Measurement of Soil Suction In Situ Using the Fredlund Thermal Conductivity Sensor*

Y.Y. Perera, Ph.D., P.E. and J.M. Padilla, Ph.D.
GCTS, 6103 South Maple Avenue, Tempe, AZ 85283, USA
D.G. Fredlund, Ph.D., P.Eng., O.C.
Department of Civil and Geological Engineering, University of Saskatchewan, Canada

Introduction

The measurement of matric suction in the field is a challenging task due to a variety of limitations, laborious procedures, and the cost of currently available methods. The most commonly used methods available for the measurement of soil suction are psychrometers, filter papers, tensiometers, and thermal conductivity sensors. The null-type pressure plate apparatus, as well as the filter paper method can be used for measuring suction in the laboratory. A list of suction measurement methods, the component of soil suction measured, valid ranges, and constraints associated with these methods are presented in Table 1.

The information in Table 1 shows that each method has its own limitations. Psychrometers are insensitive in the low suction ranges, sensitivity deteriorates with time, are sensitive to thermal field, and require frequent maintenance. Filter paper calibrations require considerable time to equilibrate, and filter paper measurements are difficult to automate. Tensiometers function in the low suction range and require daily maintenance.

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Table 1. **Methods for measuring total and matric suction** (Ridley & Wray 1995, Fredlund & Rahardjo 1989).

Device	Method (Property Measured)	Suction Measured	Range (kPa)	Principal constraints
Thermocouple psychrometers	Indirect (Relative Humidity)	Total	100 to 7500	Affected by temperature fluctuations and gradients. Sensitivity deteriorates with time.
Thermistor psychrometers	Indirect (Relative Humidity)	Total	100 to 10,000	Poor sensitivity in the low suction range. Frequent re-calibration is required.
Transistor psychrometers	Indirect (Relative Humidity)	Total	100 to 71,000	Frequent re-calibration is required. Specimens must be tested in order of increasing suction to avoid hysteresis.
Filter paper (non-contact)	Indirect (Water content)	Total	400 to 30,000	Calibration is sensitive to the equilibration time.
Filter paper (in-contact)	Indirect (Water content)	Matric	Entire range	Automation of the procedure is difficult.
Pressure plate (Null technique)	Direct	Matric	0 to 1500	Range of suction limited by the air-entry value of the plate (laboratory usage).
Standard tensiometer	Direct	Matric	0 to 90	Requires daily maintenance. Temperature fluctuations affect readings.
Osmotic tensiometer	Direct	Matric	0 to 1500	Reference pressure can deteriorate with time. Temperature dependent.
Imperial College tensiometers	Direct	Matric	0 to 1800	Range in suction is limited by the air-entry value of the ceramic. Cavitation problems with time.
Porous block (Gypsum, nylon, fiberglass)	Indirect (Electrical resistance)	Matric	30 to 3000	Observations need to be corrected for temperature. Blocks are subject to hysteresis and changes in calibration due to salt. Response to suction can be slow.
Original heat dissipation sensors	Indirect (Thermal conductivity)	Matric	0 to 1,000 +	High failure rate. Fragile ceramic.
Fredlund Thermal Conductivity Sensor	Indirect (Thermal conductivity)	Matric	0 to 1,500 +	Range in suction is controlled by the pore-size distribution of the ceramic.

The Fredlund thermal conductivity sensor (FTC sensor) holds promise for field applications due to low maintenance, durability, ability to automate the testing, insensitivity to salinity and soil type, and reasonable cost.

The FTC sensor was developed by GCTS based on previous models developed by Fredlund and other researchers at the University of Saskatchewan, Canada (Fredlund et al., 2000; Shuai et al., 2000; Marjerison, et al., 2001; Feng et al., 2002; Shuai et al., 2002;

Feng et al., 2003; Nichol et al., 2003; Shuai et al., 2003; Tan et al., 2003). Considerable attention had been given to the accuracy and durability of the sensor during the development process (Padilla et al., 2004). As the name suggests, the thermal conductivity of the ceramic tip of the sensor forms the basis for measuring the matric suction in a soil. A miniature-heating element embedded in the ceramic tip (Figure 1) is heated by sending a specific quantity of thermal energy to the resistor in the ceramic. The temperature rise in the ceramic is monitored by a temperature sensor located near the heating element. The temperature rise of the sensor is a function of the water content of the ceramic, which, in turn is a function of the matric suction of the soil.

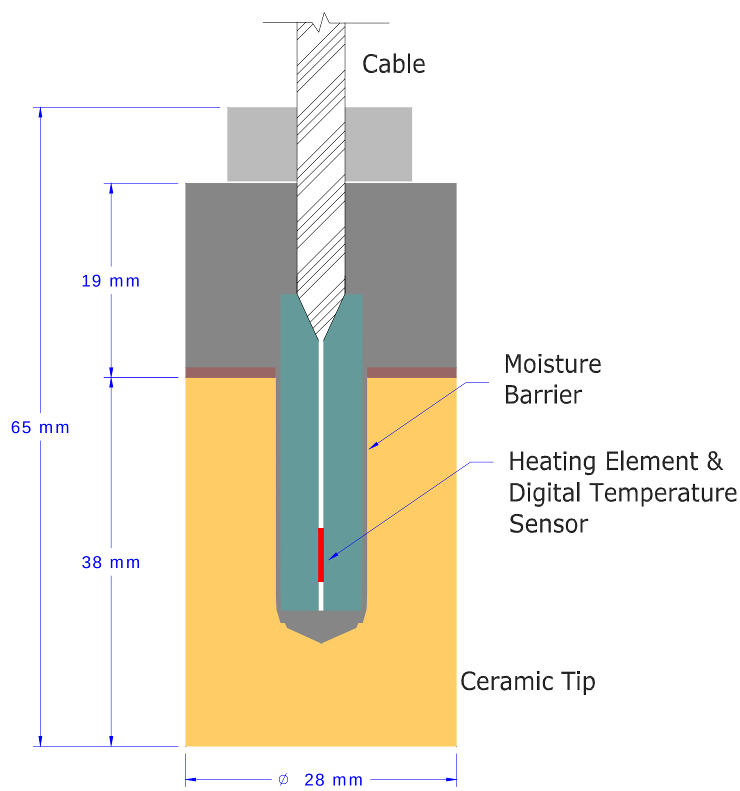

Figure 1. Cross-section of Fredlund Thermal Conductivity Sensor.

The main features of this sensor include state-of-the-art digital design, high resolution in temperature measurements, high accuracy in suction measurements, and the ability to use cables more than 100 m in length. Digital signals reduce the cable resistance and temperature effects, which enables the use of longer cables.

The FTC sensor records the ambient temperature (i.e. *in situ* soil temperature) in addition to the primary parameter, the temperature rise. The *in situ* soil temperature is a very useful piece of information in engineering applications such as performance of highway pavements where both temperature and water content play a significant role in pavement strength.

It should be noted that the suction measurements obtained from FTC sensors under freezing conditions are meaningless, but freezing cannot harm the functionality of the sensor.

Theoretical Background

The thermal conductivity of a porous media increases with increasing water content. Therefore, the measurement of the thermal conductivity of a standard porous block that has come to equilibrium with a soil can be used to measure the water content of the ceramic block. The water content of the ceramic block is dependent on the matric suction of the soil surrounding the ceramic block. Hence, the thermal conductivity of the porous block can be calibrated against the applied matric suction.

Several devices had been developed adopting this method since the early 1940s. The materials used for the porous ceramic block over the years have included plaster of paris, gypsum, castone, and a variety of ceramics. Earlier versions of the sensors did not perform well in the field due to deterioration of electronics and the porous block with time.

As shown in Figure 1, the FTC sensor uses a standardized ceramic block as the porous media and heat is provided to the block by a miniature-heating element. The thermal conductivity of the block is obtained by measuring the temperature rise within the block using a digital temperature sensor. The temperature rise is governed by the heat dissipation, which in turn is dependent upon the thermal conductivity. For example, if the block is wet, more heat will be dissipated during the time the heat pulse is applied, resulting a lower temperature rise than if the block were dry. Sending a constant current for 60 seconds to the ceramics block when the block is completely dry, and doing the same when the ceramic block is saturated, generates two heating curves as shown in Figure 2. The temperature rise corresponding to the dry condition was about 16 ^{o}C compared to a temperature rise of about 12 ^{o}C corresponding to wet conditions.

The calibration curves, which are predetermined in the laboratory form the key information required for matric suction measurements. The calibration curve provides the relationship between the temperature rise of the sensor and the applied matric suction. Once the temperature rise of the sensor is known in the field, the matric suction for the soil can be determined by entering the calibration curve. The section on "Sensor Calibration" presents more information on this topic.

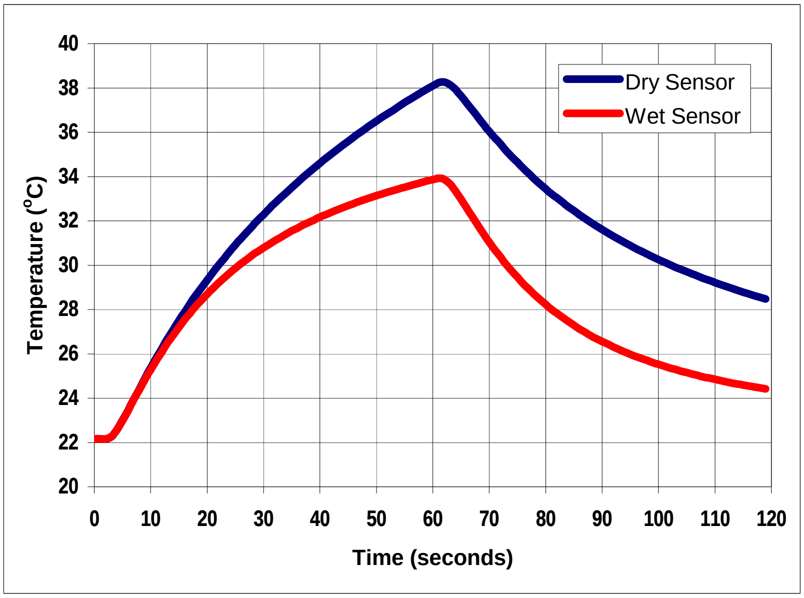

Figure 2. Heating curves showing temperature rises in wet and dry sensors.

Summary of Test Procedure for the Field

FTC sensors can be used to obtain the field matric suction measurements in unsaturated soil masses or waste piles. Suction measurements better than 5% of the measured suction value are possible with FTC sensors (Padilla et al., 2004). Multiple sensors can be buried at selected locations and connected to a datalogger using electrical cables. The datalogger is programmed to send signals to the sensors at desired time intervals to collect temperature readings and to store the data. Based on the temperature rise at each sensor, a corresponding matric suction value is computed from the calibration curve. The calibration curves are predetermined in the laboratory and provided with the sensors. The sensors can be monitored on a long-term basis and the data reduction can be performed based on weather the ceramic is undergoing a wetting or drying process. See the section on “Calculations of Matric Suction” for more details on this topic.

Apparatus: Fredlund Thermal Conductivity Sensor (FTC Sensor)

FTC Suction Sensors

The field investigation plan determines the most suitable number of sensors for a particular project. It is possible to install up to 16 sensors on a project and have the sensors connected to one data acquisition system. Each sensor comes with 10 meters of electrical cable fitted with a connector. A photograph of a sensor is shown in Figure 3.

The actual length of the cables required for a particular project can be determined based on the sensor installation layout. A typical sensor layout plan containing 15 sensors is shown in Figure 4. Additional lengths of cable required for a project need to be obtained separately.

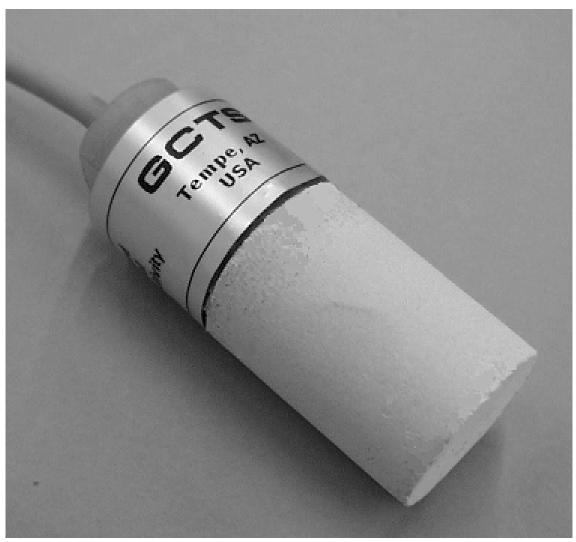

Figure 3. Photograph of FTC sensor.

Datalogger

The datalogger is powered by a 12-volt battery and accommodates 16 sensors via a 16-channel multiplexer. The datalogger can be connected to a PC, laptop, or a PDA via a USB port. The datalogger can be programmed to monitor the sensors for up to a 3-

month period and the data generated is stored in non-volatile memory. At each reading event, the suction sensor controller (see Figure 5) delivers a constant current over a designated time period to each sensor and extracts the data from the heating curve. See Figure 2 for examples of heating curve responses.

The datalogger comes with the software required to run the monitoring programs. The programs can be run in either a 'STANDALONE' mode or a 'DIGITAL' mode. The 'STANDALONE' mode operates without an external computer and stores primary data (i.e. date, time, sensor identification, ambient temperature, and temperature rise) for up to a three-month period. The 'DIGITAL' mode interfaces with a computer (i.e. PC, laptop, or PDA) directly and offers higher flexibility in operation. For example, in addition to the primary data, the entire heating curve can be retrieved for more detailed study in the 'DIGITAL' mode. The electronics in the datalogger should be protected in the field by enclosing it in a weatherproof case.

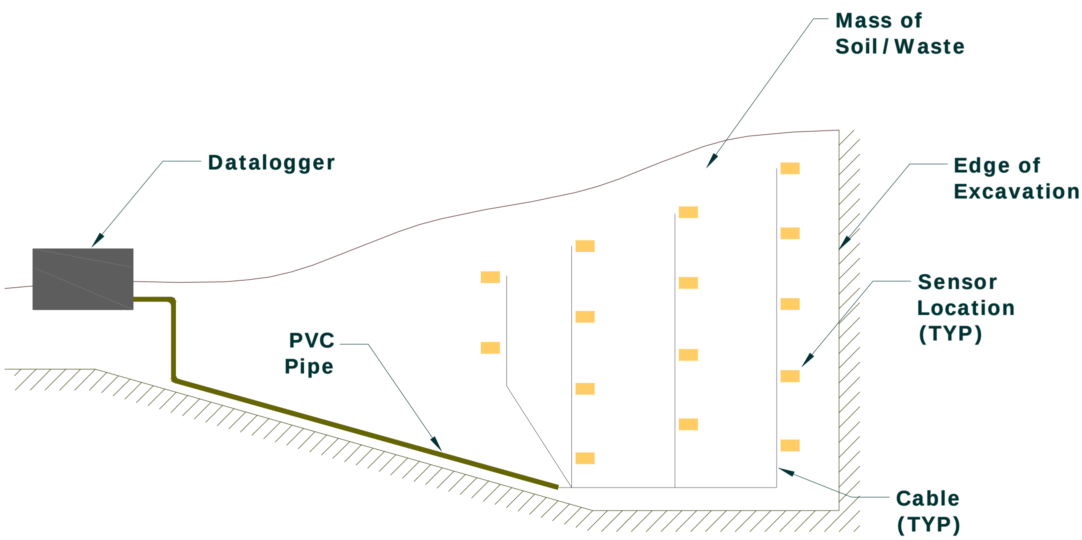

Figure 4. A sensor installation layout (Tan et al. 2003).

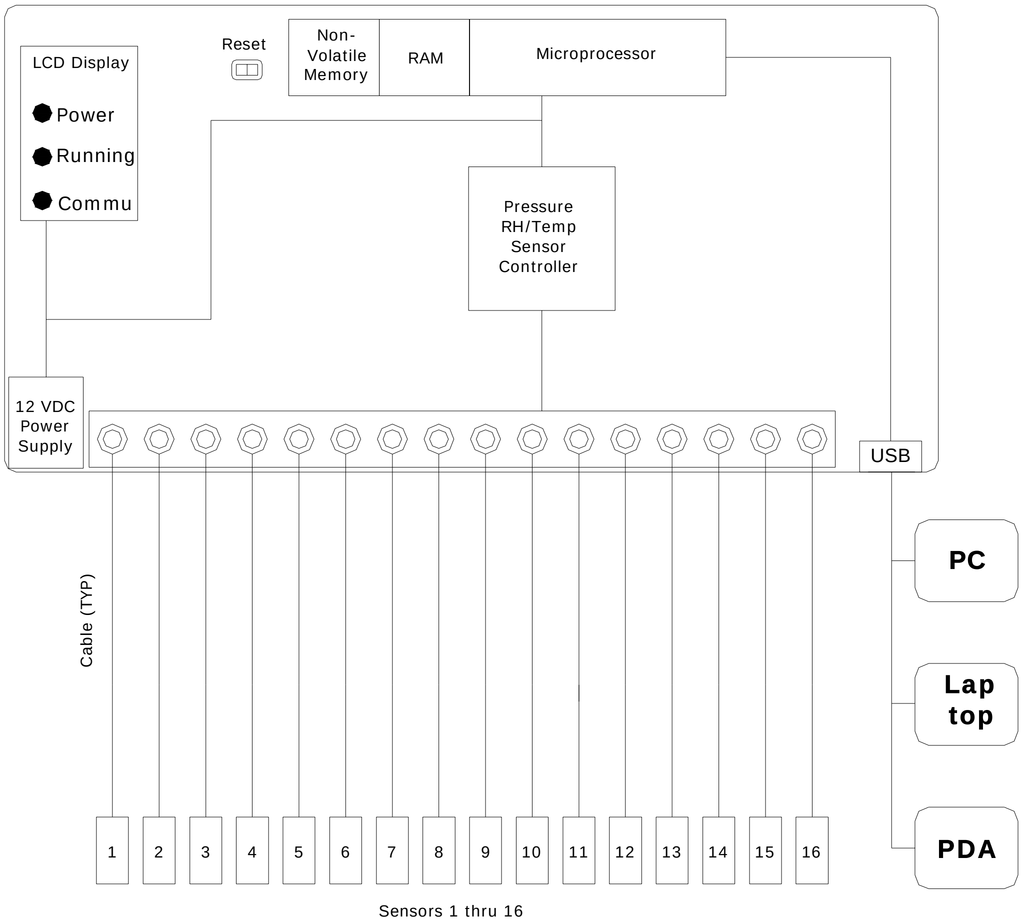

Figure 5. A schematic of the GCTS datalogger.

Installation Equipment

Installation equipment required for a project depends on the physical site conditions and nature of the project. Earth moving equipment such as backhoes can be used to make a large-scale initial excavation, if this is necessary. Hand-held electrical augers, manual augers, extension rods, driving tools, tamping rods, and oil sampling tools are a few pieces of equipment that are valuable for actual sensor installation (Marjerison et al., 2001).

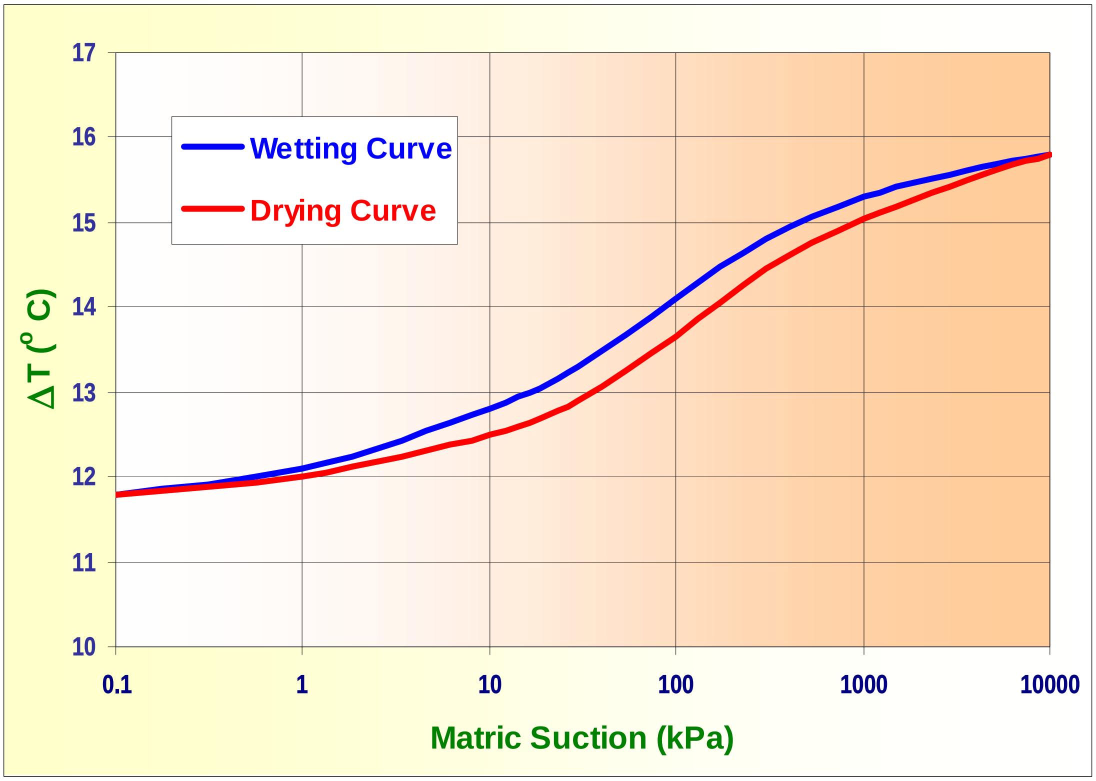

Figure 6. Typical calibration curve.

Sensor Calibration

Calibration curve represents the response of a sensor under an applied matric suction. The response is measured as a temperature rise in the sensor when a specific quantity of heat is applied to the ceramic. Due to hysteresis effects associated with the porous ceramics (Feng Man et al., 2002), the sensors respond differently during drying and wetting. Therefore, two calibration curves, one for "drying" and the other for "wetting", are required to obtain the most accurate matric suction measurements in the field. A typical calibration curve is shown in Figure 6. Normally, batch calibration data associated with the "drying" curve is input to the datalogger and data reduction is automatically carried out. The ceramic sensors are manufactured in batches. Only one of the sensors from each batch of ceramics is subjected to the calibration procedure. The batch calibration is sufficient to provide adequate accuracy for the matric suction determination for most situations. However, if necessary, standard calibration or full calibration data can be measured on each suction sensor. Differences between the three calibration procedures are shown in Table 2.

Table 2. Types of calibration procedures.

Calibration Procedure	**Sensors Used**	**Applied Suctions** (kPa) (1M = 1,000,000)	**Steps**
Batch	1 per batch	0, 10, 100, 500, 1M*	5
Standard	Individual	0, 10, 100, 500, 1M*	5
Full	Individual	0, 10, 50, 100, 500, 1000, 1M*	7

* 1M suction is considered as the theoretical suction when the ceramic is completely dry.

Field Test Procedure

Suction sensors are applicable to a variety of engineering applications such as modeling seepage and contaminant movement in tailings and mine waste. The installation of durable field suction sensors can provide valuable data over a period of several years for a reasonable cost. Matric suction measurements are also useful in assessing the strength of an unsaturated soil for slope stability conditions (Fredlund and Rahardjo 1993). Another application of the sensors is to obtain measurements of matric suction beneath highway pavements and railway systems. The strength of a highway pavement system is mainly dependent upon temperature and moisture conditions beneath the pavement. Data from suction sensors installed in a highway test section can be effectively used in pavement design and the monitoring of performance.

Preparation for Field Work

A sensor installation plan must be prepared considering the nature of engineering application in hand and the site conditions. The sensor installation plan could include the information on number of sensors, sensor locations, excavation boundaries, method of excavation and backfilling, cable paths, location of datalogger, and monitoring plan.

The monitoring plan should include the duration of the monitoring program, frequency of the readings, and the type of data needed (i.e. either primary data or primary data and heating curve data). The installation tools and supplies required for the project must be prepared. Excavation permits and access permits must be acquired, if these are necessary.

Suction sensors also can be installed in boreholes provided that the boreholes are backfilled such that there is no preferential pathway for water movement through the backfilling. If sensors are to be installed in boreholes, a drill rig can be used for drilling and a special installation tools and backfilling procedures should be adopted.

Installation of the Suction Sensors

The site excavation should be conducted according to the plan. The locations where the sensors are to be installed should be maintained in an undisturbed condition as much as possible during excavation activities. Later backfill should be made to correspond approximately to the field density. The sensor locations are usually established by drilling with hand-held augers in approximately a horizontal direction. The sensor is then inserted into the hole. The hole is backfilled using the tamping tool ensuring that the cable is properly buried without any damage. It is preferred that sensors are installed in a horizontal direction rather than in vertical direction since vertical holes are more susceptible to providing unwanted avenues for water ingress. However, properly backfilled, vertical holes are also suitable for sensor installation in some situations. Once all the sensors are installed, the cables can be run to the location of the datalogger, preferably via a PVC conduit. The main excavation should be backfilled ensuring the backfilled density is approximately equal to the *in situ* density prior to the excavation. The installation is completed by connecting the cables to the datalogger and securing the datalogger in a weatherproof enclosure.

Programming the Datalogger

The datalogger needs to be programmed according to the monitoring plan. The initial tests can be performed using a PC, laptop, or the PDA directly sending signals to the sensors. In this way, the functionality of each sensor can be immediately determined. It is preferable to read the sensors less than or equal to four times per day allowing sensors to equilibrate at least six hours between the readings.

Monitoring the Suction Sensors

The installed sensors will take some time to reach equilibrium with the surrounding soil mass. Therefore, the initial readings taken during the first few days may not represent the true condition. In clayey soils, it may take as long as two weeks for complete equilibration with the surrounding environment. In silts and sands, less time may be required but it also depends on the magnitude of the matric suction.

Calculation of Matric Suction

The primary data collected from the suction sensors include the ambient temperature and temperature rise for each sensor. The temperature rise data should be reduced to obtain the suction corresponding to the calibration curve (i.e. drying mode). In the process, two corrections should be applied to the readings; namely the **hysteresis correction** and the **ambient temperature correction**. These corrections are built into the software in the datalogger and are automatically applied. The corrections can also be manually applied as described in the following paragraphs.

Hysteresis Correction

Depending on the direction of water movement in the soil (i.e. either wetting or drying of the soil), the correct calibration curve should be selected. The direction of moisture movement can be determined by considering a few readings just prior to the current reading. For example, the drying curve (see the curve shown as a solid line in Figure 6) is applicable if the current temperature rise is higher than the few previous readings; otherwise the wetting curve is applicable.

Temperature Correction

The temperature rise used for the calibration curve corresponds to a standard temperature of 23 ^{o}C. This is the temperature maintained in the laboratory during the calibration process. Temperature rises in the field at ambient temperatures can deviate from the laboratory calibration value. Therefore, a correction must be applied prior to entering the calibration curve. Nichol et al. (2003) proposed a correction for the field temperature. According to the Nichol et al. (2003) study, the correction is not only dependent on the ambient temperature but also dependent on the magnitude of the matric suction as shown in Figure 7. The field measured temperature rise is multiplied by the "correction factor" from Figure 7 to obtain the temperature rise that would have been measured at 23 ^{o}C.

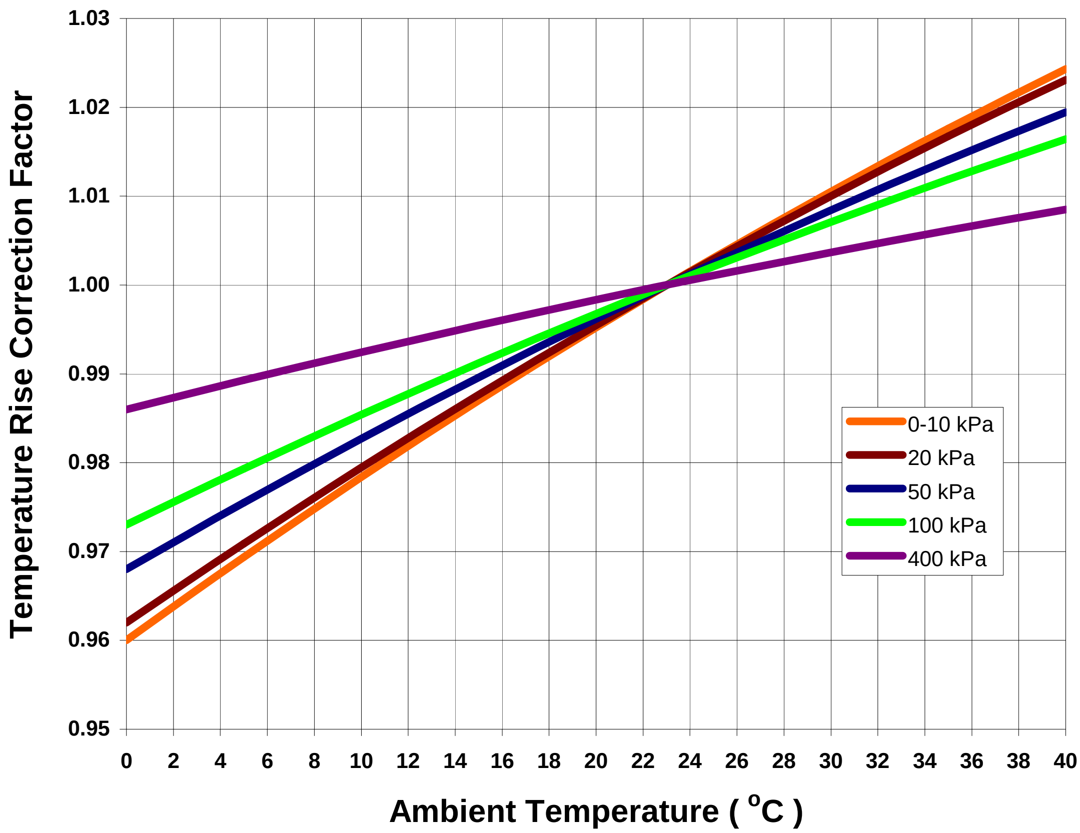

Figure 7. Correction factor for ambient temperature (Nichol et al. 2003).

Reporting of Results

The primary information to include in a report is the variation of matric suction and temperature with respect to time. Additional information such as environmental changes involving rainfalls and snowfalls can be included in the report to assist the analysis of the data.

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