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Standard Practice for Using the Electronic Piezocone Penetrometer Tests for Environmental Site Characterization and Estimation of Hydraulic Conductivity[1]

This standard is issued under the fixed designation D6067/D6067M; 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 The electronic cone penetrometer test often is used to determine subsurface stratigraphy for geotechnical and environmental site characterization purposes (**1**).[2] The geotechnical application of the electronic cone penetrometer test is discussed in detail in Test Method D5778, however, the use of the electronic cone penetrometer test in environmental site characterization applications involves further considerations that are not discussed. For environmental site characterization, it is highly recommended to use the Piezocone (PCPT or CPTu) option in Test Method D5778 so information on hydraulic conductivity and aquifer hydrostatic pressures can be evaluated.

1.2 The purpose of this practice is to discuss aspects of the electronic cone penetrometer test that need to be considered when performing tests for environmental site characterization purposes.

1.3 The electronic cone penetrometer test for environmental site characterization projects often requires steam cleaning the push rods and grouting the hole. There are numerous ways of cleaning and grouting depending on the scope of the project, local regulations, and corporate preferences. It is beyond the scope of this practice to discuss all of these methods in detail. A detailed explanation of grouting procedures is discussed in Guide D6001.

1.4 Cone penetrometer tests are often used to locate aquifer zones for installation of wells (Practice D5092/D5092M, Guide D6274). The cone test may be combined with direct push soil sampling for confirming soil types (Guide D6282/D6282M). Direct push hydraulic injection profiling (Practice D8037/D8037M) is another complementary test for estimating hydraulic conductivity and direct push slug tests (D7242/D7242M) and used for confirming estimates. Cone penetrometers can be equipped with additional sensors for groundwater quality evaluations (Practice D6187). Location of other sensors must conform to requirements of Test Method D5778.

1.5 This practice is applicable only at sites where chemical (organic and inorganic) wastes are a concern and is not intended for use at radioactive or mixed (chemical and radioactive) waste sites due to specialized monitoring requirements of drilling equipment.

1.6 *Units*—The values stated in either SI units or in-lb 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. Units for conductivity are either m/s or cm/s depending on the sources cited.

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

1.8 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.9 *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 consideration of a project's many unique aspects. The word "Standard" in the title means only that the document has been approved through the ASTM consensus process.*

1.10 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

[1] This practice 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 the list of references at the end of this guide.

*A Summary of Changes section appears at the end of this standard

2. Referenced Documents

2.1 *ASTM Standards:*[3]

C150/C150M Specification for Portland Cement
D653 Terminology Relating to Soil, Rock, and Contained Fluids
D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction
D5088 Practice for Decontamination of Field Equipment Used at Waste Sites
D5092/D5092M Practice for Design and Installation of Groundwater Monitoring Wells
D5778 Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils
D6001 Guide for Direct-Push Groundwater Sampling for Environmental Site Characterization
D6026 Practice for Using Significant Digits in Geotechnical Data
D6187 Practice for Cone Penetrometer Technology Characterization of Petroleum Contaminated Sites with Nitrogen Laser-Induced Fluorescence
D6235 Practice for Expedited Site Characterization of Vadose Zone and Groundwater Contamination at Hazardous Waste Contaminated Sites
D6274 Guide for Conducting Borehole Geophysical Logging - Gamma
D6282/D6282M Guide for Direct Push Soil Sampling for Environmental Site Characterizations
D7242/D7242M Practice for Field Pneumatic Slug (Instantaneous Change in Head) Tests to Determine Hydraulic Properties of Aquifers with Direct Push Groundwater Samplers
D8037/D8037M Practice for Direct Push Hydraulic Logging for Profiling Variations of Permeability in Soils

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of terms related to this standard, refer to Terminology D653.

3.1.2 *coefficient of permeability, k, [LT^{-1}]*—the rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions (usually 20°C).

3.1.3 *hydraulic conductivity, k*—the rate of discharge of water under laminar flow conditions through a unit cross-sectional area of porous medium under a unit hydraulic gradient and standard temperature conditions [20°C].

3.1.3.1 *Discussion*—In hydraulic conductivity testing, the term coefficient of permeability is often used instead of hydraulic conductivity, and colloquially the term permeability is often used interchangeably with hydraulic conductivity. The terms are used interchangeably in this standard as different information resources are cited in the document that use different terms. A more complete discussion of the terminology associated with Darcy's law is given in the literature

3.1.4 *hydraulic conductivity (in field aquifer tests), n*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.2 *Definitions of Terms Specific to This Standard in Accordance with D5778:*

3.2.1 *cone tip, n*—the conical point of a cone penetrometer on which the end bearing component of penetration resistance is developed.

3.2.2 *cone resistance, q_c, n*—the measured end-bearing component of penetration resistance. The resistance to penetration developed on the cone is equal to the vertical force applied to the cone divided by the cone base area.

3.2.3 *cone penetration test, n*—a series of penetration readings performed at one location over the entire vertical depth when using a cone penetrometer. Also referred to as a cone sounding

3.2.4 *electronic cone penetrometer, n*—a friction cone penetrometer that uses force transducers, such as strain gauge load cells, built into a nontelescoping penetrometer tip for measuring within the penetrometer tip, the components of penetration resistance.

3.2.5 *electronic piezocone penetrometer, n*—an electronic cone penetrometer equipped with a low volume fluid chamber, porous element, and pressure transducer for determination of pore water pressure at the porous element soil interface measured simultaneously with end bearing and frictional components of penetration resistance.

3.2.6 *equilibrium pore water pressure, u_o, n*—at rest water pressure at depth of interest. Same as hydrostatic head. **D653**

3.2.7 *excess pore water pressure, $\Delta u = u - u_0$, n*—the difference between pore water pressure measured as the penetration occurs (u), and estimated equilibrium pore water pressure (u_0), or: $\Delta u = (u - u_0)$. Excess pore water pressure can either be positive or negative for shoulder position filters.

3.2.8 *friction ratio, R_f, n*— the ratio of friction sleeve resistance, f_s, to cone resistance, q_c, measured with the middle of the friction sleeve at the same depth as the cone point. It is usually expressed as a percentage.

3.2.9 *friction reducer, n*—a narrow local protuberance on the outside of the push rod surface, placed at a certain distance above the penetrometer tip, which is provided to reduce the total side friction on the push rods and allow for greater penetration depths for a given push capacity.

3.2.10 *friction sleeve resistance, f_s, n*—the friction component of penetration resistance developed on a friction sleeve, equal to the shear force applied to the friction sleeve divided by its surface area.

3.2.11 *friction sleeve, n*—an isolated cylindrical sleeve section on a penetrometer tip upon which the friction component of penetration resistance develops.

3.2.12 *penetrometer, n*—an apparatus consisting of a series of cylindrical push rods with a terminal body (end section)

[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.

called the penetrometer tip and measuring devices for determination of the components of penetration resistance.

3.2.13 *penetrometer tip, n*—the terminal body (end section) of the penetrometer which contains the active elements that sense the components of penetration resistance.

3.2.14 *piezocone, n*—same as electronic piezocone penetrometer.

3.2.15 *piezocone pore pressure, u, n*—fluid pressure measured using the piezocone penetration test.

3.2.16 *push rods, n*—the thick walled tubes or rods used to advance the penetrometer tip.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *bentonite, n*—the common name for drilling fluid additives and well construction products consisting mostly of naturally occurring sodium montmorillonite. Some bentonite products have chemical additives that may affect water quality analyses.

3.3.2 *dissipation test, n*—test where the dissipation of excess pore water pressure generated during push is monitored versus time to evaluate depth specific hydraulic conductivity and final pressure head of the soil when penetration is stopped.

3.3.2.1 *Discussion*—Either complete or 50 % dissipation time is monitored. Complete dissipation can be used to determine equilibrium pore water pressure and thus hydrostatic head at a point in the aquifer. The time required for dissipation depends on the soil type.

3.3.3 *soil behavior type index, I_c, n*—Index where the normalized cone parameters Q_t and F_r can be combined into one Soil Behavior Type index, I_c, where I_c is the radius of the essentially concentric circles that represent the boundaries between each SBT zone on the normalized soil behavior type classification charts.

3.3.3.1 *Discussion*—I_c is determined by equation using normalized tip resistance, friction ratio and is a function and effective confining stresses. For the equation for I_c, refer to references by Lunne & Robertson (**1**, **2**).

3.4 *Symbols:*

3.4.1 I_c—soil behavior type index.

3.4.2 t_{50}—time for dissipation of 50 percent of the excess pore water pressure during dissipation tests.

3.4.3 Δ_u—excess pore pressure.

3.4.4 *qt*—Corrected cone resistance—The cone resistance qc corrected for pore water effects. qt = qc + u_2(1- a_n).

3.4.4.1 *Discussion*—(Typical CPT a_n = net area ratio is 0.7 to 0.8.)

3.4.5 *Qt*—Normalized cone resistance—The cone resistance expressed in a non-dimensional form and taking account of the in-situ vertical stresses. Qt = (qt – σv)/ σv'.

3.4.6 *Qtn*—Normalized cone resistance (dimensionless)—The cone resistance expressed in a non-dimensional form taking account of the in-situ vertical stresses and where the stress exponent Qtn = $((qt - \sigma_v)/ p_a) * (p_a/\sigma_v')^n$.

3.4.6.1 *Discussion*—(n) varies with soil type. When n = 1, Qtn = Qt.

3.4.7 *k*—Coefficient of hydraulic conductivity or permeability (D18 Standards Preparation Manual).

3.4.8 *K*—Intrinsic (absolute) permeability in area units (D18 Standards Preparation Manual).

3.5 *Acronyms:*

3.5.1 *CPT*—Cone Penetration Test.

3.5.2 *PCPT or CPTu*—Piezocone Penetration Test. **D5778**

4. Significance and Use

4.1 Environmental site characterization projects almost always require information regarding subsurface soil stratigraphy and hydraulic parameters related to groundwater flow rate and direction. Soil stratigraphy often is determined by various drilling procedures and interpreting the data collected on borehole logs. The electronic piezocone penetrometer test is another means of determining soil stratigraphy that may be faster, less expensive, and provide greater resolution of the soil units than conventional drilling and sampling methods. For environmental site characterization applications, the electronic piezocone also has the additional advantage of not generating contaminated cuttings that may present other disposal problems (**2**, **3**, **4**, **5**, **6**, **7**, **8**, **9**, **10**). Investigators may obtain soil samples from adjacent borings for correlation purposes, but prior information or experience in the same area may preclude the need for borings (**11**). Most cone penetrometer rigs are equipped with direct push soil samplers (Guide D6282/D6282M) that can be used to confirm soil types.

4.2 The electronic piezocone penetration test is an in situ investigation method involving:

4.2.1 Pushing an electronically instrumented probe into the ground (see Fig. 1 for a diagram of a typical cone penetrometer). The position of the pore pressure element may vary but is typically located in the u_2 position, as shown in Fig. 1 (Test Method D5778).

4.2.2 Recording force resistances, such as tip resistance, friction sleeve resistance, and pore water pressure.

4.2.3 Data interpretation.

4.2.3.1 The most common use of the interpreted data is stratigraphy based on soil behavior types. Several charts are available. A typical CPT soil behavior type classification chart is shown in Figs. 2 and 3 (**1**, **2**). Figure 3 uses tip and friction sleeve resistance data normalized to the estimated in-situ ground stresses. The first step in determining the extent and motion of contaminants is to determine the subsurface stratigraphy. Since the contaminants will migrate primarily through the more permeable strata, it is impossible to characterize an environmental site without valid stratigraphy. Cone penetrometer data have been used as a stratigraphic tool for many years. The pore pressure channel of the cone can be used to evaluate the presence and hydraulic head of groundwater or to locate perched water zones.

4.2.3.2 Hydraulic conductivity can be estimated based on soil behavior type (Figs. 1 and 2). These estimates span two to three orders of magnitude. Alternately, pore pressure data (4.5) can be used for refined estimates of hydraulic conductivity.

4.2.3.3 Robertson proposed the following equations estimating *k* from I_c and shown on Fig. 4 (**11**). These equations are

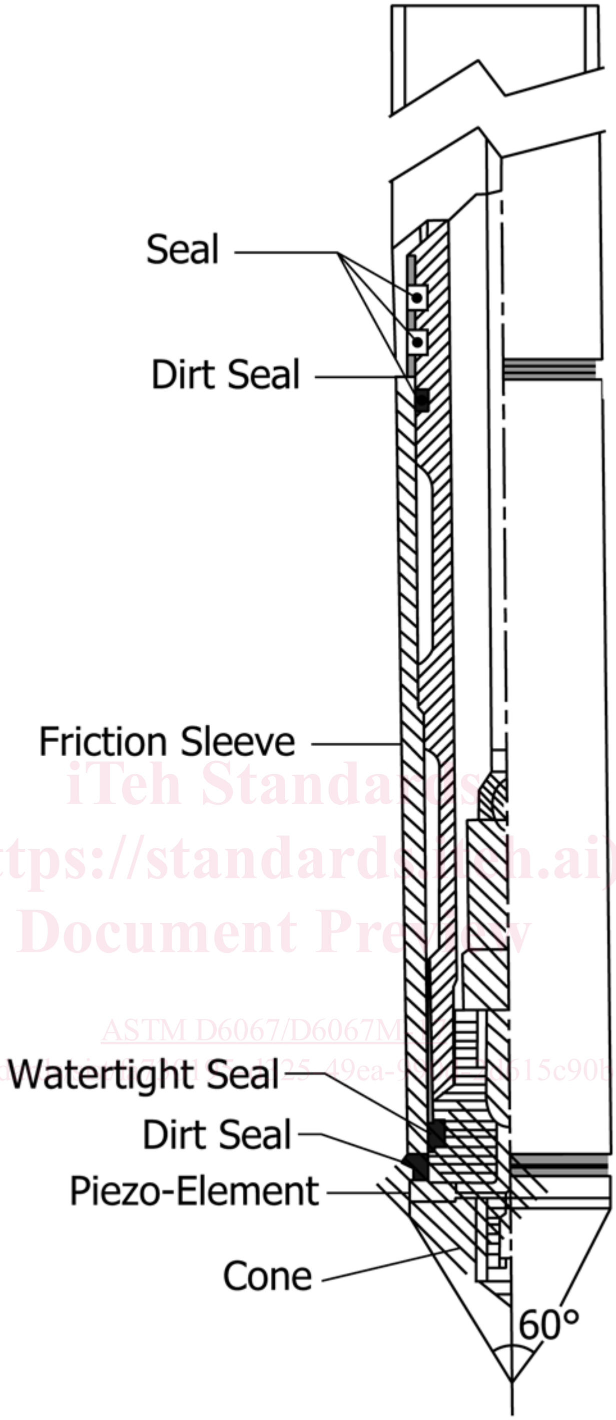
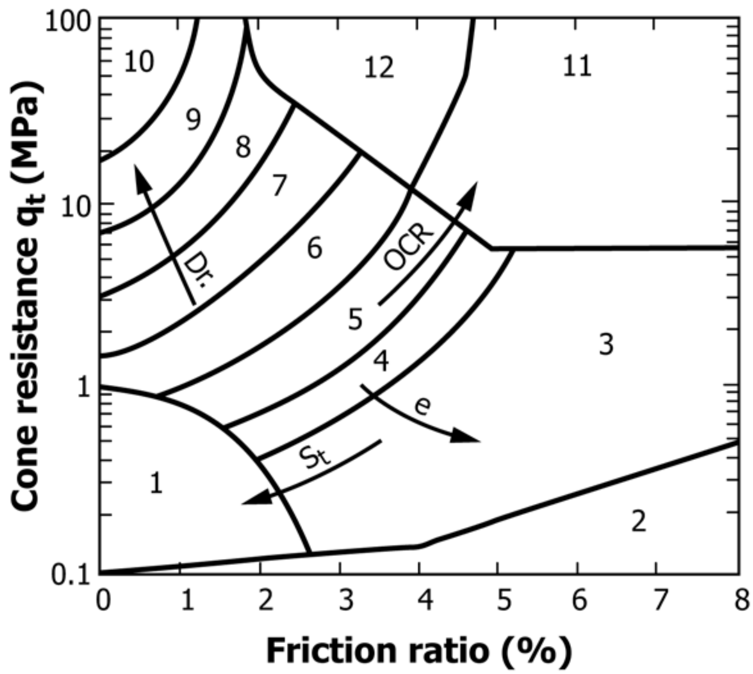


FIG. 1 Electronic Cone Penetrometer (Test Method D5778-07)

used for some cone penetration testing commercial software for estimates of *k* based on normalized soil behavior type. However, as shown on Tables 1 and 2, the values estimated from I_c are not very accurate for example, the estimated *k* value may range over two orders of magnitude.

4.3 When attempting to retrieve a soil gas or water sample, it is advantageous to know where the bearing zones (permeable zones) are located. Although soil gas and water can be retrieved from sediments with low hydraulic conductivity, the length of time required usually makes it impractical. Soil gas and water samples can be retrieved much faster from permeable zones, such as sands. The cone penetrometer tip and friction data generally can distinguish between lower and higher permeability zones less than 0.3 m [1 ft] very accurately.

4.4 The electronic cone penetrometer test is used in a variety of soil types. Lightweight equipment with reaction weights of less than 10 tons generally are limited to soils with relatively small grain sizes. Typical depths obtained are 20 to



Zone	Soil Behavior Type
1	Sensitive fine grained
2	Organic material
3	Clay
4	Silty Clay to clay
5	Clayey silt to silty clay
6	Sandy silt to clayey silt
7	Silty sand to sandy silt
8	Sand to silty sand
9	Sand
10	Gravelly sand to sand
11	Very stiff fine grained*
12	Sand to clayey sand*

* Overconsolidated or cemented

FIG. 2 Simplified Soil Classification Chart for Standard Electric Friction Cone (Robertson and Campanella 1986) (1)

40 m [60 to 120 ft], but depths to over 70 m [200 ft] with heavier equipment weighing 20 tons or more are not uncommon. Since penetration is a direct result of vertical forces and does not include rotation or drilling, it cannot be utilized in rock or heavily cemented soils. Depth capabilities are a function of many factors (D5778).

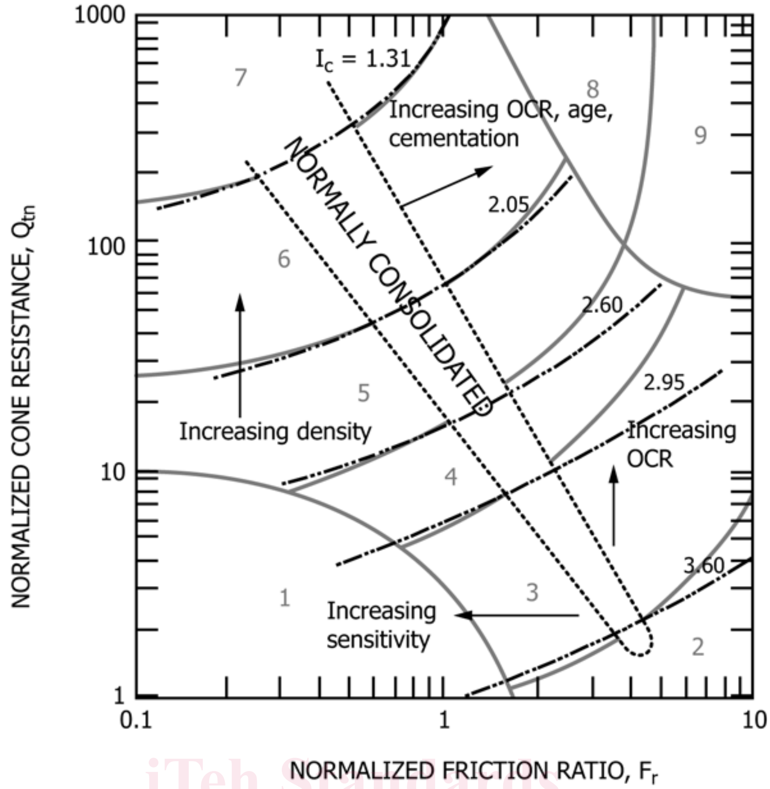
4.5 *Pore Pressure Data:*

4.5.1 Excess pore water pressure data often are used in environmental site characterization projects to identify thin soil layers that will either be aquifers or aquitards. The pore pressure channel often can detect these thin layers even if they are less than 20 mm [1 in.] thick.

4.5.2 Excess pore water pressure data taken during push are used to provide an indication of relative hydraulic conductivity. Excess pore water pressure is generated during an electronic cone penetrometer test. Generally, high excess pore water pressure indicates the presence of aquitards (clays), and low excess pore water pressure indicates the presence of aquifers (sands). This is not always the case, however. For example, some silty sands and over-consolidated soils generate negative pore pressures if monitored above the shoulder of the cone tip. See Fig. 1. The balance of the data, therefore, also must be evaluated. There have been methods proposed to estimate hydraulic conductivity from dynamic excess pore water pressure measurements (**12**, **13**, **14**).

4.5.3 *Dissipation Tests:*

4.5.3.1 In general, since the groundwater flows primarily through sands and not clays, modeling the flow through the sands is most critical. The pore pressure data also can be monitored with the sounding halted. This is called a pore pressure dissipation test. A rapidly dissipating pore pressure indicates the presence of an aquifer while a very slow



Zone	***Soil Behavior Type***	I_c
1	*Sensitive, fine grained*	N/A
2	*Organic soils – clay*	> 3.6
3	*Clays – silty clay to clay*	2.95 – 3.6
4	*Silt mixtures – clayey silt to silty clay*	2.60 – 2.95
5	*Sand mixtures – silty sand to sandy silt*	2.05 – 2.6
6	*Sands – clean sand to silty sand*	1.31 – 2.05
7	*Gravelly sand to dense sand*	< 1.31
8	*Very stiff sand to clayey sand**	N/A
9	*Very stiff, fine grained**	N/A

**Heavily overconsolidated or cemented*

FIG. 3 Normalized CPT Soil Behavior Type (SBT_N) chart, Q_t–F (Robertson 1990) (1, 2)

dissipation indicates the presence of an aquitard. Fig. 5 shows a typical dissipation test showing the t_{50} determined by waiting for 50 % of the highest pressure registered to dissipate. In some soils there can first be a lag before the peak pore pressure occurs. This example also shows that sufficient time was reached to allow the pore pressure to reach full equalization.

4.5.3.2 Fig. 6 shows one proposed relationship between t_{50} dissipation time and horizontal, hydraulic conductivity reported by Robertson (**2, 11**). This chart uses a tip resistance normalized for overburden stresses in the ground. This requires the estimation of the wet and saturated density of the soil and estimated water table location (**2**). The data points on the chart are laboratory test data from correlated samples. Figure 6 is developed for 10 cm^2 diameter cones and a correction factor is required for 15 cm^2 cones (multiply *k* values by factor of 1.5) (**2**).

4.5.3.3 Included in Fig. 6 is a proposed relationship between dissipation time, soil type, and hydraulic conductivity proposed