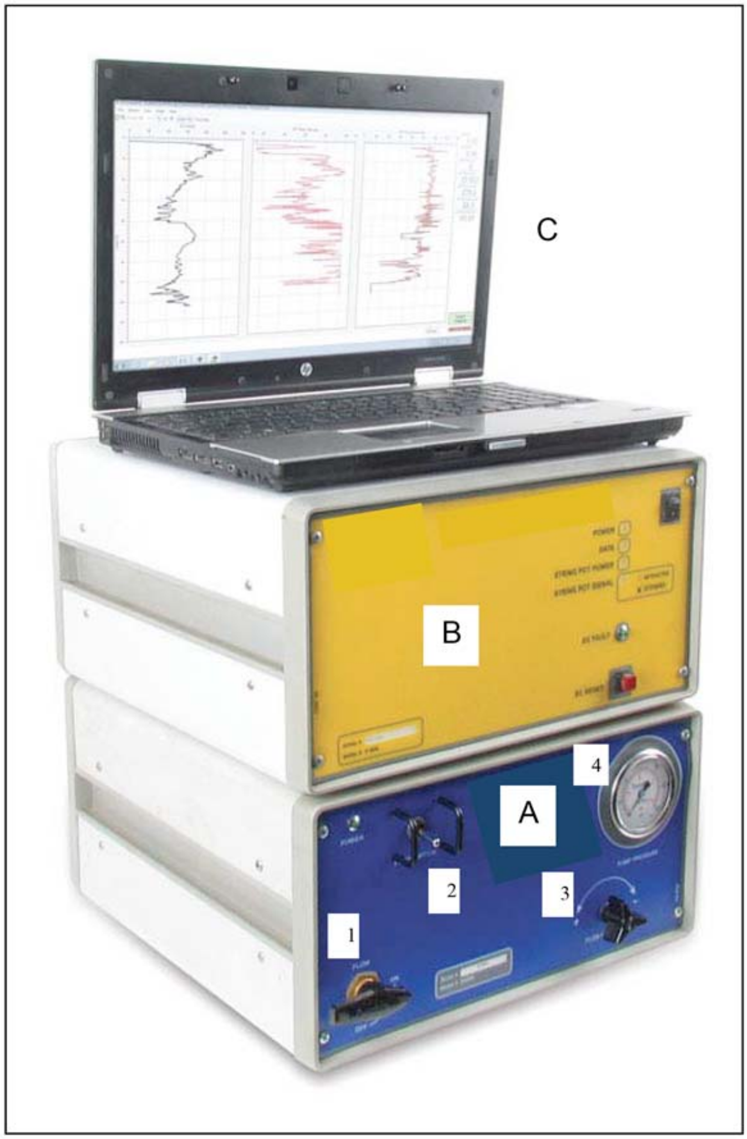
6.12 *Viewing Software*—A software package that allows the log file to be displayed graphically on screen and printed for reporting purposes from the saved acquisition file. Some software packages enable the user to review pressure dissipation test files to determine the piezometric pressure at the given depth and plot piezometric profiles (28). Some viewing software packages also may be used to create simple 2D cross sections from multiple logs. Log data also may be exported to other software programs for analysis and plotting and for creation of 2D and 3D representations of log data.

6.13 *Global Positioning System*—GPS connections for acquiring latitude and longitude coordinates of log locations are provided in some hardware/software systems. GPS data may be saved with the log file.

6.14 *Stringpot*—A depth measuring potentiometer (Fig. 4). It is mounted to the direct push machine or anchored to the ground. The stringpot transfers voltage to the data acquisition system as the length of the string changes during probe advancement. This allows for accurate measurement of the probe depth below ground surface and also rate of probe movement. When location elevations are surveyed elevations may be input to some viewing software packages to convert depth to elevation.

6.15 *Drive Rods*—Steel rods having adequate strength to sustain the force required to advance the probe into the subsurface. The rods are sequentially added to the tool string to advance the probe to depth. The trunkline is pre-strung through all rods before the logging process is started. Typical diameters for percussion probing applications are 1.5, 1.75 and 2.25 in. [38, 44 and 57mm]. When operated with a CPT system either 36mm or 44mm diameter CPT rods can be used.

6.16 *Direct Push Machine*—A track or vehicle mounted machine with hydraulic rams supplemented with vehicle



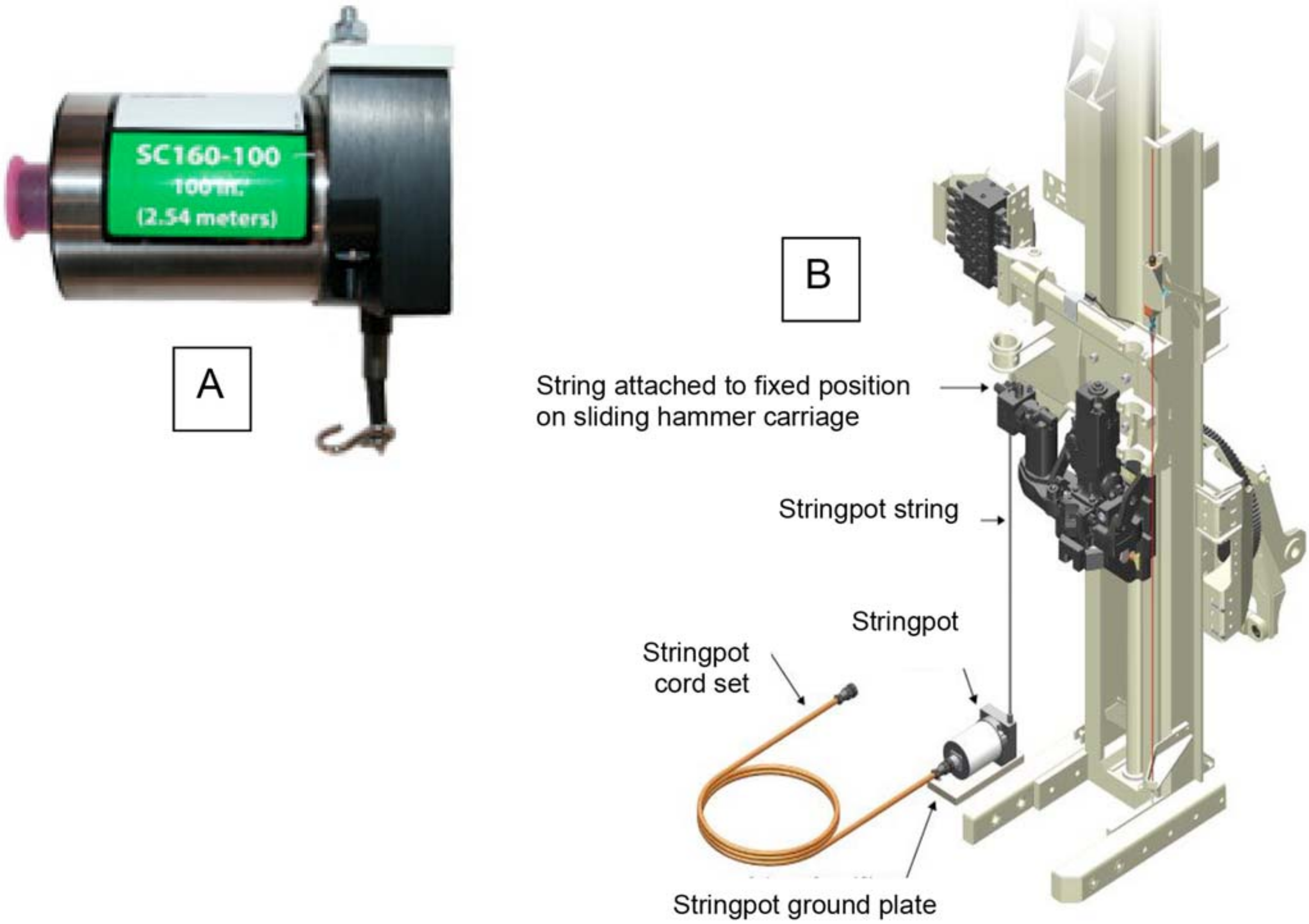
(A) The flow module, contains pump, flow meter and line pressure transducer:
  (1) flow shut-off valve
  (2) pump on-off switch
  (3) pump flow control valve
  (4) line pressure gauge
(B) Field instrument: converts analog signal to digital output for computer
(C) Laptop computer with acquisition and viewing software installed

FIG. 3 Common Electronic Components of an Injection Logging System

weight and/or a hydraulic hammer used to advance drive rods and tools into unconsolidated formations. Rotary drilling rigs can be modified to perform direct push advancement of tools and for injection logging, often by addition of a suitable direct push hydraulic hammer system and/or hydraulic rams. Depth of penetration is dependent on local formation conditions, but depths in excess of 20 to 30 meters are routinely achieved. Review site specific soil and geological data to determine if direct push logging is an appropriate method on a site-by-site basis.

7. Reagents and Materials

7.1 *Injection Fluid*—Clean water, free of any potential contaminants, is used for the injection fluid during injection logging. Distilled or de-ionized water may be used as the injection fluid if desired. Water is usually injected at a rate of 200mL/min to 300mL/min but higher or lower injection rates may be used if desired. For a typical 60 ft [20m] depth log about 10 to 15 gal [40 to 60L] of water is required. This includes continued flow during retraction of the probe that is



(A) Stringpot assembly.

(B) Anchoring the stringpot at ground surface and attaching the string to the sliding mast of the direct push machine to track depth as the probe is advanced into the subsurface.

FIG. 4 Stringpot Used to Track Probe Depth

required to keep the screen open and prevent damage to the down hole pressure sensor.

8. Preparation of Apparatus

8.1 *General*—The injection probe and logging system must be assembled and set up properly to obtain valid log data. Quality assurance tests must be performed before and after each log and at the end of the working day to verify pressure transducer and system performance. The following provides a brief overview of system preparation and QA test procedures for the HPT injection logging system, for complete details refer to the manufacturers operating procedure (7). If a different injection logging system is used follow the manufacturer's specifications for that system. At this time the HPT system is the only commercially available injection logging system.

8.2 *Regulatory Considerations*—Contact the appropriate state and local agencies to obtain drilling licenses and permits that may be required to conduct the logging operation. Local and state regulations also may control injection of clean water or any fluids into the subsurface. Contact the appropriate agencies to evaluate permitting requirements for injection of water or other fluids into the subsurface. Some agencies may require at least limited oversight during initial logging and water injection to verify procedures are acceptable. Water injection volumes may be below minimum reporting requirements in many jurisdictions.

8.3 *HPT System Assembly*—The following subsections provide a brief overview of the HPT probe and system assembly. Refer to the manufacturer's operating procedure (7) for complete details and guidance.

8.3.1 *HPT Probe to Trunkline Assembly*—The electrical conductivity and down-hole transducer connections are made after the trunkline is strung through the drive rods, probe drive head and connection tube (Fig. 5).

8.3.1.1 *Electrical Conductivity*—Thread the male and female connectors together. Snug the connectors gently and then wrap them with electrical tape as strain relief against vibration as the probe is driven to depth.

8.3.1.2 *Down-Hole Pressure Transducer*—Using appropriate tools and fittings connect the down-hole transducer to the water supply line (Fig. 5). Next connect the tubing at the top of the probe to the barb fitting on the base of the down-hole

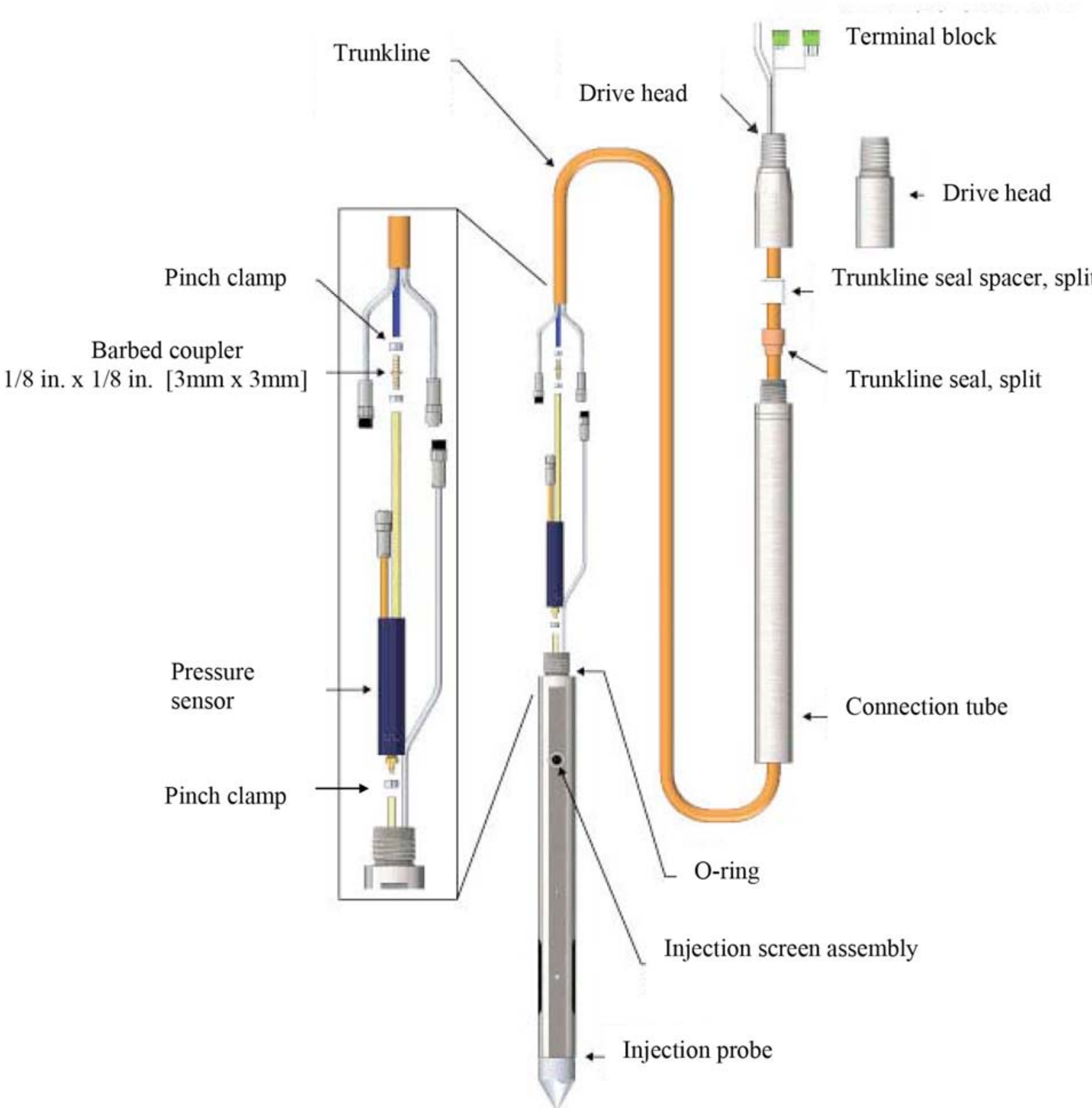


FIG. 5 Assembly of an Injection Logging Probe and Attachment to the Trunkline

pressure sensor. Before assembly cut the water supply tubing as required to prevent kinking of the tube during probe assembly and logging. Attach the electrical connector for the pressure sensor to the appropriate electrical connector at the end of the trunkline. Snug the connectors gently and then wrap them with electrical tape as strain relief against vibration as the probe is driven to depth.

8.3.1.3 *Seal and Probe Body Assembly*—Thread the connection tube onto the HPT probe (Fig. 5) being sure not to twist or kink the water supply tubes or damage any electrical connections. The water seal assembly is placed over the trunkline above the connection tube and below the drive head. Apply water to the seal to make assembling the drive head to the connection tube easier. Snug all threaded connections with pipe wrenches.

8.3.2 *Attach Trunkline to Flow Module and FI*—Connections between the trunkline and up hole electronics and water supply are made following manufacturers specifications.

8.3.2.1 *Down-Hole Sensor Connection*—The trunkline connection for the down-hole pressure sensor is installed in the receptacle on the back of the flow module. Refer to the manufacturer's operating procedure for details (7).

8.3.3 *Power and Communication Connections*—The power cords for both the FI and Flow Module are connected to a clean, grounded power supply. The power supplied by generators or landline must be properly grounded and free of excessive noise, both of which can impair signal integrity and quality. Connect the field instrument to the flow module using the serial cable between the ports on the back of each instrument. A USB cable is then used to connect the FI to a laptop computer in which the acquisition software has been installed.

8.3.4 *Stringpot Setup and Connection*—Anchor the string pot to the ground (Fig. 4) or use a machine specific bracket to attach the stringpot to the DP machine probe derrick. The string is then attached so that the string length changes as the HPT probe and tool string are advanced into the subsurface. Be sure string movement is free and unencumbered so depth tracking is accurate. The stringpot and string must be mounted so that if the DP machine foot is lifted off the ground during tool advancement depth is correctly tracked. The stringpot cable is then used to attach the stringpot to the field instrument for depth tracking.

8.4 *System Startup*—When all plumbing and electrical connections are completed initiate power to the flow module, field instrument and portable computer. Also start the injection pump to pump water into the trunkline and purge all air from the trunkline and probe plumbing and injection port.

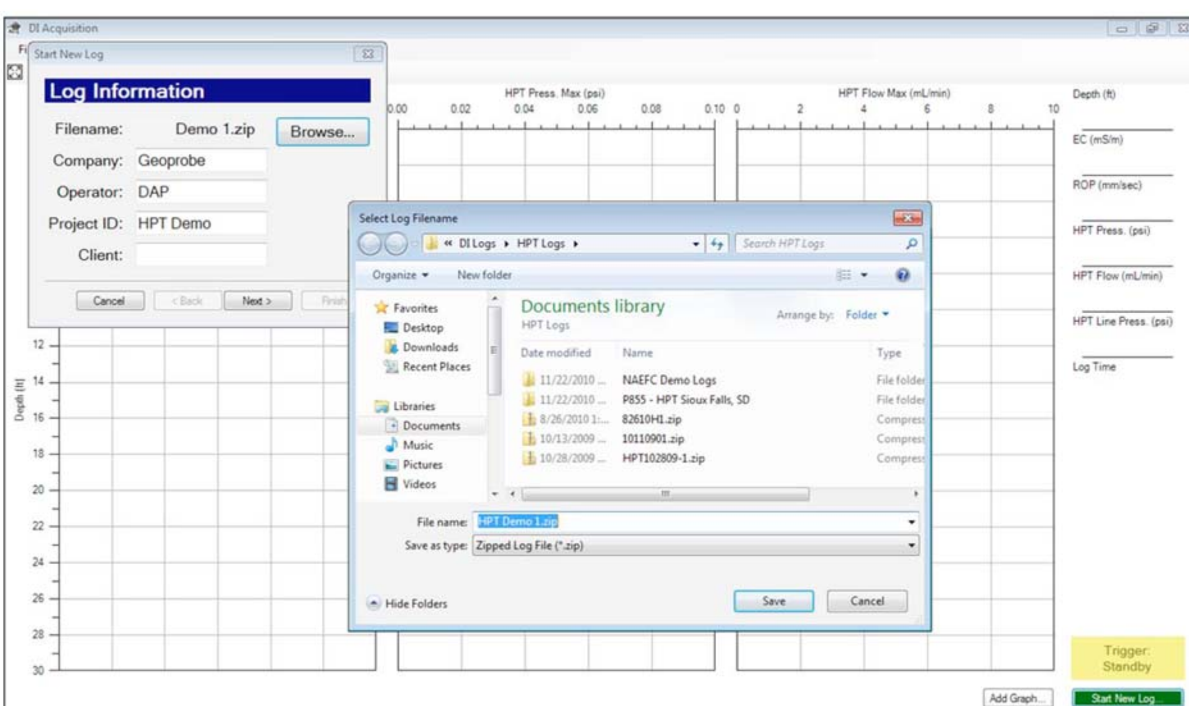
8.5 *Start Acquisition Software*—Initiate the acquisition software and start a new log (Fig. 6). Assign filename for the log and provide other requested information as prompted. Once the initial operating data is entered the software will then begin the quality assurance pre-log test sequence.

9. Quality Assurance Testing

9.1 The following steps outline the pre-log quality assurance tests required for the down-hole pressure sensor, EC array and EC system. For complete details refer to the manufacturer's operating procedure (7). If a different injection logging system is used follow the manufacturer's specification for that system. Both the EC array and the HPT pressure sensor circuits must be tested before and after each log to verify the log data is valid. If CPT or other sensors are run in tandem with injection logging then pre-log QA tests should be run on those systems.

9.2 *Electrical Conductivity QA Test*—Assemble the EC test load and test jig (Fig. 7) and attach the test jig to the EC array on the probe and perform the QA test as specified in the manufacturer's operating procedure. The QA test results are captured by the software and saved. If the readings are all within specified limits of the target values the EC array passes the QA test. If the system fails the QA test, then follow the onscreen instructions to select a dipole EC array for the probe. If the system indicates that no valid dipole arrays are available, then troubleshoot the system per the manufacturer's instructions and repeat the process until a valid EC array passes the QA test. For complete details refer to the manufacturer's operating procedure (7).

9.3 *Entry of System Operating Parameters*—Once the EC test is completed the acquisition software opens a window for the entry of operating parameters including the selection of the injection probe model, desired EC array (Wenner; top, middle or bottom dipole), rod length, string pot cable length, and down-hole sensor calibration data. Select the appropriate options and follow prompts in the software for adding calibration parameters for a new down-hole pressure transducer when required. If a new down-hole pressure sensor has been installed the calibration information for that sensor must be entered in the software to obtain accurate pressure data.



This is an example of one software system used for injection logging. Other similar systems may be used.

FIG. 6 Initiate Acquisition Software and Start New Log File to Prepare for Logging

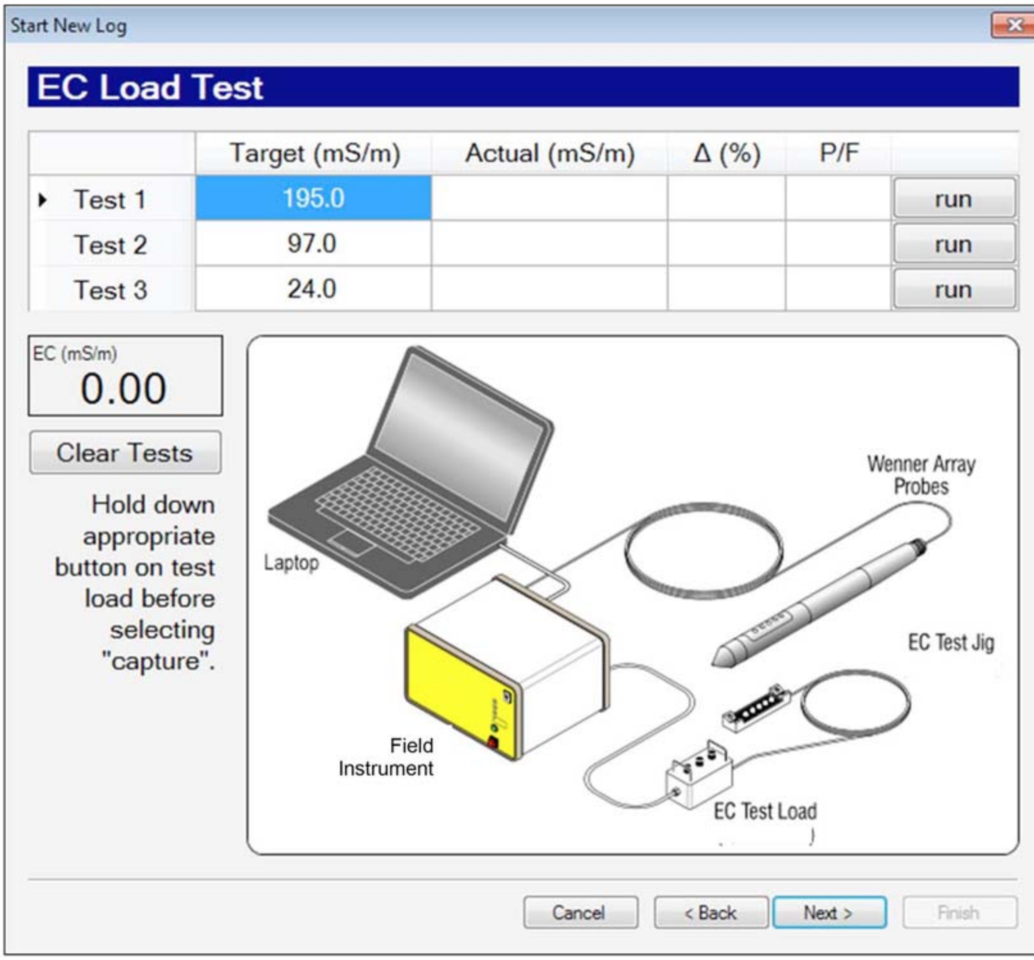


FIG. 7 Electrical Conductivity Quality Assurance Test Screen and Setup for a Typical Injection Logging System

9.4 *Quality Assurance Test of the Down-hole Pressure Transducer*—The following basic steps are required to test the down-hole pressure transducer to verify it is operating correctly before the log is started. Quality assurance testing is an integral part of ensuring the quality of pressure data obtained from the injection logging system. A pressure transducer QA test must be conducted before and after each log is run in the field. Without a pre-log QA test for each log it is not possible to verify the accuracy of the down-hole pressure data.

9.4.1 *Trunkline and Probe Purge*—Air and air bubbles (which are compressible) must be purged from the water injection system, probe and line to obtain accurate pressure logs. With the water flow line connected to the supply port on the back of the Flow Module open the line valve and turn on the water pump (Fig. 3). Use the pump flow control knob to adjust the injection flow to the desired rate, often 250mL/min is used. It may require two to three minutes for water to begin flowing from the injection screen. Sputtering and air bubbles are usually observed. Once flow begins to stabilize place the thumb or finger over the injection screen and restrict flow to increase pressure in the trunkline then release. Repeat several times for 2 to 3 minutes to surge the line pressure and dislodge and remove all air bubbles from the trunkline and probe.

9.4.2 *Down-hole Pressure Transducer Quality Assurance Testing Procedure*—The QA test of the down-hole pressure transducer verifies the ability of the pressure transducer to accurately measure a known height difference in a water column (typically 6-in. [150mm]). This test also acquires the down-hole transducer measurement of atmospheric pressure at the time of logging. The atmospheric pressure as measured by the down-hole pressure transducer is critical data required to obtain accurate water levels, piezometric profiles, corrected pressure logs and estimated hydraulic conductivity logs.

9.4.3 *Reference Tube*—The injection probe is inserted in the reference tube (Fig. 8) and the tube is filled with water as described below to perform the reference test. The reference tube is fitted with a valve located 6 in. [150mm] below the top rim. When this valve is closed and the Reference tube is completely filled with water, then the water level is at the "Top" level for the reference test. When the valve is open and the water level fills the tube to the level of the open valve, then the water level is at the "Bottom" level for the Reference Test. The Reference Tube must be sufficient height so that when the tube is filled to the height of the open valve (Bottom Level) the water level completely covers the HPT injection port of the probe. The distance from the screened injection port to the

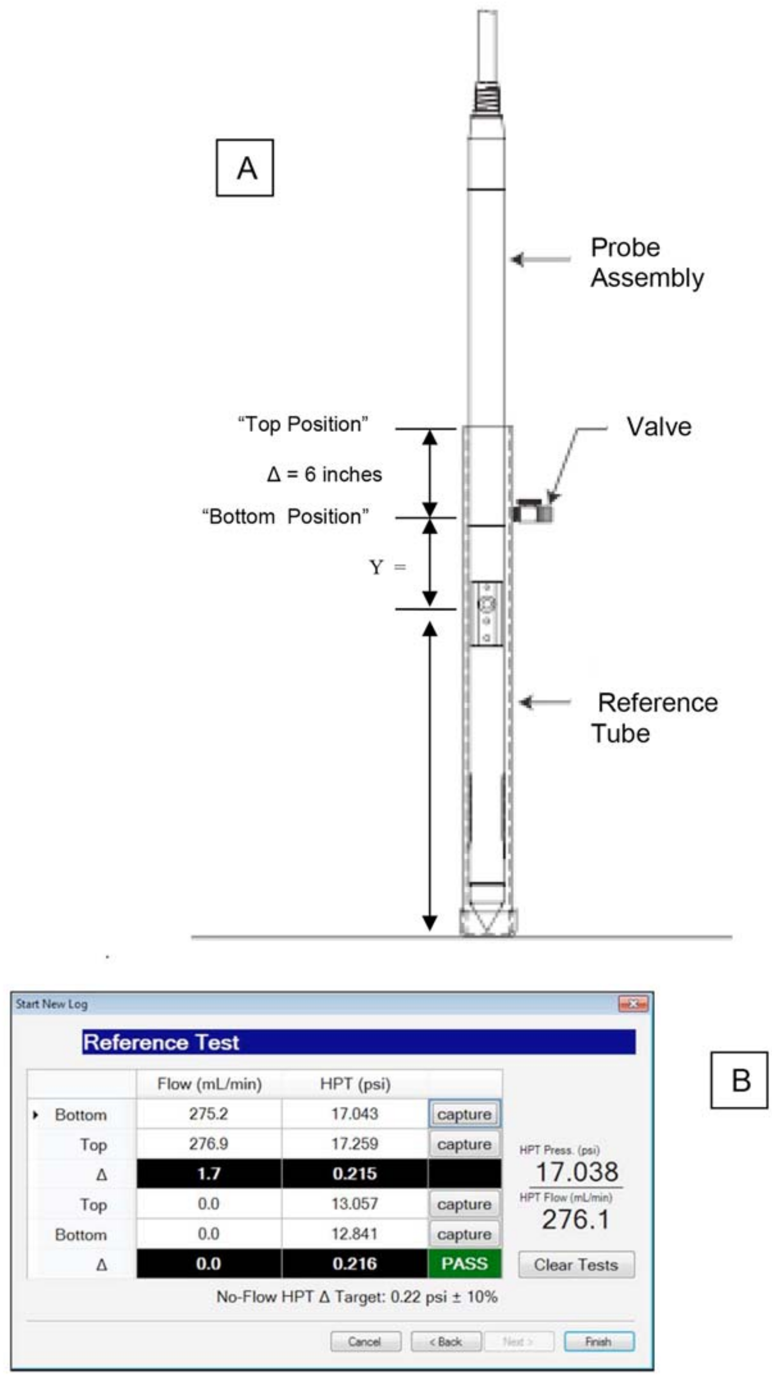


FIG. 8 Injection Probe Submerged in the Reference Tube for Pressure Sensor Quality Assurance Testing (A) and the Reference Test Window (B) in a Typical Acquisition Software System

Bottom Level of water in the reference tube must be known and entered into the acquisition software either manually or automatically according to the injection probe model to allow for completion of the QA test.

9.4.4 *Flow Tests*—Set the water flow at the rate to be used during the logging operation (for example, 250mL/min). Allow the reference tube to fill until water flows from the open valve at a stable rate. Capture/record the "bottom with flow" pressure value in the QA test window (Fig. 8). Close the valve and allow the reference tube to fill with water until overflowing. Capture/record the "top with flow" pressure value when flow has stabilized. In general the pressures observed during the flow tests will exceed atmospheric pressure (about 14.7 psi [101kPa]) due to the internal system friction with water flowing. Also, the difference observed between the top and bottom flow tests will often exceed 0.22 psi [1.5kPa] of pressure exerted by the 6-in [150mm] difference in the water column height. If the pressure observed during the flow tests exceeds 20 psi [140kPa] then corrective measures should be taken. Occasionally the screen becomes clogged with mud during retrieval from a previous log. In this case remove the screen, flush out the HPT probe and clean and replace the screen. If the screen has been damaged, install a new screen. If the pressure reading continues to exceed 20 psi [140kPa] other corrective measures are required, this may include replacement of the down-hole pressure transducer. For complete details refer to the manufacturer's operating procedure (7).

9.4.5 *No-Flow tests and Quality Assurance Test Result*—With the reference tube full turn off the water pump and close the flow valve on the front of the flow module. Allow the pressure to stabilize and capture/record the "top with no-flow" pressure value in the QA test window of the software. Now open the valve on the reference tube and let the water drain until it stops flowing. When the pressure is stable capture the "bottom no-flow" pressure value in the QA test window. The software will subtract the "bottom no-flow" pressure value from the "top no-flow" pressure value to determine the ΔP value and check the result against the QA criteria of:

ΔP = (observed pressure at top no-flow) – (observed pressure at bottom no-flow) = 0.22* psi [1.5kPa] ± 10%

(* Depending on the logging system used different ΔP and QA ranges may be specified by the manufacturer.)

If the ΔP value calculated lies within the QA test window of ±10% the pressure sensor passes the QA test and logging may begin. If the pressure sensor does not pass the QA test corrective action must be taken before logging may begin. Sometimes mud collects behind the injection screen and this will cause pressure anomalies during the QA test. Remove the injection screen and flush the system and clean the screen, replace and re-test. If the pressure QA test continues to fail other corrective measures may be required, up to and including replacement of the pressure sensor. See the manufacturer's operating procedure (7) for further details. Following corrective measures the QA tests must be repeated successfully before logging may begin. Also observe the "bottom no-flow" pressure result. If this value exceeds 20 psi [140kPa] after the injection port and screen have been cleaned and flushed the down-hole sensor must be replaced, regardless of passing the ΔP QA test described above.

9.5 *Trouble Shooting*—If problems persist with either the EC QA test or the HPT sensor after initial corrective measures trouble shooting of the system may be required. See the manufacturers operating procedure (7) for information on system trouble shooting.

10. Field Procedures

10.1 General Requirements: The following section describes the general procedure for HPT logging once the quality assurance tests have been successfully completed. If a different injection logging system is being used follow that manufacturer's specifications.

10.1.1 Prior to driving the HPT probe into the subsurface, ensure that the proper utility clearances for direct push equipment have been obtained. Be sure that hazards from underground and overhead utilities are accounted for in the clearance process. Not all utilities or underground pipelines may be covered by the local One-Call utility clearance service provider. Obtain a list of potential subsurface utilities and pipelines in the area that may require independent clearance and contact for clearance as needed. Also, remember that privately owned, site specific subsurface structures and utilities usually will not be covered by one-call service providers. Coordinate with the property owner for appropriate site specific clearances (if any) before advancing tools into the subsurface. Some federal, state or local agencies may require utility clearance with an air-knife or hand auger before probe advancement may begin.

10.1.2 Most operators will place a rod wiper "doughnut" on the ground at the logging location. The probe and drive rods are advanced through the rubber doughnut as logging is performed. When the log is completed the drive rods and probe are retracted through the rubber doughnut which is held in position by a metal weldment placed under the foot of the direct push or rotary drilling machine modified for DP operation. The rod wiper greatly reduces decontamination effort and also significantly minimizes worker exposure to potentially contaminated soil.

10.2 *Logging Procedures:*

10.2.1 *Establishing Log Zero Depth*—With injection flow set at the desired rate place a slotted drive cap on the assembled probe and position the probe beneath the DP machine hammer or hydraulic ram. Plumb the machine mast and plumb the probe for vertical advancement. Slowly push and gently hammer the probe (if needed) until the injection screen bisects the ground surface. This is zero depth for the log. Re-plumb machine and probe as needed for vertical advancement.

10.2.2 *Software Trigger On for Logging*—Once the injection screen is set at ground surface for logging click on the "Trigger Standby" icon on the software screen so that it changes to "Trigger Logging." Now depth and log data will be acquired, saved and plotted onscreen as the probe and tool string are advanced.

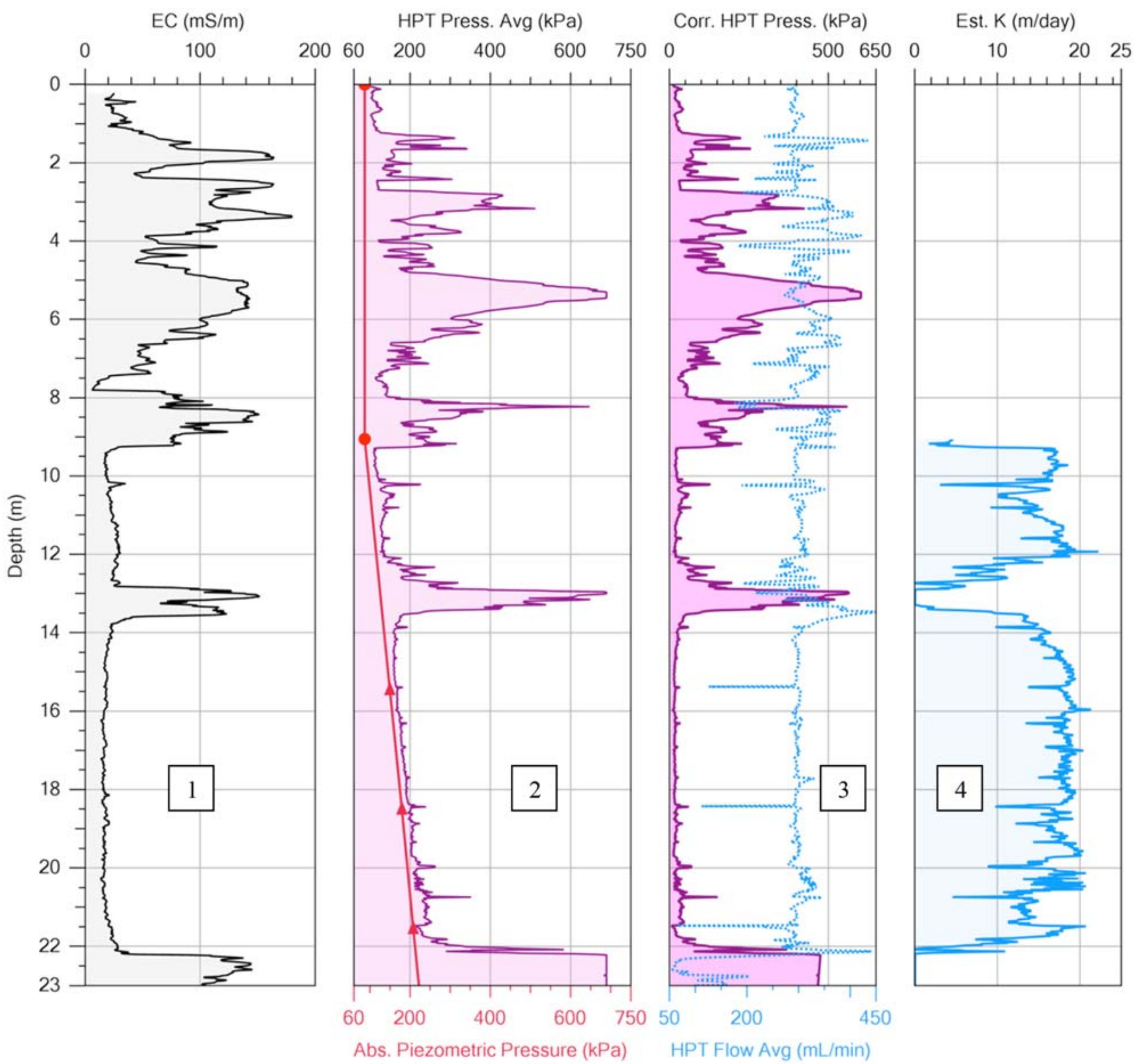
10.2.3 *Probe Advancement*—The DP machine hydraulic slides and percussion hammer are now operated manually to advance the injection probe at an approximate rate of 0.1 ft/s [2cm/s] into the formation. The rate of penetration (speed) graph may be displayed onscreen to assist the operator in advancing the tool at the desired rate. Avoid exceeding the 2cm/s rate so that the pressure and flow data will be consistent down the log. Modest variations in rate of advancement have not been found to impact log quality. Note any pauses or irregularities in the advancement of the tool besides the rod break pauses below.

10.2.4 *Logging*—The tool string is advanced until the top of the rod is 3 to 5 in. [80 to 120mm] above grade. The probe derrick is raised and the next rod is slid over the pre-strung trunkline and threaded onto the top of the tool string. Be sure to snug each rod with a pipe wrench as it is added to the tool string, this will minimize thread damage to the tooling. Place the slotted drive cap on the tool and use the probe and machine hydraulics to advance the tool string to depth. Repeat process until desired depth is obtained or refusal occurs. Hammer only as needed to increase tool life.

10.2.5 *Trunkline Management and Tool Maintenance*—Proper management of the trunkline through each drive rod as it is added or removed from the tool string can improve logging efficiency. Keeping threaded fittings clean and free of burrs also will facilitate the logging process. Regularly check threaded fittings for burrs, damage or wear and touch up with a file or grinding tool as needed. Replace worn or damaged rods to prevent loss of tooling and probe down hole.

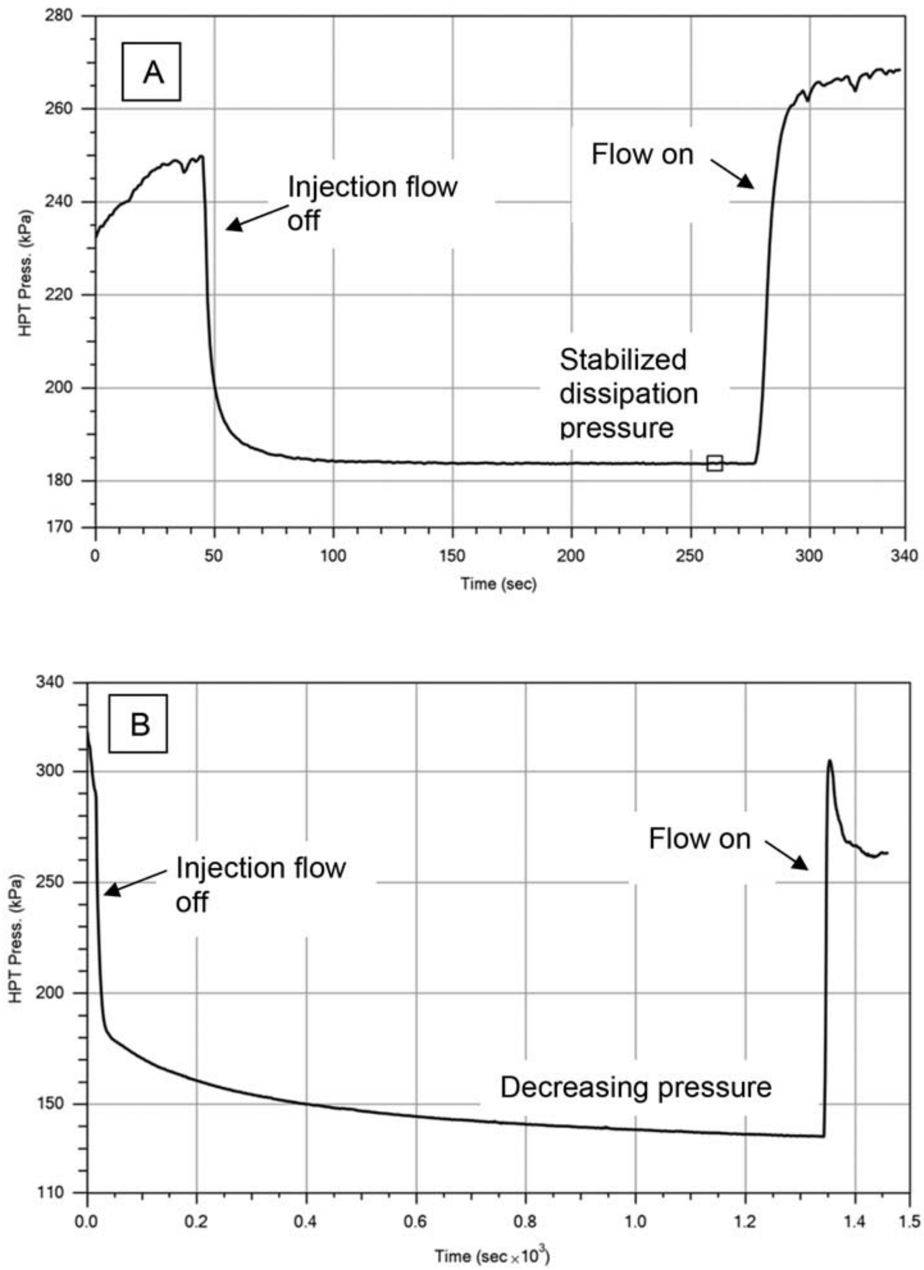
10.2.6 *Real Time Observation of Logs*—As the probe is advanced into the subsurface the HPT pressure, flow rate and electrical conductivity or other logs are observed onscreen (Fig. 9). Data is recorded every 0.05 ft [~15mm] in the log file and stored for later retrieval, viewing, printing and presentation. Line pressure and rate of penetration may be viewed onscreen if desired. The line pressure can be used as a general log quality control parameter. The line pressure and injection pressure should mimic one another in pressure increase and decrease as the probe is advanced. However, the line pressure does not see the piezometric pressure while the down-hole pressure sensor does see this increase. Thus, as the probe is advance below the local water level the injection pressure and line pressure will diverge due to the increasing piezometric pressure. For additional information on HPT log interpretation and cross sections of logs see Appendix X1.

10.3 *Dissipation Testing*—Pressure dissipation tests (Fig. 10) are typically performed below the water table at one or more depths during log advancement. Pressure dissipation tests are used to establish the ambient piezometric pressure at the



This log was obtained in an alluvial aquifer in approximately two hours, including tool retraction, with a two person crew. From left to right the graphs display: 1) electrical conductivity (EC), 2) total injection pressure and piezometric profile line with measured dissipation pressures (triangles) and calculated water level (circle) 3) corrected injection pressure (Pc) and water flow rate (dashed line) and 4) estimated hydraulic conductivity. Elevated EC readings and injection pressures indicate lower permeability (increased clay content at this site) while lower EC and lower injection pressure correlate with more permeable sands and gravels in the formation. Note good correlation between the EC and injection pressure in this log, in some settings EC and injection pressure will not always correlate.

FIG. 9 Typical Hydraulic Injection Pressure Log



In dissipation test (A) the pressure quickly drops and stabilizes at the ambient piezometric pressure in the local formation, the quick drop and stabilization indicates a permeable formation. The stabilized dissipation pressure observed here can be used to plot the potentiometric profile and calculate the static water level for the zone tested, as displayed above (Fig. 9). Dissipation test (B) shows an initial rapid drop in formation pressure when the injection flow is first turned off. However, the pressure continues to slowly drop for over 1300 seconds, showing no sign of stabilization. This test indicates a low permeability formation and may require hours to reach full stabilization. Pressures observed in this test should not be used to plot the potentiometric profile as the pressure observed is still falling and is not in equilibrium with the formation potentiometric pressure.

FIG. 10 Pressure Dissipation Tests

selected depth(s). The ambient piezometric pressure may then be used to calculate the local static water level and piezometric profile at the given location. Dissipation tests also may be used to calculate the corrected injection pressure over the log. The corrected injection pressure is a function of the formation hydraulic conductivity (K) at each depth increment. Furthermore, the corrected injection pressure log and flow log may then be used to estimate K (**5**) at each depth increment in the saturated zone (Fig. 9).

10.3.1 *Where to Conduct a Dissipation Test*—It is generally most useful and efficient to perform pressure dissipation tests in permeable zones of the formation (sands and gravels). In permeable zones any induced pressure from water injection and insertion of the probe will dissipate quickly to the potentiometric pressure (Fig. 10). A good zone for dissipation testing is usually identified by having low injection pressure and low electrical conductivity (in fresh water formations). Occasionally it may be useful to conduct a pressure dissipation test in a lower permeability zone where injection pressure is high (for example, >20 psi [140kPa] over hydrostatic pressure). This may be done to demonstrate that slow to very slow dissipation of the induced pressure does occur to verify a zone is indeed low permeability. In some low permeability zones complete pressure dissipation could take hours, or even days. In these settings the pressure is allowed to dissipate for a reasonable time (for example, 5 to 15 minutes) to demonstrate that elevated HPT pressure dissipates slowly and does correspond to low permeability.

10.3.2 *Dissipation Test Procedure*—Stop advancement of the injection probe at the desired depth. Start a time file in the acquisition software to acquire the pressure versus time data.

10.3.2.1 Turn off the water pump to stop the flow of water to the probe.

10.3.2.2 Close the inline flow valve on the front of the Flow Module to stop water flow down the trunkline.

10.3.2.3 Observe the injection flow and pressure decrease on the time file onscreen. Allow the pressure to stabilize and remain stable for at least one to two minutes in order to verify ambient piezometric pressure is measured. Check the digital pressure readout on screen to verify the pressure has stabilized (there is usually some minor noise in the transducer reading at the third to fifth decimal places). In some settings it is difficult to visually see a continual slow drop or rise in the dissipation pressure. Waiting an extra minute or two is wise to be sure a fully dissipated test is obtained. Also expanding the axis on the pressure plot will help to confirm a stable or drifting pressure. Tests that are not fully dissipated will result in incorrect piezometric pressure profiles, incorrect static water level calculations, and incorrect estimates for hydraulic conductivity if included in the model and calculations.

10.3.2.4 Once any excess pressure has fully dissipated and is stable record the observed pressure. Then open the shut-off valve on the flow module and turn the water pump back on. You should observe both injection flow and pressure rise in the dissipation time file onscreen.

10.3.2.5 Once the flow and pressure have stabilized end the dissipation test.

10.3.2.6 Close the time file widow and return to the depth logging screen. See Fig. 10 for additional information on dissipation tests.

10.3.2.7 Resume logging and advancement of the probe to the desired depth. Conduct additional dissipation tests at the next desired depths. It is often good practice to perform at least 2 or 3 dissipation tests during each log, especially when high permeability zones are separated by lower permeability layers. This provides a measure of quality control for the dissipation test and also may be used to evaluate the presence of vertical gradients across the formation or confined zones. Some formations may consist entirely of fine-grained materials. Under these conditions it may not be possible to obtain a fully dissipated test in a reasonable amount of time. A few partial dissipation tests, lasting no more than 10 to 15 minutes, may be performed at selected locations and depths across the site to verify site conditions.

10.4 *End Log*—Once the probe has been advanced to the maximum desired depth, or refusal has been encountered, probe advancement is halted. Acquisition of depth and log data is stopped by the acquisition software and cannot be resumed. Retrieval of the tool string may begin.

10.5 *Post Logging Procedures*—These procedures include tool retrieval, post log QA testing, equipment decontamination and boring abandonment.

10.5.1 *Probe and Tool Retrieval*—There are at least two options for retracting the tool string and injection probe. Either a slotted pull cap and hammer latch or the rod grip system may be used to retract the tools. If running a CPT system the rod clamp may be used to retract the tools. (**Warning—**Injection water flow must be maintained at all times as the tool string is advanced or retracted. Water flow through the screen prevents intrusion of mud into the screen and potential damage to the probe and pressure sensor during advancement and retraction. Constant water flow also prevents clogging of the screen while advancing the probe and measurement of incorrect pressure data.)

10.5.1.1 A slotted pull cap may be threaded on the top of the tool string and the probe derrick is lowered into position. The hammer latch is then flipped down into position to grasp the pull cap and pull the tool string back. The hydraulic system is operated to raise the probe derrick and pull the tool string up. The top rod is removed and the process repeated to retract all tools. This method provides the most power for retraction of tools from difficult to penetrate formations. However, recovery with the pull cap/hammer latch method is relatively slow and tedious.

10.5.1.2 The rod grip system may be used to more efficiently retract and recover the tool string in most formations. The probe derrick is retracted and lowered just behind the top rod. The detachable rod grip handle is placed over the tool and latches onto two socket head cap screws on the hammer block. As the probe derrick is raised the rod grip handle seats the rod into a V-block on the hammer assembly and the tool string is retracted. The rod grip handle can be moved quickly up and down the tool string to efficiently retract the tools and probe from the subsurface.

10.5.1.3 *Trunkline and Rod Management*—Handling of the drive rods and management of the trunkline as the tool string is recovered is important. Sufficient trunkline should be left between each rod as it is added to the rod rack so that the trunkline is not kinked or damaged. Also, retrieving the probe too quickly through some clay layers may lead to intrusion of clay into the screen and potential transducer damage. A moderate retrieval rate may be most appropriate.

10.5.1.4 *Probe Maintenance*—Once the probe is recovered the probe and screen should be cleaned and brushed with a wire brush to clean any mud from the face of the screen. Dirt and mud should be washed off of the EC electrodes for post log quality assurance testing.

10.5.2 *Post Log QA Tests*—Once the injection probe is recovered and cleaned a post log quality assurance test should be performed. Proceed with the post log QA tests in the same manner as the pre-log QA tests were performed (refer to Section 9). If another log will be run immediately following completion of the current log, post log QA tests may be bypassed. In this case the next pre-log QA test may be used as the post log QA test for the log just completed. If the log completed is the last log of the day the post log QA tests should be performed to validate the last log and injection probe and system performance.

10.5.3 *Equipment Decontamination*—Appropriate decontamination of the probe, drive rods, trunkline and accessory tools should be performed (Practice D5088). Logging equipment decontamination would generally be considered "non-sample contact" equipment decontamination. Appropriately contain and dispose of any contaminated cleaning solutions.

10.5.3.1 Decontamination of the drive rods with the pre-strung trunkline requires special consideration. (**Warning—** High pressure sprayers may cut through the trunkline jacketing and wire insulation inside the trunkline. This type of damage will quickly render the trunkline useless. Use lower pressure water spray and appropriate cleaning solutions (for example, soapy water) and brushes to clean the tools and trunkline. Some organic solvents at high concentration, or pure product, may degrade the trunkline jacketing. Avoid exposure of the trunkline to these conditions.)

10.5.3.2 At a minimum, at the end of each day the injection probe should be disassembled, washed and cleaned and allowed to dry over night. All connections, electrical and plumbing, should be checked the following morning and the probe re-assembled properly before logging is resumed.

10.6 *Bore Hole Abandonment*—Appropriate abandonment methods and materials (Guide D5299) must be used to seal each bore hole after logging is completed. Check with state and local regulators to assure that requirements for sealing and abandoning bore holes are met. If bottom-up grouting of the borehole is required a second tool string with expendable point (or PVC pipe) may be lowered down the boring for tremie or pressure injection of grout slurries.

11. Report: Records

11.1 Record at a minimum the following general information.

11.1.1 Facility name, location and site contacts

11.1.2 Name of project manager

11.1.3 Date and Time the log is obtained

11.1.4 Logging Contractor, field technician and assistants

11.1.5 File name of the injection log, log location and total depth

11.1.6 Down-hole pressure transducer serial number

11.1.7 Equipment used in the investigation (model number of flow module and field instrument)

11.1.8 Site and location specific information relevant to the project. (For example, Petroleum UST, dry cleaning shop, dense till with cobbles, etc.).

11.1.9 Much of the data outlined here can be entered in the digital log information file in the field when the log is completed. This information is saved with the digital data file.

11.2 The computer and software system must record at a minimum the following test data (1.6);

11.2.1 Record and report all depths to the nearest 0.1 ft [0.05m]. For each depth record the following data:

11.2.2 Record and report injection pressure to three significant digits.

11.2.3 Record and report electrical conductivity to three significant digits.

11.2.4 Record and report water flow rate to three significant digits.

11.2.5 Record and report trunkline pressure to three significant digits.

11.2.6 Record and report other down-hole sensor (CPT, MIP, LIF, OIP, etc.) data to three significant digits.

11.3 The computer and software system must record at a minimum the following QA test data (1.6);

11.3.1 Record and report pressure sensor QA test results to three significant digits.

11.3.2 Record and report EC QA test results to three significant digits.

11.3.3 Record and report other down-hole sensor (CPT, MIP, LIF, OIP, etc.) QA test data to three significant digits.

12. Precision and Bias

12.1 *Precision*—Test data on precision is not presented due to the nature of this Practice. It is either not feasible or too costly at this time to have 10 or more agencies participate in an in situ testing program at a given site.

12.2 *Bias*—There is no accepted reference value for this practice, therefore, bias cannot be determined.

13. Keywords

13.1 direct push; electrical conductivity; HPT; hydraulic conductivity; hydraulic profiling tool; injection logging; permeability; pressure dissipation test; soil investigations

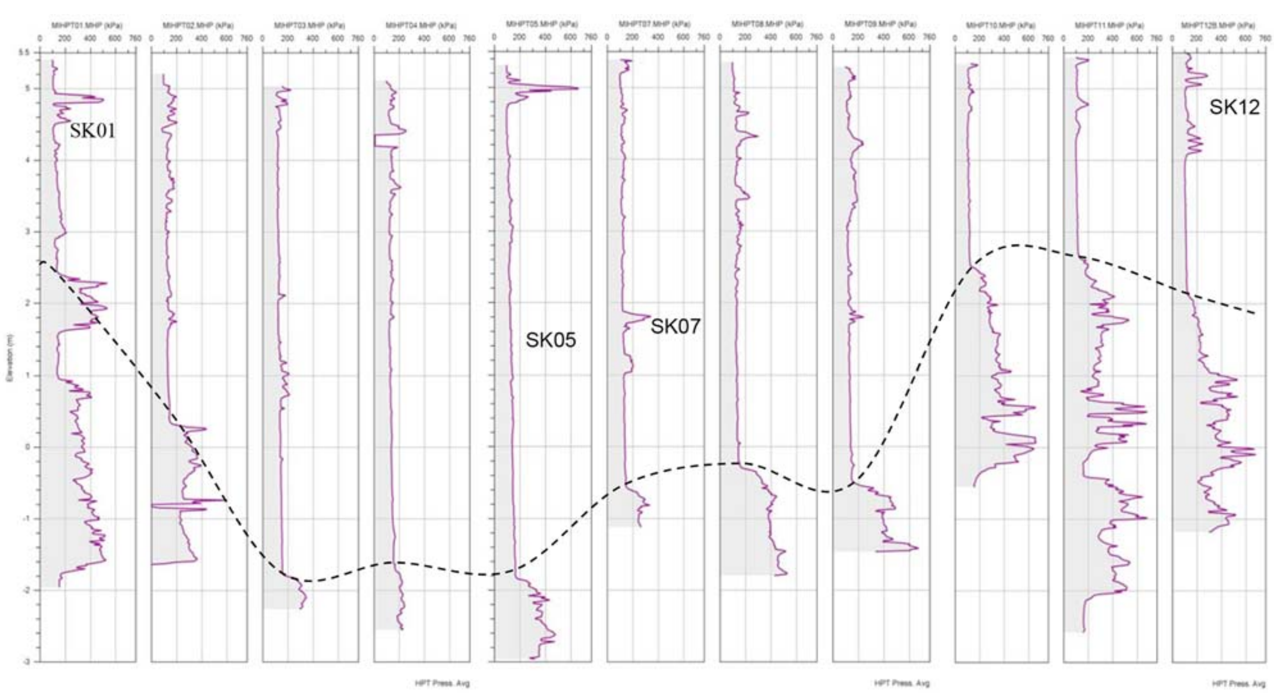
APPENDIX

(Nonmandatory Information)

X1. HYDRAULIC INJECTION LOG INTERPRETATION AND CROSS SECTIONS

X1.1 *Interpretation of injection pressure logs* is relatively simple and intuitive. Increasing injection pressure at the same flow rate indicates decreasing permeability and conversely lower injection pressure at the same flow rate indicates increasing permeability. Review of the injection pressure log and corrected pressure log (Fig. 9) indicates there are high pressure zones centered around 1.5m, 3m, 5.5m, 9m, and 13m depth in the profile. Sampling adjacent to the log found these zones consisted primarily of silt-clays having low permeability. Conversely, lower pressure zones between approximately 7-8m, 9-13m and 14-22m consisted primarily of sand and gravel of high permeability. So we see the upper 9m of the formation is primarily a fine grained material with increasing silt and sand in some intervals resulting in the lower HPT pressure zones. From just below 9m to about 22m the formation is primarily coarse grained sand and gravel with a clay layer between approximately 13-14m depth. The coarse grained part of the formation between 9-22m is part of an alluvial aquifer that provides about eight million gallons of water per day to the local community. Injection pressure logs are often run in linear transects across a site to obtain information on hydrostratigraphy and contaminant migration pathways. One transect of pressure logs from a site located in glaciated terrain (Fig. X1.1) revealed that a contaminant plume was migrating along a buried stream valley.

X1.2 *Interpretation of electrical conductivity (EC) logs* can be more complex than injection pressure logs. Several factors influence bulk formation EC. Some of the factors include clay content, degree of saturation, mineralogy, grain size and presence or absence of ionic compounds (for example, salt, sodium persulfate, etc.). Generally, in freshwater formations clay content and clay mineralogy are often the primary cause of higher EC readings. Some clay materials exhibit EC of 200mS/m and higher. Conversely, clean silica sand has very low electrical conductance and thick layers of clean, dry sand can exhibit EC below 1mS/m. However, when saturated with groundwater the EC of such sand formations often will be higher (sometimes >20mS/m) due to the specific conductance of the pore water (see Fig. 9, 9.5m to 22m). However, it is important to note that not all clays exhibit high electrical conductance. Some clay minerals have low EC, similar to that of sand. Under these conditions only the injection pressure log can distinguish between the clay and sand layers of the



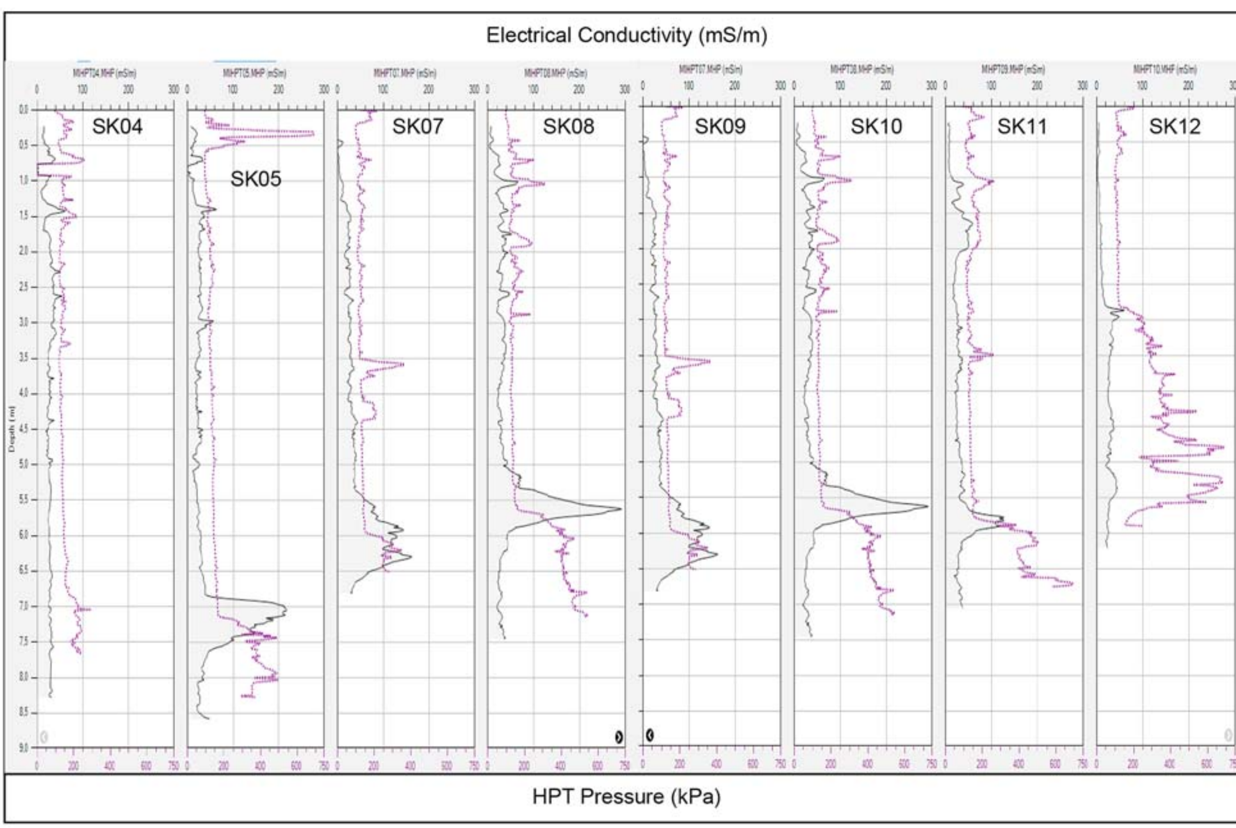
This is a cross section of eleven Injection pressure logs plotted at elevation, the logs were spaced 25 ft [8m] apart. The logs were obtained at a site in Skuldelev, Denmark which is glaciated terrain. Groundwater is contaminated by perchloroethylene (PCE) and its degradation products at this site. The contaminant plume core was found to be located around the SK05 and SK07 logs using MIP logs and groundwater profiling. Continuous soil coring at three locations confirmed that the HPT pressure increase at depth correlated with a gray clay-till underlying the site. Above the till, in the lower injection pressure zone, the formation consisted primarily of sand and gravel with a few silt-clay layers. A dashed line is drawn along the top of the pressure increase, essentially the contact between the underlying clay-till and overlying sand-gravel. The dashed boundary appears to outline a buried stream channel cut in the clay-till by a stream, possibly as glaciers receded. The small valley was later filled with sand and gravel, possibly outwash from the glaciers as they continued receding. The PCE plume is migrating along the buried steam channel (8).

FIG. X1.1 Injection Pressure Log Cross Section

formation (see Fig. X1.1 and Fig. X1.2, especially log SK04). Additionally, silt usually has a low EC, and mixtures of silt with clay will result in lower bulk EC readings. A clean silt layer, such as a loess deposit, can exhibit low EC but may display elevated HPT pressure. Carbonate cementing of sands may also exhibit relatively low EC but elevated injection pressure. Targeted sampling always should be used to confirm log interpretation.

X1.3 *Ionic contaminants,* such as sea water, road salt, sodium persulfate injections, etc. will increase the EC of a given formation. At sufficiently high concentrations of an ionic contaminant, the bulk formation EC can greatly exceed the natural formation EC. This makes it impossible to interpret formation lithology based solely on EC when elevated levels of ionic compounds are present. In these situations having both EC data and HPT pressure data will help with accurate interpretation of the subsurface lithologic conditions and definition of ionic contaminant plumes or areas of seawater intrusion. Ionic compounds like sodium persulfate are often used to remediate chlorinated volatile organic compounds such as perchloroethylene (PCE). A transect of injection logs run down gradient of a sodium persulfate injection pilot study detected EC anomalies above the underlying clay-rich till at a site in Denmark (Fig. X1.2). A continuous soil core obtained at a background location (SK04) revealed that the clay-till underlying a very permeable sand and gravel at this site had low electrical conductivity and could not be easily distinguished from the sand and gravel based only on the EC log. However, increasing injection pressure clearly defined the change from the overlying sand and gravel to the underlying clay-till. When the EC logs are overlain with the injection pressure logs it is apparent that sodium persulfate has migrated along the top of the clay-till, resulting in an EC anomaly that can be mapped with the combined EC and injection pressure logs (Fig. X1.2).

X1.4 *Pressure dissipation tests* can provide information on the piezometric pressure at the depth they are performed (Fig. 10). The tests must be run for sufficient time to completely



This is a cross section of hydraulic injection pressure logs (dashed lines) and electrical conductivity (EC) logs (solid line with gray fill). The logs were obtained at a site in Skuldelev, Denmark which is glaciated terrain. Groundwater is contaminated by perchloroethylene (PCE) and its degradation products. A sodium persulfate pilot test was performed on a DNAPL zone just upgradient from this transect of logs. The injection pressure logs and selected soil coring revealed that the injection pressure increase at depth correlated with the top of a clay-till underlying the site (see Fig. 10). The background log at SK04 reveals that there is little difference between the EC of the overlying sand and gravel and underlying clay till, confirmed with soil coring. For logs SK05 through SK11 the EC increased above the clay till and then dropped off as the probe was advanced through the till. The increase of EC above the clay till, and the lack of correlation between the injection pressure and EC response identify an EC anomaly. Groundwater profiling at location SK05 revealed a significant increase in specific conductance of the groundwater with depth as the EC anomaly was approached. Samples from nearby monitoring wells displayed elevated specific conductance and also elevated levels of sodium as compared to background conditions. Here the EC anomaly visible in logs SK05 through SK11 shows where the sodium persulfate injectate has migrated along the surface of the clay-till and began to diffuse into the clay-till. This demonstrates the effective use of combined injection pressure logs and EC logs to locate and track ionic plumes in the subsurface. Note: repeated use of the injection probe and steel rods in corrosive environments could lead to degradation and damage of the steel, threaded joints and system parts. *Notes: mS/m = milliSiemen per meter: kPa = kiloPascal.*

FIG. X1.2 Hydraulic Injection Pressure and Electrical Conductivity Cross Section

dissipate the excess pressure induced in the formation by insertion of the probe and injection of water. Even in very permeable formations dissipation tests should be run for at least two minutes to assure that pressure equilibrium with the formation is achieved. It is wise to run more than one dissipation test during a log if time and subsurface conditions permit. If sand layers are separated by clay layers it is useful to run a dissipation test in each sand layer to determine if any vertical groundwater gradients may be present. Once the log is completed the viewing software allows the operator to use the dissipation test(s) to plot the piezometric profile and determine the static water level for water table aquifers. If confined zones are present running a dissipation test in each zone will allow for the determination of the piezometric level for each zone. Of course, conducting dissipation tests under artesian conditions will result in the water level being plotted above ground surface.

X1.5 *Corrected pressure logs* may be calculated in the viewing software when one or more pressure dissipation tests are run to complete pressure dissipation. The viewing software subtracts the atmospheric pressure (P_{atm}) and piezometric pressure (P_{piezo}) from the total injection pressure (P_{tot}) to obtain the corrected injection pressure (P_c). That is: $P_c = P_{tot} - (P_{atm} + P_{piezo})$. This calculation is performed for each depth increment of the log. The corrected HPT pressure is the pressure required to inject water into the formation at the given flow rate and is a function of the formation hydraulic conductivity at that depth and location. So the corrected pressure log (Fig. 9, graph 3) provides a more accurate view of the changes in formation permeability with depth than the total injection pressure. Based on Darcy's Law (**29**) we know that hydraulic conductivity (K) can be defined as a function of flow (Q) and pressure (P) in a porous medium. That is K = f (Q/P). An empirical model was developed to use the corrected injection pressure (P_c) and the injection flow rate (Q) at a given depth to determine an estimate of hydraulic conductivity (Est. K) (Fig. 9, graph 4) for saturated formations (**5, 10**). This model has a lower boundary of approximately 0.1 ft/day [0.03m/day] and an upper boundary of about 75 ft/day [25m/day]. The Est. K log can be useful in delineating migration pathways and locating barriers in the subsurface. The Est. K logs and corrected pressure logs also may be used to guide additional testing to obtain quantitative measurements of K in unconsolidated formations. This is often accomplished with slug testing (Practice D7242) of direct push installed groundwater sampling devices (Guide D6001) or collection of core samples (Guide D6282, Practice D1587) especially in fine grained zones for laboratory tests of permeability (Test Methods D2434, D5856, D5084)

REFERENCES

(1) Dietrich, Peter, James J. Butler, Jr., and Klaus FaiB, 2008. A Rapid Method for Hydraulic Profiling in Unconsolidated Formations. *Ground Water*, Vol. 46, No. 2. March-April.

(2) Kober, Rolf, Gotz Hornbruch, Carsten Leven, Lars Tischer, Jochen GroBmann, Peter Dietrich, Holger WeiB and Andreas Dahmke. 2009. Evaluation of Combined Direct-Push Methods Used for Aquifer Model Generation. *Ground Water*, Vol. 47, No. 4, July-August. Pages 536-546.

(3) Dietze, Michael and Peter Dietrich. 2012. Evaluation of Vertical Variations in Hydraulic Conductivity in Unconsolidated Sediments. *Ground Water*, Vol. 50, No. 3. May-June. Pages 450-456.

(4) Reiffsteck, Ph., B. Dorbani, E. Haza-Rozier and J.-J. Fry. 2010. A New Hydraulic profiling tool including CPT measurements. Presented at the 2nd International Symposium on Cone Penetration Testing. Volume 2: Equipment and Procedures, Paper No. 1-11, 8 pages. www.cpt10.com/cpt10pdfpapers.html

(5) Geoprobe Systems. 2010. Tech Guide for Calculation of Estimated Hydraulic Conductivity (Est. K) Log from HPT Data. Kejr Inc., Salina, Kansas. November. 20 pages. www.geoprobe.com

(6) Sanchez-Vila, Xavier Jesus Carrera and Jorge P. Girardi, 1996. Scale effects in transmissivity. *Journal of Hydrology*, Vol. 183. Pages 1-22.

(7) Kejr Inc. 2013. Geoprobe Hydraulic Profiling Tool (HPT) System, Standard Operating Procedure, Technical Bulletin No. MK3137. Salina, Kansas, USA. February. www.geoprobe.com

(8) McCall, W., Thomas M. Christy, Daniel Pipp, Mads Terkelsen, Anders Christensen, Klaus Weber and Peter Engelsen. 2014. Field Application of the Combined Membrane-Interface Probe and Hydraulic Profiling Tool (MiHpt). *Groundwater Mon. & Rem.*, Vol. 34, No. 2, pages 85-95.

(9) McCall, Wesley, Thomas M. Christy, Thomas Christopherson and Howard Isaacs. 2009. Application of Direct Push Methods to Investigate Uranium Distribution in an Alluvial Aquifer. *Ground Water Mon. & Rem.*, Vol. 29, No. 4, pages 65-76.

(10) Kejr Inc., 2011. Application of the Geoprobe HPT Logging System for Geo-Environmental Investigations, Geoprobe Technical Bulletin No. MK3184. February. 36 pages. www.geoprobe.com

(11) Pitkin, S., et. Al,(2004) "Evaluation of the Waterloo Profiler as a Dynamic Site Investigation Tool," Proceedings of the Fourth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Paper 1B-07, A.R. Gavaskar and A.S.C. Chen (Eds.), Battelle Press, Columbus, OH, www.battelle.org/bookstore.

(12) Liu, Gaisheng, James J. Butler, Jr., Geoffrey C. Bohling, Edward Reboulet, Steve Knobbe and David W. Hyndman, 2009. A new method for high-resolution characterization of hydraulic conductivity. *Water Resources Research*, Vol. 45, W08202.

(13) Quinnan, J.A., N.R.H. Welty and E. Killenbeck, 2010. Hydrostratigraphic and permeability profiling for groundwater remediation projects. 2nd International Symposium on Cone Penetration Testing, Volume 2 & 3, Paper No. 3-33. May.

(14) McCall, Wesley, Thomas M. Christy and Mateus E. Knabach. 2016. Applying the HPT-GWS for Hydrostratigraphy, Water Quality and Aquifer Recharge Investigations. *Groundwater Mon. and Rem.* (In press).

(15) Schulmeister, M.K., J.J. Butler, Jr., J.M. Healey, L. Zheng, D.A. Wysocki, and G.W. McCall. 2003. Direct-push electrical conductivity logging for high-resolution hydrostratigraphic characterization. *Ground Water Mon. & Rem.*, V. 23, no. 3. Pages 52-62.

(16) Kejr, Inc., "A Percussion Probing Tool for the Direct Sensing of Soil Conductivity," Technical Bulletin No. 94-100, Geoprobe Systems, 1995. www.geoprobe.com

(17) Liu, Gaisheng, James J. Butler Jr., Edward Reboulet and Steven Knobbe. 2011. *Hydraulic conductivity profiling with direct push methods*. Grundwasser – Zeitschrift der Fachsektion Hydrogeologie. DOI 10.1007/s00767-011-0182-9.

(18) Chapuis, Robert P., and Djaouida Chenaf. 2010. Driven Field Permeameters: Reinventing the Wheel?*Geotechnical News*. March.

(19) Chapuis, RP, Morin, R., and Gill, D.E. 1992. Développement et évaluation d'un perméamètre autoforeur pour sols silteux (Development and evaluation of a self-boring permeameter for silty soils). Proc., 45th Canadian Geotechnical Conference, Toronto, pp. 77A-1 to -10.

(20) Chapuis, R.P., J.J. Pare and J.G. Lavallee. 1981. Essais de permeabilite in situ a niveau variable (In Situ Variable Head Permeability Tests) in Proceeding of the 10th ICSMFE Conference. Vol. 1, pages 401-406. Stockhlom.

(21) Chapuis, Robert P., Marc L;Ecuyer, and Michel Aubertin. 1993. Field Permeability Tests in Mine Tailing. In the Proceeding of 46th Annual Canadian Geotechnical Conference(Conference Canadienne De Geotechnique). Saskatoon, Sask. Pages 51-59.

(22) Chapuis, R.P. 2001. Extracting Piezometric Level and Hydraulic Conductivity from Tests in Driven Flush-Joint Casings. *Geotechnical Testing Journal*, GTJODJ, Vol. 24, No. 2. Pages 209-219.

(23) Chapuis, Robert P., and Djaouida Chenaf. 2003. Variable-Head Field Permeability Tests in Driven Flush-Joint Casings: Physical and Numerical Modeling. *Geotechnical Testing Journal*, Vol. 26, No. 3. Paper ID GTJ10411 263. August.

(24) Lunne, T., P.K. Robertson and J.J.M. Powell. 1997. *Cone Penetration Testing in Geotechnical Practice*. Spon Press/Taylor & Francis Group. London and New York.

(25) Geoprobe Systems. 2016. *Optical Image Profiler for UV Induced Hydrocarbon Fluorescence*. http://geoprobe.com/geoprobe-systems-direct-image-products#news

(26) Simoni, G. and V. Giovanni. 2006. Use of a resistivity cone and fuel fluorescence detector for the detection and mapping of contaminated sites. Newsletter Associazione Geotecnica Italiana, No. 3. 7 pages.

(27) Geoprobe Systems. 2016. *Windows DI Acquisition Software for FI6000 v. 1.7*. http://geoprobe.com/downloads/windows-di-acquisition-software-for-fi6000-v-15

(28) Geoprobe Systems. 2015. *Direct Image Viewer 2.0*. http://geoprobe.com/downloads/direct-image-viewer-20

(29) Fetter, C.W., 1994. *Applied Hydrogeology*, Third Edition. Prentice-Hall, New Jersey.