Standard Guide for Conducting Borehole Geophysical Logging—Electromagnetic Induction[1]

This standard is issued under the fixed designation D 6726; 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 guide is focused on the general procedures necessary to conduct electromagnetic-induction, induction, electromagnetic-conductivity, or electromagnetic-resistivity logging (hereafter referred as induction logging) of boreholes, wells, access tubes, caissons, or shafts (hereafter referred as boreholes) as commonly applied to geologic, engineering, ground-water and environmental (hereafter referred as geotechnical) investigations. Induction logging for minerals or petroleum applications is excluded.

1.2 This guide defines an induction log as a record of formation electrical conductivity or resistivity with depth as measured by the induction method in a borehole.

1.2.1 Induction logs are treated quantitatively and should be interpreted with other logs and data whenever possible.

1.2.2 Induction logs are commonly used to: (*1*) delineate lithology; (*2*) evaluate formation water quality and effective porosity, and (*3*) correlate stratigraphy between boreholes.

1.3 This guide is restricted to induction measurements that are at a frequency of less than 50 KHz; are non-directional; and average formation properties around the circumference of the borehole; which are the most common induction measurement devices used in geotechnical applications.

1.4 This guide provides an overview of induction logging including (*1*) general procedures; (*2*) specific documentation; (*3*) calibration and standardization; and (*4*) log quality and interpretation.

1.5 To obtain additional information on induction logs see References section in this guide.

1.6 This guide is to be used in conjunction with Standard Guide D 5753.

1.7 This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This guide should not be used as a sole criterion for induction logging and does not replace education, experience, and professional judgement. Induction logging procedures should be adapted to meet the needs of a range of applications and stated in general terms so that flexibility or innovation are not suppressed. Not all aspects of this guide 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 without consideration of a project's many unique aspects. The word standard in the title of this document means that the document has been approved through the ASTM consensus process.

1.8 The geotechnical industry uses English or SI units. The induction log is typically recorded in millisiemens per meter (mS/m) or millimhos per meter (mmhos/m).

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 requirements prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 420 Guide to Site Characterization for Engineering, Design, and Construction Purposes[2]

D 653 Terminology Relating to Soil, Rock and Contained Fluids[2]

D 5088 Practice for Decontamination of Field Equipment at Non- Radioactive Waste Sites[2]

D 5608 Practice for Decontamination of Field Equipment Used at Low Level Radioactive Waste Sites[2]

D 5730 Guide for Site Characterization for Environmental Purposes with Emphasis on Soil, Rock, Vadose Zone, and Ground Water[2]

D 5753 Guide for Planning and Conducting Borehole Geophysical Logging[2]

D 6167 Guide for Conducting Borehole Geophysical Logging—Mechanical Caliper[3]

D 6235 Practice for Expediated Site Characterization of Vadose Zone and Ground Water Contamination of Hazardous Waste Contaminated Sites[3]

D 6274 Guide for Conducting Borehole Geophysical Logging—Gamma[3]

D 6429 Guide for Selecting Surface Geophysical Methods[3]

D 6431 Guide for Using the Direct Current Resistivity

[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.01 on Surface and Subsurface Characterization.

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 04.09.

Method for Subsurface Investigations[3]

3. Terminology

3.1 *Definitions*—Definitions shall be in accordance with terms and symbols given in Terminology D 653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *accuracy*—how close a measured log value approaches true value. It is determined in a controlled environment. A controlled environment represents a homogeneous sample volume with known properties.

3.2.2 *depth of investigation*—the radial distance from the measurement point to a point where the predominant measured response may be considered centered, which is not to be confused with borehole depth (for example, distance) measured from the surface.

3.2.3 *measurement resolution*—the minimum change in measured value that can be detected.

3.2.4 *repeatability*—the difference in magnitude of two measurements with the same equipment and in the same environment.

3.2.5 *vertical resolution*—the minimum thickness that can be separated into distinct units.

3.2.6 *volume of investigation*—the volume that contributes 90 percent of the measured response. It is determined by a combination of theoretical and empirical modeling. The volume of investigation is non-spherical and has gradational boundaries.

4. Summary of Guide

4.1 This guide applies to induction logging and is to be use in conjunction with Guide D 5753.

4.2 This guide briefly describes the significance and use, apparatus, calibration and standardization, procedures and reports for conducting induction logging.

5. Significance and Use

5.1 An appropriately developed, documented, and executed guide is essential for the proper collection and application of induction logs. This guide is to be used in conjunction with Guide D 5753.

5.2 The benefits of its use include improving: selection of induction logging methods and equipment; induction log quality and reliability; and usefulness of the induction log data for subsequent display and interpretation.

5.3 This guide applies to commonly used induction logging methods for geotechnical applications.

5.4 It is essential that personnel (see Section 8.3.2, Guide D 5753) consult up-to-date textbooks and reports on the induction technique, application, and interpretation methods.

6. Interferences

6.1 Most extraneous effects on induction logs are caused by logging procedures, instrument problems, borehole conditions, and geologic conditions.

6.2 Logging procedures include incorrect range setting, incorrect calibration, and logging too fast.

6.3 Instrument problems include electrical leakage and temperature drift.

6.3.1 Induction probes need to warm up and stabilize with the borehole environment. Some probes record internal electronic temperature; this temperature record should not be confused with a borehole fluid temperature log.

6.4 Effects of borehole fluid is dependent on probe design, borehole diameter, and borehole-fluid conductivity. Induction measurements can be made in air-, water-, or mud-filled boreholes. Induction probes are designed to minimize effects of borehole fluid. Conductivity of borehole fluid will significantly affect induction response only in larger diameter boreholes (typically, greater than 8 to 10 in. (20 to 25 cm) diameter).

6.4.1 Effects of mud-invasion zone is dependent on probe design, invasion depth, and mud and formation conductivity.

6.4.2 Steel or other conductive material interferes and may prohibit induction measurements. PVC casing and other nonconductive casing does not affect induction response. Clay seals and sand/gravel packs may affect induction response in larger diameter boreholes (typically, greater than 8 to 10 in. (20 to 25 cm) diameter).

6.5 *Geologic Conditions*:

6.5.1 In high-conductivity formations and ground water, the electrical conductivity measured by induction is less than the true electrical conductivity due to skin effects. Some probes correct for skin effect assuming a homogeneous medium.

6.5.2 In steeply dipping formations (greater than 60 degrees), electrical anisotropy affects apparent bed thickness and location of bed contacts and corrections need to be applied.

6.6 Theoretical and empirical tool response curves and inversion algorithms may be applied to correct for many interferences.

7. Apparatus

7.1 A geophysical logging system has been described in the general guide (Section 6, Guide D 5753).

7.2 Induction logs are collected with probes that have electromagnetic transmitter and receiver coils (Fig. 1).

7.2.1 Transmitter and receiver coils typically are spaced about 20 in. (50 cm) apart. In deep-induction configurations, coils are spaced at about 40 in (1 m) apart.

7.2.2 The transmitter coil emits an electromagnetic signal in the range of 20 to 40 KHz that induces eddy currents in the medium surrounding the borehole.

7.2.3 The receiver coil senses the primary and secondary magnetic fields.

7.2.4 Strength of the secondary magnetic field is a function of the electrical conductivity of the surrounding medium.

7.2.5 One or more additional coils are used to cancel the primary field, reduce sensitivity to the borehole fluid, and focus the horizontal response.

7.3 Volume of Investigation and Depth of Investigation of induction measurements are dependent on coil configuration and increases with increased spacing between transmitter and receiver coils.

7.3.1 The Depth of Investigation typically varies from 20 to 30 in. (50 to 75 cm) (Fig. 2), but is up to 130 in. (325 cm) in deep-induction configurations.

7.3.2 The radial distance from which log response is negligible typically varies from 3 to 5 in. (7.5 to 12.5 cm), but is 20 in. (50 cm) or more in deep-induction configurations.

7.3.3 Induction probes used for geotechnical applications

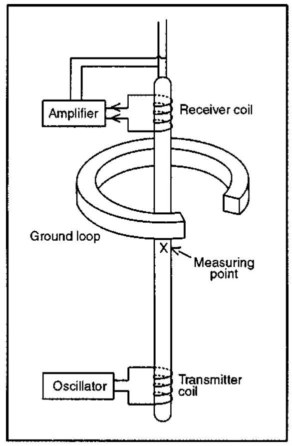

FIG. 1 Electromagnetic-Induction Logging System (8)

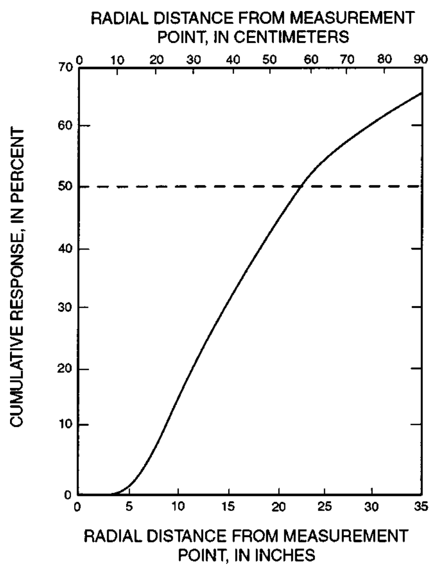

FIG. 2 Cumulative Response Versus Radial Distance for a Typical Electromagnetic-Induction Probe Showing Depth of Investigation and Radial Focusing (11)

typically can be logged inside of a 2 in. (5 cm) diameter monitoring well.

7.3.4 Dual-induction probes have coil configurations that measure two different depths of investigations including deep induction and generally are greater than 2 in. (5 cm) in diameter.

7.4 Vertical Resolution of induction measurements is dependent on coil configuration.

7.4.1 Vertical Resolution is approximated by dividing the transmitter-receiver coil spacing by 1.5.

7.4.2 Vertical Resolution typically is about 14 in. (35 cm).

7.4.3 Vertical Resolution is up to 6 feet in deep-induction configurations.

7.5 Typical accuracy is within 5 percent at 30 mS/m.

7.6 Additional logs may also be run in combination with induction.

7.6.1 Induction probes commonly have the capability to simultaneously record gamma along with electrical conductivity.

7.6.2 Induction and gamma logs can be collected in open or boreholes cased with non-conductive materials (PVC, fiberglass, etc.) that are air, water, or mud filled.

7.6.3 Some induction probes may also record magnetic susceptibility simultaneously with the electric conductivity measurement. Note induction probes typically are not optimized for magnetic susceptibility measurements.

7.7 Measurement resolution of induction probes is determined by probe design. Measurement resolution is typically 0.01 mS/m.

7.8 A variety of induction logging equipment available is for geotechnical investigations. It is not practical to list all of the sources of potentially acceptable equipment.

8. Calibration and Standardization of Electromagnetic-Induction Logs

8.1 *General*:

8.1.1 National Institute of Standards and Technology (NIST) calibration and standardization procedures do not exist for induction logging.

8.1.2 Induction logs can be used in a qualitative (for example, comparative) or quantitative manner depending upon the project objectives.

8.1.3 Induction calibration methods and frequency shall be sufficient to meet project objectives.

8.1.3.1 Calibration and standardization should be performed each time an induction probe is suspected to be damaged, modified, repaired, and at periodic intervals.

8.1.3.2 Induction probe calibration is sensitive to the effects of temperature, humidity, calibration coil position, and conductive material.

8.2 Calibration is the process of establishing values for induction response and is accomplished in free air and with representative physical models. Calibration data values related to the physical properties are recorded in units (for example, counts per second) that are converted to units of electrical conductivity (mS/m).

8.2.1 At least two, and preferably more, values, which approximate the anticipated operating range, are needed to establish a calibration curve (for example, 10 and 100 mS/m).

8.2.2 Typical tolerances for calibration are 5 percent of measured standard.

8.2.3 Calibration is done in an area free of conductive objects within the Volume of Investigation.

8.2.4 Free-air calibration check to approximately zero electrical conductivity is accomplished by suspending the probe in air where humidity is minimal and away from conductive material.

8.2.5 The physical model typically used to calibrate induction response is a calibration ring.

8.2.5.1 A calibration ring is a ring of non-conductive material (plastic or wood), which has a wire loop with a resistance that produces a known response.

8.2.5.2 The position of the calibration ring on the probe must be duplicated for accurate calibration. Calibration rings designed not be positioned at the center of the measurement point are more sensitive to changes in their position.

8.2.6 Calibration also can be established in a body of water such as a lake with a known electrical conductivity that is large enough to be infinite with respect of the Volume of Investigation of the probe.

8.2.7 Calibration should be performed when the probe temperature is as close to the borehole temperature as possible. This is most readily performed by recalibrating immediately after logging a borehole.

8.3 Standardization is the process of checking logging response to show evidence of repeatability and consistency.

8.3.1 Calibration insures standardization.

8.3.2 A representative borehole may be used to periodically check induction probe response providing the borehole and surrounding environment does not change with time or changes and their effects on induction response can be documented.

9. Procedure

9.1 See Section 8, Guide D 5753 for planning a logging program, data formats, personnel qualifications, field documentation, and header documentation.

9.1.1 Induction specific information (for example, coil spacing, transmitter frequency) should be documented.

9.2 Identify induction-logging objectives.

9.3 Select appropriate equipment to meet objectives.

9.3.1 Induction logs are commonly run with gamma logs to aid in lithologic and water-quality interpretations. Although less commonly run, neutron logs also aid interpretations.

9.3.2 Combination induction and gamma probes commonly have the induction transmitter and receiver in the lower part and the gamma detector in the upper part. This may be inappropriate for shallow boreholes and induction and gamma may have to be run separate to meet project objectives.

9.3.3 Induction probes typically are run free-hanging where the probes lies against one side of the borehole. Centralizers constructed of plastic or other non-conductive material are sometimes used in boreholes 6 in. (15 cm) diameter or greater. Induction response may be somewhat different depending on the method used (for example, free-hanging or centralized).

9.3.4 Induction-probe and cable decontamination is addressed according to project specifications (see Practice D 5088 for non-radioactive waste sites and Practice D 5608 for low-level radioactive waste sites).

9.4 Select when in the logging sequence the induction probe is run (see section 8.2.2.1, Standard Guide D 5753).

9.4.1 Induction probes are run after any television camera and fluid property probes are run to minimize disturbance to the borehole fluid that can degrade these logs.

9.4.2 Induction probes are run before any probe utilizing nuclear sources and more expensive centralized probes to insure borehole stability whenever possible.

9.5 Induction-probe operation typically is checked before the start of each run.

9.6 Select and document the depth reference point.

9.6.1 The selected depth reference point needs to be stable and accessible (for example, land surface, top of casing).

9.7 Determine and document probe zero reference point (for example, top of probe or cablehead) and depth offset to induction measurement point.

9.7.1 The measurement point of the induction probe is midway between the transmitter and receiver coils (Fig. 1). This point, which is not visible on the outside of the probe, commonly is marked and is referenced to the probe zero reference.

9.7.2 Position the probe zero reference point with respect to the depth reference point and initialize depth recording/display systems.

9.8 Select horizontal and vertical scales for log display to meet project objectives.

9.8.1 Preferred horizontal scale divisions are multiples of 2 or 5 such that the log value can be easily determined on the plot (0-25, 0-400, etc.)

9.8.2 Preferred vertical scales are multiples of 2 or 5 such that the depth can be easily determined on the plot (for example, 1/5, 1/10. . . . 1/100, etc.).

9.9 Select digitizing interval to meet project objectives (see Section 8.3.1.2, Guide D 5753).

9.9.1 Digitizing interval needs to be at least as small as the Vertical Resolution of the induction probe, which is typically about 1.2 ft (35 cm).

9.9.2 Typically, this interval is no larger than 0.5 ft (15 cm) to insure that the optimum vertical resolution is achieved.

9.10 The induction probe is lowered to the bottom of the borehole.

9.10.1 Induction log values should be monitored as the probe is lowered to check probe operation, determine proper horizontal scale for the lay plot, and, with some systems, to determine range settings.

9.10.2 Selection of probe speed while lowering is based on knowledge of borehole depth, stability and other conditions; tension on the measuring wheel and smoothness of probe descent should be monitored to insure that depth errors are not being introduced.

9.11 Select logging speed.

9.11.1 Logging speed should be determined by the application of the data acquired to meet project objectives.

9.11.2 Typically, induction logging speed is 15 to 30 ft per minute (4.5 to 9 m per minute).

9.11.3 Proper logging speed is indicated by induction logs that show distinct beds and water-quality zones, which correlate with other information.

9.12 Collect induction data while the probe is moving up the borehole; data collection while logging insures that the probe is retrieved smoothly and continuously.

9.12.1 In unstable boreholes, it is advantageous to collect data while the probe is lowered and being pulled up the borehole.

9.13 When the induction probe reaches the top of the borehole:

9.13.1 Check depth reference and document After Survey Depth Error (ASDE).

9.13.2 Determine if ASDE meets project objectives.

9.13.3 Typical tolerance for ASDE is $\pm$ 0.4 feet per 100 foot interval logged.

9.13.4 Typical depth tolerance for repeat logs is within 0.4 percent.

9.14 Selected borehole intervals should be repeated (that is, relogged.) under similar logging parameters as the initial log. Repeat logs provide information on the stability of the induction equipment. The repeated interval should have enough variability, if possible, to check repeatability and resolution.

9.14.1 Repeat logs should be compared with the original log to insure correct operation of the probe prior to ending a logging event.

9.14.2 Repeat sections may not repeat exactly due to a different orientation of the logging probe on the repeat run or changes in the borehole environment between logging runs.

9.15 Evaluate the field log quality and compare log with drilling and completion information.

9.16 Induction logs typically are not smoothed by filtering.

9.17 Post-acquisition calibration checks may be required to meet the objectives of the logging program and may be more accurate than the pre-logging calibration check because the tool is stabilized in the borehole environment.

10. Interpretation of Results

10.1 See Section 8.5, Guide D 5753 for procedures on Log Interpretation.

10.2 Induction logs should be analyzed as part of a suite to take advantage of the synergistic nature of log data.

10.3 The induction log should be depth correlated with the other geophysical logs as the first step to interpretation.

10.4 Other pertinent information including lithology, water quality, and borehole construction should be integrated with the induction log data.

10.5 Electrical conductivity as measured by the induction method is primarily affected by two parallel conduction paths: mineral matrix and the formation water.

10.5.1 Mineral matrix conductivity is generally determined by the type, amount of dissolved solids (solutes) and temperature.

10.5.2 Formation water conductivity generally is determined by the type, amount of dissolved solids (solutes) and temperature.

10.6 Gamma logs, which are good indicators of clay content and grain size in some depositional environments, are particularly useful in the interpretation of induction logs.

10.7 Induction logs can be used to identify and correlate lithology (Fig. 3) within and between boreholes. In certain sedimentary rocks (for example, arkosic, glauconitic sands), induction logs may be a better indicator of clay content and grain size than gamma logs.

10.8 Specific conductance and(or) dissolved-solids content of ground water sampled from selected zones may be correlated with induction logs to provide estimate of ground-water quality if the effects of clay content, grain size, porosity, cementation, and other formation properties can be accounted for by lithologic, gamma, and other logs. Distribution of contaminants of interest can be estimated from induction logs

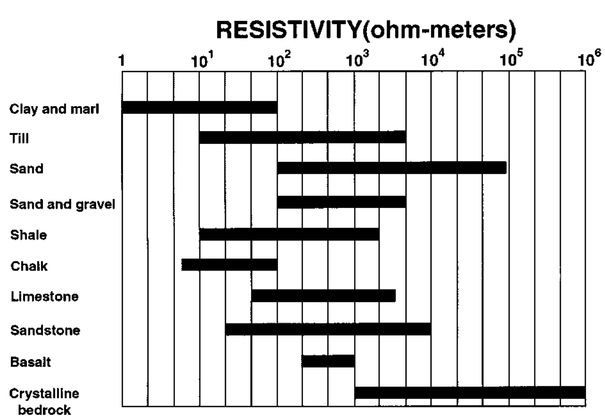

FIG. 3 Resistivity Range for Common Unconsolidated and Consolidated Rock Lithologies (4, 10, 16)

if they are correlated with specific conductance and(or) dissolved solids in the formation water.

10.9 Induction logs can be used to detect the presence of metal (for example, casing, landfill) or sulfide mineralization near the borehole.

11. Report

11.1 Section 9, Guide D 5753 should be consulted for requirements of the report.

11.2 Providers of induction logs shall: (*1*) describe the components of the induction logging system, (*2*) the principles of the methods used, (*3*) methods and results of calibration and standardization, (*4*) performance verification (for example, correlation with other logs, repeat sections, ASDE, etc.), and (*5*) uniqueness of interpretations.

11.3 Information on the software and algorithms used should be included in the report.

11.4 Any deviations from this guide should be documented.

11.5 Presentation of induction logs should be designed to meet project objectives.

11.5.1 Depth (y-axis) and units of measurement (x-axis) scales should be clearly marked (Fig. 4). Units of measurement are displayed as conductivity in mS/m or resistivity in ohm-m on linear or logarithmic scales. Any scale "wraps"should be clearly marked.

11.5.2 Presentation of field logs may differ than that presented in the final report.

12. Keywords

12.1 borehole geophysics; electrical conductivity; electromagnetic-induction log; ground water; induction; resistivity; water quality; well logging

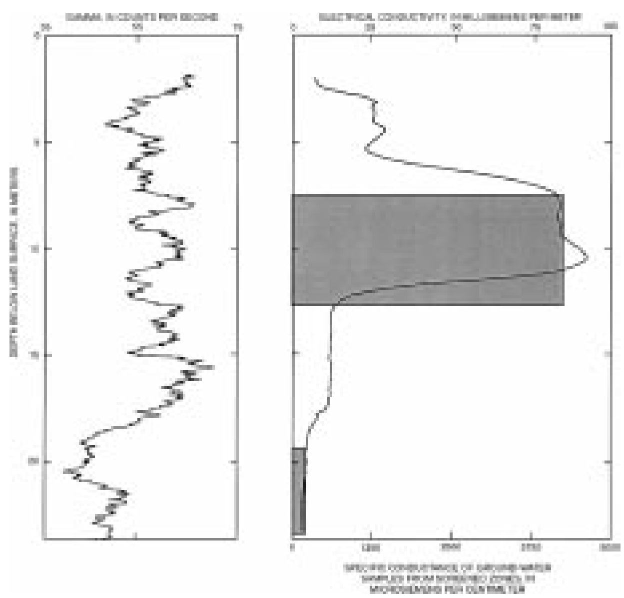

FIG. 4 Electromagnetic-Induction and Gamma Logs and Specific Conductance of Ground-Water Samples from Screened Zones for a Monitoring-Well Pair Completed in a Sand Aquifer near a Municipal Landfill (19)

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