A LABORATORY STUDY OF THE PERFORMANCE OF DIFFERENT SOIL SUCTION MEASUREMENT SENSORS

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GEO REPORT No. 317

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GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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PREFACE

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H.N. Wong
Head, Geotechnical Engineering Office
January 2016

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FOREWORD

Sensors using different measurement techniques to measure soil moisture and soil suction are available in the market for practical applications. A study of the performance of typical types of sensors has been carried out in the Public Works Central Laboratory. The performance of the sensors was studied under laboratory controlled conditions and the findings are presented in this report.

The study was commenced by Mr Thomas H H Hui. Dr Royce Kwok subsequently took over the study under the supervision initially of Dr H K Tam and later Mr Tony M F Lau. The technical staff of the PWCL, in particular Messrs L P Chan, W C Leung and H L Li, assisted in procuring the testing equipment and carrying out the tests. All contributions are gratefully acknowledged.

Ken K S Ho
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ABSTRACT

A range of sensors with different operating principles have been used in field monitoring to determine, either directly or indirectly, the variation of soil suction with time on slopes subject to rainfall. A systematic study was carried out in the Public Works Central Laboratory to better understand the performance of these sensors in steady-state and transient conditions under a controlled testing environment. The sensors' performance in terms of response time, repeatability, variability and measurement accuracy has been quantified. A simple set-up was used successfully to establish the soil-water characteristic curves for soils with different particle size distribution, together with the relationships between soil matric suction and the respective measuring parameters for those test sensors that employ an indirect method to estimate the soil suction. The influence of soil hysteresis in monitoring soil suction under repeated wetting and drying cycles was also examined.

Of the various sensor types tested, tensiometer has performed well, in terms of its repeatability, limited variability and good measurement accuracy, for the direct measurement of soil matric suction. The response of sensor that employs the time domain reflectormetry method as an indirect method of suction measurement has proved to be virtually instantaneous, but it appeared to have considerable variability and a poor accuracy in the determination of soil suction based on correlations. Sensors that measure heat dissipation and change in electrical resistance respectively have demonstrated their potential for use in determining soil matric suction by means of correlations. However, the applicability of the conditions under which the specific relationships between soil suction and the relevant measuring parameters are established may be affected by the variability of the groundmass in the field.

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CONTENTS

1. INTRODUCTION

1.1 Background of the Study

Unsaturated soil mechanics has advanced rapidly since the concept of stress state variable of soil matric suction was put forward in the 1970s (Fredlund & Morgenstern, 1977). Soil matric suction is an equivalent suction derived from the partial pressure of the water vapour that is in equilibrium with the soil water, and can be obtained through the measurement of negative pore water pressure. The soil matric suction will increase the shear strength of the soil. Therefore, reliable soil suction measurements are of the essence in achieving a proper understanding of the actual behaviour of unsaturated soil slopes under rainfall infiltration.

The investigation of soil suction in Hong Kong commenced in the late 1970s, during which time, tensiometers were used in field measurements on slopes (Anderson, 1984; Ng & Shi, 1998; Shen, 1998). Attempts were made to develop specific suction-moisture relationships (i.e. soil-water characteristic curves), and prediction models of soil suction were established and numerical analyses of slope stability based on soil suction measurements were undertaken (e.g. Anderson, 1984; Sun et al, 1997; Ng & Pang, 2000a & 2000b; Fredlund et al, 2001; Ng et al, 2001 & 2010; Ho et al, 2006). Recently, other soil suction sensors or soil moisture sensors, such as heat dissipation and water content reflectometry sensors, have been developed for use in field measurements, which were included in pilot field instrumentation trials by the Geotechnical Engineering Office (GEO) (Lau et al, 2008).

Some observations were made by OAP (2009) in respect of the field response of some selected soil moisture/suction sensors during rainfall (Table 1). To better understand the performance of the different commercially available soil suction or soil moisture sensors (from which soil suction could be deduced), a laboratory study was launched by the Public Works Central Laboratory of the Geotechnical Engineering Office.

1.2 Objectives and Scope

The objectives of the present study are as follows:

(a) to investigate the performance of some selected soil suction and soil moisture sensors in terms of their response, including repeatability and variability, under laboratory-controlled conditions,

(b) to establish the soil-water characteristic curves for granitic and volcanic soil samples,

(c) to establish empirical relationships between the soil matric suction and measurement parameters for those sensors that rely on indirect suction measurement techniques, and

(d) to test the sensors under wetting and drying conditions in order to simulate the field conditions.

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The study was divided into the following two phases:

(a) Phase I - Prepared the soil samples and carried out calibration tests for the soil suction and soil moisture sensors, together with tests to investigate the effect of initial saturation of the sensors.

(b) Phase II - Conducted tests on the sensors under wetting and drying conditions.

The functioning of the sensors was verified prior to the above tests. Under the present study, the measurement process of the soil matric suction or soil moisture content from the sensors was automated (see Section 2.3). On this basis, the effect on measurement due to reproducibility was considered minimal and did not form part of the scope of the study.

2. TEST SENSORS AND DATA LOGGERS

2.1 General

Soil suction is commonly regarded as the free energy state of soil water, consisting of two components, namely, soil matric suction and osmotic suction (Fredlund & Rahardjo, 1993). While the soil matric suction can be determined through measurement of the negative pore water pressure, the osmotic suction is related to the salt content in the pore water of soil and can be determined by measuring the partial pressure of water vapour that is in equilibrium with a solution identical in composition with that of the soil water. As most geotechnical problems in unsaturated soils do not involve any major changes in the salt content of the pore water, the matric suction change can be directly substituted for the total suction change or vice versa (Krahn & Fredlund, 1972; Fredlund & Rahardjo, 1993), and hence only the soil matric suction is of more relevance in practice.

A number of soil suction measurement techniques, using either the direct or indirect method of measurement, have been employed in research laboratories and engineering practice. The direct suction measurement techniques typically include the axis-transition technique (e.g. pressure plate extractor), tensiometer and suction probe (Navaneethan et al, 2005; Stannard, 1992; Ridley & Burland, 1993; Guan, 1996). Indirect suction measurement techniques may include the time domain reflectometry (TDR) probe, electrical conductivity sensor, thermal conductivity (or heat dissipation) sensor and filter paper technique (Topp et al, 1980; Eldredge et al, 1993; Fisher, 2000; ASTM D5298, 2000) for measurement of matric suction, the squeezing technique and saturation extract method (Krahn & Fredlund, 1972) for measurement of osmotic suction, and the relative humidity sensor and chilled-mirror hydrometer technique (Albrecht et al, 2003; Zhang et al, 1996) for total suction measurement.

2.2 Sensors Selected for the Study

Of the various soil suction measurement techniques as noted in Section 2.1, the tensiometer, TDR probe, heat dissipation sensor, electrical conductivity sensor, and relative humidity sensor are relatively common for use in field measurements (Anderson, 1984; Bond, 2006; OAP, 2009). Taking cognizance of this and the availability of these sensors, SWT4R

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Tensiometers, CS605 TDR Probes, CS616 Water Content Reflectometers (WCR Probes), CS210 Enclosure Relative Humidity (RH) Sensors, 229 Heat Dissipation (HD) Sensors, and Watermark 200 Granular Matrix (GM) Sensors (Plates 1 to 6) have been selected for the present study. Except for the SWT4R Tensiometers, which were supplied by Delta-T Devices Ltd. through Promat (HK) Ltd., all other sensors were supplied by Campbell Scientific, Inc. through SolData Inc.

The operating principles of the various sensors used in the study are detailed in Appendix A. Table 2 also summarizes the principles as well as the salient specifications for the sensor types used. Given that the dielectric constants as measured from the CS605 TDR Probes, the output periods from CS616 WCR Probes, the temperature rises from the 229 HD Sensors and the electrical resistances from the Watermark 200 GM Sensors are all temperature dependent, the temperature of the test medium at the time of measurement should be the same as that during the calibration; otherwise, the relevant readings from the respective sensors would have to be corrected for temperature variation. The corresponding correction algorithms have already been incorporated in the respective data logger programs (see Section 2.3) by the suppliers/manufacturers for temperature correction of the measurements using the CS616 WCR Probes, 229 HD Sensors and Watermark 200 GM Sensors (Campbell Scientific, Inc., 2006a; 2006b & 2009a).

In ASTM D6780 (2005), the temperature effect on dielectric constants as measured from TDR probes is highlighted, and the temperature correction procedures as developed by Drnevich et al (2002) are recommended for a TDR test in order to adjust the dielectric constants (at a given temperature to a standard temperature of 20°C). However, it is noted in the above standards that temperature correction is not needed for most soils at a temperature between 15°C and 25°C. Using the above temperature correction procedures, it can be shown that over a temperature range of 18°C to 22°C, the maximum difference between the corrected and uncorrected dielectric constants would not exceed 1%.

In this study, temperature correction was not made to adjust the dielectric constants output from the CS605 TDR Probes. Instead, the laboratory room temperature was maintained constant, typically at about 19°C to 20°C (Section 4.1) during the tests. Temperature correction was automatically made through the existing correction algorithms incorporated in the data logger program during measurements made with the use of CS616 WCR Probes, 229 HD Sensors and Watermark 200 GM Sensors.

It should be noted that the SWT4R Tensiometer, instead of the Jetfill Tensiometer (which was adopted by OAP (2009)), was used in the study. This is because the SWTDR Tensiometer operates on the same principle as the Jetfill Tensiometer but it has a faster response due to the pressure sensor being close to the ceramic filter (see Appendix A). The CS616 WCR Probe was only studied under the Phase I Tests, because the probes were only acquired at a late stage of the study and that they operate on similar principles to that of CS605 TDR Probe, except that a different output is given (Appendix A).

2.3 Data Loggers

Two data loggers, namely, Nos. 1 and 2 (Plate 7), were acquired from SolData Inc. for use with all the test sensors. Both data loggers comprised the same integral components manufactured by Campbell Scientific, Inc., including a CR1000 Logger, a TDR 100

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Reflectrometer, a SDMX50 Multiplexer, an AM 16/32B Relay Multiplexer, a CE4 Excitation Module and a wiring panel, to communicate with the test sensors and perform the logging functions. The CR1000 Logger was the core of the data logger, which comprises data memory and communication ports for collecting data from the sensors. This was connected to a personal computer for data acquisition. The TDR 100 Reflectrometer generated time electromagnetic pulses specifically for the CS605 TDR probes. It also sampled and digitized the resulting reflection waveform for analysis and storage. The multiplexers were to allow the data loggers to take measurement form more sensors (the analog inputs were increased by sequentially multiplexing sensor leads into common leads). The SDMX50 Multiplexer was specifically designed for the CS605 TDR Probes, whereas the AM 16/32B Relay Multiplexer works with the other test sensors. The CE4 excitation module was designed to provide a constant current to the heating element of the 229 HD Sensors.

The essential difference between these two data loggers is the number of channels to link to the individual sensors for monitoring. Typically, Data Logger No. 1 provided two channels for each type of sensors, whereas Data Logger No. 2 provided six channels. Each data logger needs to be activated and managed by a software (i.e. Loggernet), which was originally written by Campbell Scientific, Inc. but modified by SolData Inc. for the present study. The program, which was written in "CRBasic", needs to run on a personal computer connected with either of the data loggers. Apart from the temperature correction procedures for the CS616 WCR Probe, 229 HD Sensor and Watermark 200 GM Sensors it also incorporates some empirical relationships (see Appendix A) to estimate the volumetric water content for both the CS605 TDR Probe and CS616 WCR Probe and the soil matric suction for the Watermark 200 GM Sensor, based on specific measurements taken by these sensors.

3. VERIFICATION OF TEST SENSORS

The proper functioning of the SWT4R Tensiometers was verified using the direct application of a vacuum suction from zero to 100 kPa. With the root mean square error (RMSE) value not greater than 0.5 kPa, the readings from the Tensiometers (Figure 1) proved to agree well with the vacuum suctions applied.

The CS605 TDR Probes were tested in distilled water at different temperatures. The dielectric constants as measured from the probes agreed closely with the published values or estimates made from literature (Coym, 2004; Meissner & Wentz, 2004; Campbell Scientific, Inc., 2009b) (Figure 2).

To verify the functioning of the CS616 WCR Probes, they were tested in air as well as in tap water and the output values agreed well with the typical values of 14 μsec in air and 42 μsec in tap water as reported in Campbell Scientific, Inc. (2006a) (Table 3).

To confirm the functioning of the 229 HD and Watermark 200 GM Sensors, which operate on indirect measurement of soil matric suction, the sensors were immersed directly in tap water and the respective sensor changes (i.e. changes of the measuring parameter of temperature rise or electrical resistance) were measured, with the suction values evaluated by reference to the relevant empirical relationships reported in literature (Campbell Scientific, Inc., 2009a; Graeme Campbell & Associates Pty Ltd., 2006; Eldredge et al, 1993; EME Systems, 2002; Fisher, 2000; OAP, 2009). The results obtained appeared reasonable, typically with low suction values of 0.24 kPa to 4.42 kPa (Tables 4 and 5).

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The CS210 Enclosure RH sensors were verified in a humidity control chamber by varying the humidity from 40% to 90%, and the readings were comparable with the humidity values maintained in the chamber. When tested in soil, all the RH sensors apparently gave an erroneous reading of 100% relative humidity, probably due to the problem of condensation as noted by Agus & Schanz (2005). The RH sensors were considered unsuitable for this type of application and they were not included in the subsequent study.

4. CALIBRATION TESTS

4.1 Test Preparation and Conditions

Five soil samples (A, B, C, D and E) were sourced from different sites (Jordan Valley, Shek O Quarry and Lantau Island), covering completely decomposed granite (CDG) and completely decomposed volcanics (CDV) of different grain sizes (Figure 3). Soil Samples A, B, C and E are all CDG and Soil Sample D is CDV. Soil Samples A, D and E are fairly representative of the grain size envelopes given by Lumb (1962 & 1965), and fall in the three zones of inorganic silts of high, medium and low plasticity, respectively (Figure 4). These samples were regarded as "fine-grained", "medium-grained" and "coarse-grained" soil, respectively. Soil Samples B and C were not selected for use in the present study.

Individual soil specimens were prepared from these samples with various moisture content (MC) values (Table 6), and they were compacted to 85% relative compaction (RC) in small boxes, each of 400 mm long, 300 mm wide and 300 mm high and are made of plexiglass (Plate 8). The specimens of Sample E only covered a narrow range of moisture contents from 3.3% to 6.9%, partly because the sample is coarse-grained with little capacity (or capillary action) to retain water, and partly due to the fact that installation of sensor was difficult in the drier soil specimens as the hole formed in the soil for accommodating the test sensors was prone to collapse. It should be noted that unless stated otherwise, the soil moisture contents as referred to in this report are gravimetric, and not volumetric, values (i.e. the moisture content is expressed as a ratio of the mass of pore water to the mass of the solid particles in the soil mass, in lieu of the ratio of the pore water volume to the total volume of the soil mass).

Sample A was selected for testing the repeatability and variability of the sensors in the Phase II Tests. In order to optimise the time required for the study, and because of the late availability of some of the sensors, not all the sensors procured for the study (Table 2) were calibrated under the Phase I Tests. The calibration carried out covered mainly four SWT4R Tensiometers (Nos. SWT4R-430 to 433), five CS605 TDR probes (Nos. TDR-1 to 5), five CS616 WCR Probes (Nos. WTDR-1 to 5), five 229 HD Sensors (Nos. HD 1 to 5), and five Watermark 200 GM Sensors (Nos. GB 1 to 5).

As per the guidance given in the respective user manuals, all sensors using porous filters or tips (i.e. the SWT4R Tesnsiometers, 229 HD Sensors and Watermark 200 GM Sensors) were saturated prior to taking measurements in the soil specimens in the small boxes. The prior saturation essentially followed the recommendations of Ridley & Burland (1999). The porous element (or the sensor) was oven-dried at 45°C and was then placed in a vacuum desiccator with continuous evacuation of about 70 kPa for at least 1 hour. Following the initial evacuation, de-aired water was gradually supplied to the desiccator until the element or the sensor was completely immersed in water. The evacuation process was then resumed

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and maintained. Full saturation was deemed to have been achieved until no gas bubbles were evident from the water in the desiccator under confirmed evacuation for at least another 4 to 5 hours.

All the test sensors were placed at the same depth of 200 mm below the soil surface in the small boxes. Plate 8 also shows the typical details of the sensor installation. All sensors, except the CS605 TDR and CS616 WCR Probes, were installed vertically. Typically, a prebored hole was formed by augering or predrilling with a diameter slightly larger than the sensor to a depth of one sensor length above the design tip level of the sensor. Where necessary, a temporary casing would be provided as a support to the hole. The augering or predrilling would continue to the design tip level, but with a reduced diameter of less than that of the sensor. The sensor was then installed to the bottom of the prebored hole.

For the installation of each of the CS605 TDR Probes and CS616 WCR Probes, a rectangular opening was formed in the plexiglass (front panel) of the small box to accommodate the probe head of each sensor. A model probe consisting of steel rods with the same number and size as those of the test probe was then pushed or hammered in and subsequently withdrawn from the box. Subsequently, the test probe was installed, following the tracking left by the model probe. Care was taken to ensure that the head of the probe was in direct contact with the soil so that the steel rods of the probe would be fully embedded in the soil.

In effect, the Phase I Tests carried out were under the steady-state conditions, with no water drainage or moisture content change allowed in the small boxes. Each of the small boxes was sealed at all times against loss of moisture, except when the test sensors were being installed or removed. Soil samples were also taken from the small boxes and oven tests were carried out to ensure that the moisture contents of the soil specimens were maintained constant. Based on the monitoring results (Tables 7 to 9), no significant changes in moisture (i.e. not more than 0.5% MC) were identified for the soil specimens in the boxes.

The temperatures of the soil specimens in the small boxes were monitored on a periodic basis, using thermal-couples calibrated to an accuracy of ± 0.1°C. Typically, the measured temperatures were close to the ambient room temperature, ranging from about 19°C to 20°C, with small differences of not more than 0.1°C between the boxes and 1.6°C in a given box (Tables 10 and 11). The soil temperatures were continuously taken during testing, as an input to correct the measurements from the CS616 WCR Probes, 229 HD Sensors and Watermark 200 GM Sensors in order to account for the temperature effects (see Section 2.2 and Appendix A).

As the 229 HD Sensor was shown by the tests to have good repeatability (i.e. small variation in measurements taken by a single sensor under the same conditions) together with a variability (i.e. difference in measurements taken between individual sensors under the same conditions) that is comparable to the SWT4R Tensiometer (see Section 4.2.4), the effect of initial saturation of these sensors was also tested to explore if it would be possible to shorten the response time by partial saturation of the sensors prior to use. The testing was carried out by varying the initial saturation of these sensors from 20% to 100% and measurements were taken from the specimens of Sample A at MCs of 12.6%, 14.9% and 17.6%. As the sensor was manufactured and integrated with its connecting cable, it was not possible to detach the sensor from the cable and obtain the self weight of the sensor for determining the water content in the sensor and expressing the water content as a percentage of the self weight

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of the sensor. Instead, the sensor and the cable were weighed altogether. The water content was then determined by subtracting the dry weight of the sensor/cable (after oven-dried at 45°C) from the wet weight of the sensor/cable (after full or partial saturation in de-aired water). The degree of saturation of a partially saturated sensor was then evaluated by comparing the weights of the water contents in the sensor under full and partial saturation conditions.

4.2 Test Results

4.2.1 SWT4R Tensiometers

Figures 5 to 10 show the tensiometer readings in the soil specimens prepared from Samples A, D and E. The tensiometers operated on soil suction values typically ranging from zero to about 90 kPa, beyond which water cavitation could occur. As evident from Figure 6, after maintaining an initial constant value of about 96 kPa, the reading from the soil specimen with 7.3% moisture content from Sample A showed an abrupt change to zero. At the time of the test, the measured soil temperature and atmospheric pressure were 19°C and 101 kPa, respectively. With this and by reference to standard pressure-temperature nomograph (e.g. in standard textbooks of chemical engineering), it can be shown that the threshold value for water cavitation under suction during measurement would be about 96 kPa. The abrupt change of the reading to zero may indicate that the actual soil matric suction in the soil specimen could have exceeded the threshold cavitation value or even the air entry value (150 kPa) of the ceramic filter, causing water cavitation possibly together with air leakage. After the measurement, the tensiometer used (No. SWT4 - 431) was extracted for inspection and it was found that the water in the ceramic filter had dried out, confirming the cause of the abrupt change of the reading.

The readings from the soil specimens of Sample A at 10.3% MC, Sample D at and below 15.6% MC and Sample E at 3.3% MC had also risen to a maximum of about 95 kPa, followed by a drop typically to below 90 kPa (see Figures 5, 6, 7, 9 and 10). The respective tensiometers were also inspected and drying out was observed. Given the threshold suction value for cavitation, water cavitation could also have occurred in these tensiometers and hence the corresponding readings should be disregarded.

An inspection was also carried out for tensiometers with suction values close to 90 kPa (e.g. the measurements as shown in Figures 5 to 8 from Tensiometer Nos. SWT4 - 430 to 433 in soil specimens prepared at 12.6% MC). At the time of removal of these tensiometers, there was no sign of abnormality (including the presence of air bubbles) and water was still seen to be present inside the ceramic filters.

The time for the tensiometers to reach a stable reading tended to increase (from 150 minutes to 4,000 minutes) as the moisture content of the soil specimens decreased (Figures 11(a) to (c)). Generally, a rapid response could result when the soil specimens were wetter than the respective optimum moisture contents (OMCs). However, the response time could be much reduced (to 5 minutes to 65 minutes) for measurements that are within ± 10% of the stable readings. The soil-water characteristic curves are shown in Figure 12 for the different soil samples, using regression analysis based on an exponential function. The increase in soil matric suction appeared to be more marked for soil specimens drier than the OMCs.

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Regarding Sample A, the correlation coefficient for the proposed relationship as shown in Figure 12 was 0.99, confirming that a strong relationship had been derived from the relevant regression data. The 95% confidence levels (CLs) of the standard deviation (SD) was estimated and shown in Figure 13. On this basis, the measurement accuracy for the sensors may be taken to be ± 3.5 kPa. The variability, as expressed in terms of the observed range, was 0.6 kPa to 4 kPa (i.e. 4.6% to 15.1% relative to the respective mean values) (Table 13). The large differences in percentage terms could be attributed to the numerical division by small suction values (of 3 kPa to 6 kPa). A good repeatability of the sensors was found (Table 14), corresponding to an observed range of 0.4 kPa to 2.2 kPa (or 4.9% to 6.3% relative to the respective mean values).

4.2.2 CS605 TDR Probes

In all the soil samples, the CS605 TDR Probes provided an instant response, virtually requiring very little time to reach the stable readings (Figures 14 to 16). The dielectric constant increased as the soil moisture content increased. Except for Soil Sample E, the estimated soil moisture contents, using the empirical relationship proposed by Topp et al (1980), were all far from the oven test values for all soil specimens of Samples A and D (Figure 17). When the actual moisture contents from the oven tests were correlated with the measured dielectric constants, data scatter was evident with a correlation coefficient of 0.88 (Figure 18). Testing of Sample D also yielded a similar relationship but with a different regression coefficient (Figure 19). For Soil Sample E, a third order polynomial similar to that of Topp et al (op cit) could be established, as the moisture content estimation based on these authors was comparable with the actual moisture contents (Figure 17).

The sensors proved to have a low variability as well as a good repeatability, with the resulting ranges of readings between 0.05 and 0.46 (i.e. 1% to 7% of the respective mean values) and between 0.09 and 0.17 (i.e. 1.7% to 3.5% of the respective mean values), respectively (Tables 15 and 16). Based on the CLs of SD for measurement of the soil moisture contents (Figure 18), the measurement accuracy was ± 3.5% MC. However, in terms of the soil matric suction measurement (Figure 20), a poor measurement accuracy of ± 30 kPa was obtained, probably due to the change of soil suction being more sensitive than the variation of the moisture content (i.e. the soil suction could change appreciably with a small change in the soil moisture content, particularly when the soil specimens are drier than the OMCs, see also Section 4.2.1).

4.2.3 CS616 WCR Probes

The CS616 WCR Probes, which measure the wave guide signal reflection time in terms of an output period, showed an immediate response (Figures 21 to 23). The period readings were also related to the soil moisture content, using quadratic polynomials, for Sample A as well as Samples D and E (Figures 24 and 25). The relationship recommended for use in the user manual (Campbell Scientific, Inc., 2006a) and those reported in OAP (2009) for other soil materials are also plotted in Figure 25. Apparently, the soil moisture content and output period relationships are soil dependent. Typically, they have a similar trend, except for Soil Samples D and E where the non-linear behaviour was more marked, possibly as a result of less test data being collected for the curve fitting. However, the resulting correlation coefficients from all test samples are above 0.95, showing that there

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is a strong correlation between the soil moisture contents and output periods.

Based on testing of Sample A, the measurement accuracy was ± 2.5% MC (Figure 24). As with the CS605 TDR Probes, a low variability as well as a good repeatability, was evident from these sensors, and the corresponding ranges of period readings were 0.17% to 0.6% MC (i.e. 0.8% to 2.4% of the respective mean values), and 0.14% to 0.18% MC (i.e. 0.7% to 0.8% of the respective values), respectively (Tables 17 and 18). However, the correlation between the soil matric suction and output period was very poor with a correlation coefficient of only 0.75 (Figure 26). The measurement accuracy in terms of the soil matric suction was ± 40 kPa.

4.2.4 229 HD Sensors

Readings from the HD Sensors are shown in Figures 27 to 29. As with the verification tests (Section 3), the measured temperature rise was corrected using the procedures proposed by Flint et al (2002) (i.e. the algorithm incorporated in Loggernet as noted in Section 2.3). The drier soil specimens resulted in a higher temperature rise. All the specimens of Sample A with moisture content values of 7.3% and 10% yielded the same temperature rise of about 3°C, which was also recorded when the sensors were tested in air after drying in an oven. The user manual of Campbell Scientific, Inc. (2006b) also noted a temperature increase of 3°C when the sensor was tested in the dry, indicating that the maximum temperature rise for the sensors in this type of application could be about 3°C, which was equivalent to a soil matric suction value of about 1,500 kPa based on projection from the empirical relationship as established later (see below). This value is smaller than the operating limit of 2,500 kPa as noted in the user manual. When the sensors were tested under wet conditions (Figures 27(g) and (h)), the temperature rise was found to be about 0.7°C, which is the same value as noted in the user manual, representing a lower operating limit of about 5 kPa for the sensors.

Typically, the drier soil specimens (e.g. drier than OMCs) required a longer response time (up to 8,500 minutes) (see Figures 30(a) to (c)). Measurements that are within ± 10% of the stable readings had a smaller maximum response time of about 5,000 minutes. The variability and repeatability of the sensors are shown in Tables 19 and 20. The sensors showed a good repeatability, with ranges varying from 0.01°C to 0.05°C (about 1% to 4% of the respective mean values). The variability between the sensors appeared to be modest (with ranges of 0.03°C to 0.17°C corresponding to 4% to 11% of the respective means), which is comparable with that of the SWT4R Tensiometers. It is evident that the moisture contents of specific soil specimens could correlate with the sensor change in temperature rise (Figure 31). The tensiometer suction has also been plotted against the temperature rise for Sample A (Figure 32). On the basis of the CLs of SD, the measurement accuracy in terms of the soil matric suction may be taken to be ± 11 kPa. The resulting relationship from the present test has also been compared with the readings from other soil samples (Figure 33). A unique relationship is likely to exist between the soil suction and the sensors' change in temperature rise, as the temperature rise may be a function of the composite water content of the sensors, which may in turn relate to the soil suction, regardless of the soil water content.

The empirical relationships of temperature rise and soil suction for similar/same sensor type have been reported in literature (OAP, 2009; Graeme Campbell & Associates Pty Ltd., 2006; Fisher, 2000) (see Figure 33). It can be seen from the figure that these relationships

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and that from the present study are comparable in trend. However, except for the OAP's relationships, the relationships were not close to the data from the present study, suggesting that the empirical relationships may be soil dependent. It is noted that the sensor type used by OAP was same as that in the present study, but those in Greaeme Campbell & Associates Pty Ltd. and by Fisher might differ. Furthermore, some discrepancy in the calibration procedures was also noted (according to the literature, the sensors were typically placed in soil and tested using pressure plate extractors under a series of pressure (suction) increments, i.e. measurements were taken under transient state conditions). The temperature correction procedures adopted by Fisher (op cit) was also slightly different from the present study and temperature correction was not noted from the calibration in Greaeme Campbell & Associates Ltd. It is noteworthy that the relationships reported in the literature typically apply to a wide soil suction range from about 10 kPa to more than 400 kPa, but the correlation itself was established using measurements of only 5 to 6 soil suction values.

The effect of saturation on the response time of the sensors was tested using Soil Sample A with moisture content values of 12.6%, 14.9% and 17% (Figures 34 and 35). The response time of the sensors under the test appeared to increase with increasing soil moisture contents when the degree of saturation of the sensors was at 20% and 50% (Figure 34). On the other hand, the response time tended to decrease when the degree of saturation of the sensor reached 80% or 100%. In terms of the response time, no obvious improvement by partial saturation was noticed (e.g. at MCs of 12.6% and 14.9%). Instead, a significant increase in the response time by about 17,000 minutes was identified at 17.6% MC, as compared with the measurements made under full saturation conditions. It should be noted that different soil matric suctions could result from unsaturated sensors, with a difference varying from about 5 kPa to 20 kPa (i.e. a difference of about 20% to more than 100%), as compared with the values obtained from full saturation of the sensors (Figure 35).

4.2.5 Watermark 200 GM Sensors

Readings from the GM Sensors in soil specimens of Samples A, D and E are shown in Figures 36 to 38. The measured electrical resistance was corrected to a standard temperature of 21°C (Section 2.2). Two anomalous readings were noted. One refers to the measurement taken from the driest specimen of Sample A (i.e. with 7.3% MC), whereas the other was taken from Sensor No. GB 1 in the soil specimen at 10.3% MC after the sensor had been used for a period of about 5 months. Figure 39 shows the measurements taken by this sensor together with Sensor No. GB 3 (which had also been used for a similar period of time). The measurements were expressed as percentage difference from the mean values as acquired from other sensors. It is evident that the measurements from the above two sensors drifted with time, possibly as a result of dissolving of the gypsum within the sensors.

Figures 40(a) to (c) show the response time of the sensors, ranging from about 300 minutes to 22,400 minutes. The time for measurements that are within ± 10% stable readings, however, reduced to a range of 20 minutes to 14,000 minutes. It is noted that the GM Sensors showed a similar trend of response to that of the HD Sensors. The measured resistance increased with the drier soil specimens and the response was generally slow in soil specimens drier than OMCs.

The performance of the Watermark 200 GM Sensors was poor in terms of both variability and repeatability (see Tables 21 and 22).

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Apart from the anomalies noted in Figures 36(b) and 39, it is clear that the electrical resistance of the sensors can be reasonably related to the moisture content of specific soil samples (Figure 41).

The tensiometer suction was plotted against the electrical resistance taken from sensors in Sample A in Figure 42, together with the CLs of SD. The measurement accuracy in terms of the soil matric suction was ± 15 kPa, slightly larger than that of the 229 HD Sensors. The relationship between the electrical resistance and soil matric suction for Sample A was also checked against the readings from other soil samples (Figure 43). A unique relationship may exist between the soil matric suction and electrical resistance of the GM Sensors, as the electrical resistance could be a function of the composite water contents of the sensors, directly corresponding to the soil matric suction actually encountered (see also Section 4.2.4).

Unlike the 229 HD Sensors, the relationships postulated in the literature (e.g. Eldedge et al, 1993; EME Systems, 2002; Campbell Scientific, Inc., 2009b) for the GM Sensors are relatively consistent in terms of trend and magnitude (Figure 43). These relationships are comparable with that from the present study, particularly at the low suction range of below about 50 kPa. It should be noted that for comparison purposes, temperature correction has been made for these relationships according to their respective correction procedures, assuming a test temperature of 20°C.

5 TESTS UNDER WETTING AND DRYING CONDITIONS

5.1 Test Preparation and Conditions

The soil sample used in the Phase II Tests was the same as that (i.e. Soil Sample A) for the testing of repeatability and variability of the different sensors in the Phase I Tests. Unlike the Phase I Tests in which different soil specimens were compacted in the small boxes to 85% RC with different MC values, the soils for the Phase II Tests were compacted to the same RC in a large steel container at the OMC of 15%.

Plate 9 shows a general view of the test set-up. The steel container is 0.6 m wide, 1.2 m long and 1.5 m high, with a plexiglass installed on the front side. There is a compartment at the bottom of the steel container with a top grating to support a layer of 5 mm to 10 mm sized aggregates, above which a layer of geotextile and the soil was placed in successive layers. The compartment in combination with the aggregates and the geotextile was to facilitate drainage of the soil. Immediately after placement of the test soil, the container was completely sealed against an initial loss of water moisture. The ambient temperature was maintained at around 19°C to 20°C, and soil specimens were taken on a regular basis from the container for determination of soil moisture contents using the oven drying method.

Figure 44 shows the layout of the installation of test sensors. Each type of the test sensors was installed at depths of 0.23 m and 0.46 m (i.e. the top and bottom layers) below the soil surface. A total of six SWT4R Tensiometers (Nos. SWT4R - 430, 431, 432, 433, 441 and 442), four CS605 TDR Probes (Nos. TDR - 1, 2, 3 and 5), and four 229 HD Sensors (Nos. HD - 2, 3, 4 and 5) were installed at these monitoring levels, and were grouped either in the left or right portion of the container. As anomalous results were identified from some of the Watermark 200 GM Sensors in the Phase I Tests (Section 4.2.5), possibly due to ageing of

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the material, only three of them (i.e. Nos. GB 2, 4 and 5) were installed for the Phase II Tests. The Phase II Tests did not involve the CS616 WCR Probes because of their late acquisition and the similarity in operating principles to those of the CS605 TDR Probes (see Section 2.2). Tensiometer Nos. SWT4R - 5 and 6 were procured at a late stage and included in the Phase II Tests only. Detailed performance of these tensiometers was not assessed under the Phase I Tests, but the tensiometers were verified against true vacuum suction, with a RMSE not exceeding 0.5 kPa (see Section 3). The SWT4R Tensiometers, 229 HD Sensors and Watermark 200 GM Sensors, all of which were associated with porous measuring tips, were fully saturated before use (i.e. before installation or re-installation in the steel container), following the saturation procedures described in Section 4.1.

Unlike the Phase I Tests, the Phase II Tests were carried out under the transient conditions, comprising two cycles of wetting and drying. The wetting and drying of the soil commenced only after all the sensors as installed had reached equilibrium (i.e. stable readings were achieved) in the container. The seal at the top soil surface was removed and the drainage valve at the bottom of the container was opened when the first wetting cycle commenced.

The wetting process was to simulate rainfall events. It involved gradually and directly watering over the surface of the soil in the steel container. It was completed in about an hour, when zero readings were recorded from all the tensiometers. The average wetting rate was equivalent to about 0.4 kPa/min, which corresponds to a change in the measured suction values from 24 kPa to zero during the first wetting cycle. No reference tensiometer readings were recorded immediately before the second wetting cycle, but the wetting rate could be more rapid as all tensiometers had reached their measurement limits (i.e. about 90 kPa) before re-wetting and the duration of the second wetting cycle was similar to that of the first cycle.

The drying process was achieved by means of evaporation from the soil surface together with the open drainage at the base of the container. At the commencement of the first drying cycle, air circulation had been provided at the bottom of the container to speed up the drying process, and this was terminated near the completion of the cycle. Based on the tensiometer readings (see Section 5.2.1), the maximum drying rate was about 3 kPa/day (0.002 kPa/min) for the first drying cycle, whereas it was 1.8 kPa/day (0.0013 kPa/min) for the second drying cycle.

5.2 Test Results

5.2.1 SWT4R Tensiometers

Before the first wetting cycle commenced, the tensiometers (as well as all the other sensors) had all achieved stable readings (Figure 45). The tensiometer readings typically varied from about 26 kPa at the top monitoring level to 24 kPa at the bottom. This variation in suction was probably due to the gravitational effect of water moisture migrating from the top level to the bottom.

The tensiometer readings under the first and second drying cycles were similar in trend, increasing slowly at low values but rapidly at high values. However, the drying rate (as expressed in terms of increase in soil matric suction over a period of time) for the second

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cycle was slower than that of the first cycle, because of the termination of the air circulation (see Section 5.1). At the beginning of the second drying cycle with the soil matric suctions between zero and 10 kPa, the drying rate was 0.0001 kPa/min to 0.0002 kPa/min, whereas the drying rate was 0.0002 kPa/min to 0.0004 kPa/min for the first drying cycle. Beyond the soil suction value of 30 kPa, the drying rate for the second drying cycle became more rapid at 0.0013 kPa/min, but was still lower (by about 40%) than the value of 0.002 kPa/min in the first drying cycle.

During the first drying cycle, most of the tensiometer readings peaked at about 70 kPa to 80 kPa, followed by an immediate drop to about 60 kPa. These tensiometers were withdrawn for a close inspection, which revealed that the ceramic filters had dried out. Presence of little air bubbles was also identified from some of the partially dried filters, probably as a result of air diffusion from the soil to the filters. After re-saturation, re-filling and re-installation of these tensiometers, the suction readings continued to rise and no anomaly was noted. The second wetting cycle then commenced when cavitation (i.e. at a suction value of about 90 kPa) was evident from all tensiometers. All tensiometers were re-saturated and re-installed at the beginning of the second cycle of testing. In light of the drying out of tensiometers as observed from the first drying cycle, Tensiometer Nos. SWT4R - 431, 433, 441 and 442 were refilled at a lower suction value of about 60 kPa before signs of drop in reading were noted during the second drying cycle. However, signs of drying out were noticed not long after the refilling at the soil matric suction of about 70 kPa to 80 kPa, and further refilling was required. A small kink was also noted in the plot of tensiometer readings (Tensiometer Nos. SWT4R - 431, 433, 441 and 432 during the first drying cycle and all the tensiometers during the second drying cycle), possibly due to the disturbance associated with soil sampling for moisture content determination.

Taking cognizance of the good agreement between the moisture contents obtained from the CS605 TDR Probes and the actual moisture contents determined by oven tests on the soils regularly sampled from the steel container (see Section 5.2.2), the soil matric suctions were also estimated from the TDR moisture contents and plotted in Figure 45, using the specific soil-water characteristic curve established under the steady-state conditions in the Phase I Tests (i.e. Soil Sample A). Typically, the tensiometer suction measured under the transient condition was higher than the steady-state condition. This was probably the result of capillary hysteresis inherent in unsaturated soils because of the existence of different pore sizes, and the inverse relation between capillary pressure and pore size. The higher matric suction as measured was an "ink-bottle" effect during drying, where water was draining through narrow pore throats, causing a greater capillary pressure (Hillel, 1982). A pronounced difference in suction was also noted between the top and bottom levels of monitoring during the transient condition, probably as a result of different water flow conditions prevailing in the soil pores at these two levels. However, when the drying effect was not prominent (e.g. soil matric suction below 10 kPa), the tensiometer measurements appeared to agree reasonably well with the steady-state estimation.

Capillary hysteresis may also occur in the porous ceramic filters of the tensiometers due to air entrapment and partial saturation of the porous medium. However, in this study, the ceramic filters of the SWT4R Tensiometers (as well as the 229 HD Sensors and Watermark 200 GM Sensors) were saturated before use, adopting the similar procedures as that of Take & Bolton (2003), who have demonstrated that saturation of the ceramic filters of tensiometers could significantly reduce the tensiometer hysteresis. As each cycle of drying in this study was applied in the absence of intermittent wetting, it was also unlikely that

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during drying, the water flow from the tensiometers to the soil could reverse its direction and induce air entrapment in the pores of the ceramic filters or in the water reservoir within the filters to give rise to tensiometer hysteresis.

Under the transient condition, the tensiometer readings may also lag behind the true suction at the time of measurement. However, taking into account the response of the SWT4R Tensiometers under the Phase I Tests (i.e. based on the time required to achieve a suction value which is within ± 10% of the stable reading), the slowest response rate was calculated to be 0.2 kPa/min. This means that the tensiometer readings as obtained probably represented the "true" suction values with no time lag, as the calculated response rate was much faster than the maximum drying rates of 0.002 kPa/min and 0.0013 kPa/min noted for the first and second drying cycles, respectively.

5.2.2 CS605 TDR Probes

Figure 46 shows the dielectric constants measured from the TDR Probes. No anomaly was noted from the dielectric constant readings. The response of the TDR Probes was virtually immediate. As with the results from the steady-state condition in the Phase I Tests, the dielectric constant increased as the soil moisture content increased (i.e. during wetting), but decreased as the moisture content decreased (i.e. during drying). Each set of the readings obtained under the first and the second drying cycles closely resembled each other, except for the change rate. A slight reduction in the change rate was obvious under the first drying cycle due to the termination of air circulation. The maximum rate of decrease in the dielectric constant readings for the first drying cycle was 1.8×10^{-5}/min, which was double the value of 0.9×10^{-5}/min for the second drying cycle. This change is comparable with the difference in the drying rates between the two drying cycles.

Figures 47 and 48 show the estimated soil suctions from the steady-state calibration in comparison with the direct tensiometer measurements at different monitoring locations. The estimated soil matric suctions were typically smaller than the tensiometer readings, due to the hysteresis in the soil as well as the poor accuracy of ± 30 kPa corresponding to the estimation of soil matric suction using the TDR probes (Section 4.2.2). However, the moisture content values determined from the TDR probes appeared to agree well with the actual moisture contents of the soil samples as obtained from the respective monitoring levels by oven tests, with a maximum difference between these two determinations being only 1.9% (Figure 49).

5.2.3 229 HD Sensors

Figure 50 shows the change in temperature rise against time. Figures 51 and 52 show the steady-state soil matric suction (i.e. estimated from the calibration under the Phase I Tests based on the sensor change in temperature rise) in comparison with the tensiometer readings. Immediately upon completion of each wetting cycle, the sensors was relatively steady with a temperature rise reading of about 0.75°C for a fairly substantial period (about 1 month for the first drying cycle and 2 months for the second drying cycle) before the readings started to rise as a result of the continuing drying (Figure 50). The rate of temperature rise during the first drying cycle slowed down after the termination of the air circulation at the bottom of the container. Unlike the CS605 TDR Probes, the soil matric suctions estimated from the steady state calibration under the Phase I Tests were comparable with the tensiometer measurements

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when the soil matric suction was below about 30 kPa. The resulting difference was typically less than ± 5 kPa, but became more significant with more than 20 kPa (or 65%) when the soil matric suction exceeded 30 kPa (Figures 51 and 52).

The measured soil matric suctions (i.e. tensiometer readings) from zero to about 90 kPa under the first and second drying cycles were also plotted against the temperature rise and compared with the calibration under the steady-state condition in the Phase I Tests for each of the respective sensors (Figure 53). There was no significant difference in the plotted results of tensiometer readings and the HD sensor change in temperature rise between the first and second drying cycles, suggesting that the different drying rates as applied did not have a significant effect on the soil matric suction and the measured temperature rise. Any observed difference (e.g. Figure 53(d)) could be a result of soil hysteresis arising from some differences in drainage paths between the first and second drying cycles. However, the general agreement as shown in Figures 53(a) to (d) between the estimated suction values and tensiometer readings was also consistent with those in Figures 51 and 52, indicating that soil hysteresis at low soil matric suctions may not have a significant impact on the composite water contents of the sensors (see Section 4.2.4). As with Figure 50, it is also noted from Figure 53 that the sensor change in temperature rise essentially remained the same for low soil matric suctions between zero and 10 kPa. This is also consistent with the lowest operating limit of 10 kPa noted in Campbell Scientific, Inc. (2006b), confirming that the sensors may not be sensitive to measurement of low soil matric suctions below 10 kPa (see also Section 4.2.4).

Apart from the measurement accuracy associated with the steady-state calibration and the possible soil variability from test to test, it is possible that the difference between the transient state and steady-state relationships as evident in Figures 53(a) to (d) (particularly in respect of the soil suction values beyond 30 kPa) could be a combination of effects due to the soil hysteresis as well as other factors including the response of the sensors, hysteresis of the sensors and differences in locations between the reference tensiometers and the HD sensors involved in the monitoring. Because the steady-state relationship (as derived from the Phase I Tests) involved no transient water flow and the measurements were taken until the stable readings had been achieved, the relationship may be regarded as being representative of measurements with no hysteretic behavior and no measurement delay due to the sensors' response time. As a result of capillary hysteresis in soils, the transient state relationship would tend to lie above the steady-state relationship. The delay in the sensors' response could also aggravate this phenomenon. Based on the results of the Phase I Tests, the slowest rate of response of the sensors was calculated to be 0.004 kPa/min, which was slower than that of the SWT4R Tensiometers but was slightly faster than the drying rate under the first or second drying cycle (i.e. 0.002 kPa/min or 0.0013 kPa/min). On this basis, it is considered that the effect due to the sensors' response should not be significant in the present study. However, the porous tips of this type of sensors may be subjected to hysteresis effect, as it has been shown by Feng & Fredlund (2003) that the hysteresis effect could give rise to an error of 30% to 70% for suction measurements higher than 100 kPa.

5.2.4 Watermark 200 GM Sensors

The GM Sensors behaved like the 229 HD Sensors in that the readings were relatively steady immediately after wetting (at a low soil matric suction value below 5 kPa and for a period of 20 days) before there was any noticeable increase in resistance readings during

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drying (Figure 54).

Immediately after the first cycle of drying and wetting, only one sensor (No. GB 2) was found to remain in operation and the other two sensors (Nos. GB 4 and 5) were either damaged during withdrawal for saturation or found to be malfunctioning prior to the commencement of the second cycle of testing. However, malfunctioning of Sensor No. GB 2 with a rapid increase in resistance reading up to about 90 kΩ was subsequently observed under the second drying cycle, from end April to May 2010, whereby measurement from this sensor was discontinued. During the above period, the estimated soil matric suction based on the reading from the sensor was more than 2,000 kPa while the tensiometer suction was low at about 10 kPa.

Figures 55 and 56 show the soil matric suctions estimated from the previous steady state calibration under the Phase I Tests for the GM Sensors and the comparison with the tensiometer readings taken directly under the transient conditions. Figure 57 shows the tensiometer readings against the sensor change in resistance during the first drying cycle for soil matric suctions ranging from zero to 90 kPa, and a comparison of the relationship with the Phase I Test calibration under steady-state condition for each of the sensors. Except where no major change in the sensor resistance was noted at low soil matric suctions below 5 kPa, the transient state relationship for the GM Sensors was comparable with the steady-state calibration. A difference of less than ± 5 kPa was identified between the transient state and steady-state relationships for soil matric suctions from about zero to 50 kPa, beyond which the difference became more significant and reached a maximum of about 25 kPa (38%).

The slowest response rate of the sensors was estimated to be about 0.001 kPa/min, which is slightly slower than the drying rate of 0.002 kPa/min in soil. In this regard, the sensors' change in resistance might also lag behind the true value. In addition, the reliability of the estimate assuming steady-state condition, together with the effect of soil hysteresis, could also affect the accuracy of the soil matric suction values (Section 5.2.3). Unlike the observation from the 229 HD Sensors (where the transient state relationship was found to lie above that from the steady-state estimation), the steady-state estimation for the GM Sensors typically plot above the transient state relationship, particularly at higher soil suctions. It is noted from the results that the GM sensors might not be reliable after being in use for a period of time, as some GM sensors were found to be malfunctioning possibly due to ageing, resulting in a large resistance readings.

6. SUMMARY AND DISCUSSION OF RESULTS

The test sensors covered by the study included SWT4R Tensiometers, CS605 TDR Probes, CS616 WCR Probes, CS210 Enclosure RH Sensors, 229 HD Sensors and Watermark 200 GM Sensors. The SWT4R Tensiometer measures the soil matric suction directly, whereas the soil suction/soil moisture values provided by other sensors are indirect, typically relying on empirical relationships established with the measuring parameters (i.e. the dielectric constant of the test medium and temperature/electrical resistance change of the test sensor). Calibration tests have been carried out using soil samples that are representative of the grain size envelopes commonly encountered in Hong Kong. These tests were conducted under steady-state conditions, using soil samples compacted to 85% RC at various moisture contents. It is evident from the results that different types of sensors varied in performance

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in terms of their response time, variability, repeatability and measurement accuracy (see Table 23). The soil-water characteristic curves for the specific soil samples as well as the empirical relationships between the soil matric suction/soil moisture and the relevant measuring parameters for sensors employing indirect suction/moisture measurement have also been established. Testing has also been carried out under transient (two cycles of wetting and drying on medium-grained soil) conditions. Useful observations have been obtained in respect of the sensors' performance due to soil hysteresis.

Based on the findings of the present study, the merits and limitations of each type of sensor are summarized in Table 24. The pertinent observations from the Phase I and Phase II Tests are summarized below:

(a) The CS210 Enclosure RH Sensors were subject to the problem of condensation and did not prove suitable for measurement of soil suction. The SWT4R Tensiometers can directly measure soil matric suction from zero to 90 kPa, whereas the soil suction determination by CS605 TDR Probes, CS616 WCR Probes, 229 HD Sensors and Watermark 200 GM Sensors is indirect, requiring specific empirical relationships to be established. With the simple set-up used in the present study, the specific relationships under steady-state conditions for all these sensors were established over a suction range of about 5 kPa to 90 kPa.

(b) The sensors' response time is sensor dependent and varies with the test soil specimen in terms of its moisture content and particle size distribution. Except for the CS605 TDR and CS616 WCR Probes, which virtually provided instantaneous response, all other sensors took a certain amount of time to achieve a stable reading, particularly when measurement was taken in soil specimens drier than the OMC of the respective soil samples. Based on the Phase I Tests, the SWT4R Tensiometers showed a relatively rapid response. For Sample A, the tensiometers only took 5 to 30 minutes to reach a reading that is within ± 10% of the stable readings, whereas the Watermark 200 GM and 229 HD Sensors required a maximum of 3,200 minutes (about 53 hours) and 14,000 minutes (about 233 hours), respectively.

(c) In terms of variability, the Watermark 200 GM Sensors were the most variable and the CS605 TDR and CS616 WCR Probes the least. The variability of both the 229 HD Sensors and SWT4R Tensiometers was not particularly significant. The repeatability of the GM Sensors was also poor, whereas all the SWT4R Tensiometers, TDR Probes, WCR Probes and HD Sensors proved to have a good repeatability.

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(d) Full saturation before use of the essence to all sensors with a porous filter. Partial saturation of the 229 HD Sensors did not shorten the response time but instead, this could result in different soil matric suctions as compared with the measurements taken using fully saturated sensors.

(e) Although the TDR and WCR Probes have the least variability in moisture content measurements, they have a relatively poor accuracy in soil matric suction estimation (± 30 to 40 kPa). It is noted, however, that the moisture content values determined from the CS605 TDR Probes were in good agreement with those determined by the oven drying method.

(f) Capillary hysteresis can have a significant bearing on the soil-water characteristic curves. The results of the Phase II Tests showed that the soil matric suction as measured from the tensiometers under transient conditions differed from the estimate based on the soil-water characteristic curves established under steady-state conditions. During the drying cycles, the difference became more marked as the suction increased, being more than 50 kPa when the soil suction was between 80 kPa and 90 kPa (i.e. the transient condition values was about 60% to 70% greater than the steady-state estimate).

(g) Regarding the 229 HD Sensors, the soil matric suction estimated from the steady-state calibration was comparable with the tensiometer measurements under the transient conditions when the soil matric suction was low (below 30 kPa). Below this soil suction, the calibration relationship as established between soil suction and the sensor change in temperature rise under steady-state conditions also proved to be comparable with the transient state relationship, which suggests that the soil hysteresis at low soil matric suctions might not have a significant impact on the composite water content of the HD sensors.

(h) As with the 229 HD Sensors, the Watermark 200 GM Sensors also displayed similar results in that the relationships between soil suctions and the sensor's changes in electrical resistances under both the transient and steady-state conditions were similar for soil matric suctions up to about 50 kPa. However, the GM Sensors did not appear to be reliable due to their malfunctioning after being in use for a period of time.

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7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The present study has systematically examined, under controlled laboratory conditions, the performance of commercially available sensors that can be used to measure or estimate the soil suction. The findings have provided useful insights on the behaviour of different sensors, which can help to put the field measurements in context and assist with their proper interpretation. Based on the present study, the following preliminary conclusions in respect of the reliability and accuracy of the test sensors for determining soil matric suction can be drawn:

(a) Of all the various types of sensors, SWT4R Tensiometer has proved to perform well, in terms of its repeatability, limited variability and good measurement accuracy, for the direct measurement of soil matric suction. The corresponding measurement range is limited to about 90 kPa due to water cavitation, which does not pose a major constraint as the soils in Hong Kong are mostly granular and not clayey in nature.

(b) Based on the present series of preliminary tests, the C210 Enclosure RH Sensor appeared to be suitable for measuring relative humidity in ambient environment but inapplicable for humidity measurements in soil (and hence not appropriate for soil suction determination), due to the condensation problem.

(c) The 229 HD Sensor and Watermark 200 GM Sensor employ indirect method for the soil matric suction measurement by correlating the soil suction with the relevant measuring parameters. Both have demonstrated their potential for use in estimating soil matric suction based on the specific conditions. However, the reliability of the conditions under which the correlations are established may be influenced by the variability of the groundmass in the field. Based on the test results, Watermark 200 GM Sensor showed a greater variability and that the measurements could become unstable after being in use for a period of time (about 5 months). Furthermore, the time required for the tested GM Sensor to achieve a stable reading was the longest (up to 22,400 minutes), as compared with the 229 HD Sensor (up to 7,000 minutes) and SWT4R Tensiometer (up to 4,000 minutes).

(d) The response of the CS605 TDR Probe and CS 616 WCR Probe was virtually instantaneous. However, these probes appeared to have considerable variability and poor accuracy in the determination of soil suction based on the specific correlations with the measuring parameters.

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7.2 Recommendations

Based on the findings of the present study, the following recommendations are made:

(a) The selection of suitable sensors is of the essence for reliable and accurate determination of soil matric suctions in the field. The performance of the sensors in terms of their repeatability, variability and measurement accuracy should be considered, together with the response time vis-a-vis the anticipated drying/wetting rate in the field. The calibration procedures as adopted in the present study can provide baseline information on the above aspects.

(b) For more reliable measurements, all sensor types incorporating porous filters (e.g. SWT4R Tensiometer, 229 HD Sensor and Watermark 200 GM Sensor) must be fully saturated before use.

(c) More thought and work need to be given to establishing the appropriate correlations between soil matric suction and the measuring parameters of the indirect measurement methods (e.g. 229 HD Sensor or GM Sensor) under appropriate conditions. Particular care is needed in assessing the applicability of the indirect methods where the ground is subject to considerable spatial variability.

(d) The effects of capillary hysteresis should be duly considered and accounted for with sensors made of porous materials (i.e. SWT4R Tensiometer, 229 HD Sensor and GM Sensor). Such effects could be implicitly included in the relevant specific relationships between soil matric suction and sensor change if the actual monitoring conditions have been closely replicated in the calibration process.

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Table 1 - Summary of Preliminary Results Reported in OAP (2009)

Soil Moisture/Suction Sensors	Results	Limitations	Lessons Learnt
CS625 WCR Probes	• The observed response from the sensors during rainfall periods appeared reasonable. • The water contents determined from the sensors were also comparable with the laboratory test values obtained from the soil samples from sites.	• As installation requires pushing the wave guide into the soil, the probes are prone to damage due to their slender nature. • The probes should be calibrated with representative soil samples as the electrical resistivity (or dielectric constants) of the soil is specific to the soil tested. • Preferential infiltration of rainfall can result in apparently fast response.	• Care is required during installation in order to avoid damage of the probes. • Soil specific calibration should be undertaken for each individual probe. • If the installation is conducted in a drillhole, the drillhole should be backfilled, and it is desirable to construct a soil mound at the ground surface to prevent preferential infiltration.
229 Heat Dissipation (HD) Sensors	• No response was noted during the rainstorm event in June 2008, but in general, the soil matric suction from the sensors showed similar overall trends and magnitudes, when compared with the readings from a nearby Jetfill Tensiometer.	• Soil specific calibration is required for each sensor in order to obtain accurate readings. • The need to heat up the sensor consumes power and is time consuming as compared with other monitoring devices.	• Use of Jetfill Tensiometers is preferable to the HD Sensors installed.
Jetfill Tensiometers	• The observed response correlated well with rainfall and the corresponding changes observed from the TDR Probes.	• Continuous maintenance is required to ensure that water is maintained within the plastic tube of the instrument. • The response time will be slow as air may build up within the tensiometer. • Good contact is required between the ceramic tip and surrounding soil, and the ceramic tip should be sealed against infiltration by backfilling with soil column above the tip. • Tensiometers installed in the field are prone to damage by human and animal activity.	• Routine site visit needs to be conducted to ensure that the water levels within the jet fill tensiometers remain sufficiently high. • Excessive gaps in contact with the ceramic tip should be avoided. • Infiltration of water and preferential flow (due to surface run-off) towards the ceramic tip can be minimized by placing soil mounds or piezometer top boxes around the installed tensiometer. • Installation of the tensiometer to the design depth in a pre-formed hole of the same (or marginally smaller) diameter to the tensiometer tube can negate the need for backfilling.

Note : The soil moisture/soil suction sensors adopted in OAP (2009) comprised CS625 Water Content Reflectometers (WCR Probes), 229 HD Sensors and Jetfill Tensiometers. The CS625 WCR Probes are the same as the CS616 WCR Probes used in the present study (Appendix A), both of which use the TDR measurement method to determine the soil moisture content.

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Table 2 - Summary of Operating Principles and Salient Specifications for the Sensors in the Study

Description	SWT4R Tensiometer	CS605 TDR Probe	CS616 WCR Probe	C210 RH Sensors	229 HD Sensor	Watermark 200GM Sensor
Operating principle	• It comprises a high air entry filter directly connected to a pressure measuring device. • It measures negative pore water pressure in the soil, which is numerically equal to the soil matric suction when the pore air pressure is atmospheric.	• It comprises three pointed steel rods and an epoxy head connected with cable, which serves as a wave guide. • An electromagnetic pulse is injected into the wave guide. The dielectric constant of the test medium is determined from the time measurement and propagation velocity based on the reflected wave. The volumetric water content (VWC) is related to the dielectric constant using empirical relationships.	• It comprises two pointed steel rods and an epoxy head connected with cable, which serves as a wave guide. • It works on a similar operating principle to that of CS605 TDR Probe, but the outputs are in terms of period (viz. micro-second) (i.e. not the dielectric constant). The VWC is related to the output period using empirical relationships.	• It comprises a bulk polymer which changes its electrical resistance as the humidity changes.	• It comprises a cylindrically-shaped porous ceramic body, in which a thermocouple is present together with a heating element. • During measurement, the water within the sensor is heated up. The temperatures at the start and the end of the heating are taken. The temperature difference is then used to compute the soil matric suction, based on empirical relationships.	• It consists of a perforated stainless steel cylinder supporting a permeable membrane, the inside of which is a tightly packed sand aggregate, concentric electrodes and a gypsum block (which acts as a buffer against soil acidity and salinity). • The electrical resistance of the sensor changes with the water condition in the unit. The resistance is related to the soil matric suction using empirical relationships.
Measurement	Soil matric suction (kPa)	VWC (%)	VWC (%)	Relative humidity (%)	Soil matric suction (kPa)	Soil matric suction (kPa)
Operating range	0 - 85 kPa	not specified	not specified	0 - 100%	10 - 2500 kPa	0 - 200 kPa
Accuracy	± 0.5 kPa	not specified	± 0.25% VWC (based on the manufacturer's empirical relationship)	± 3% RH between 10% and 90% RH	not specified	not specified
Number of sensors used in the study	6	6	5	6	6	6

Notes:
(1) The operating principles for each sensor type are detailed in Appendix A.
(2) The specifications of "Measurement", "Operating range" and "Accuracy" for the sensors are based on the respective information provided by suppliers/manufacturers. It should be noted that "Measurement" for CS605 TDR Probe, CS616WCR Probe, 229 HD Sensor, and Watermark 200GM Sensor does not refer to the measuring parameters of the sensors but the derived quantities as noted in the respective users' manuals.

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Table 3 - Verification of CS616 WCR Probes in Air and Tap Water

Record No.	Output Period (μsec)									
	WTDR-1		WTD-2		WTDR-3		WTDR-4		WTDR-5	
	Air	Water	Air	Water	Air	Water	Air	Water	Air	Water
1	15.02	43.29	14.84	43.09	14.85	43.10	14.90	43.15	14.87	43.26
2	14.89	43.29	14.84	43.11	14.88	43.06	14.90	43.15	14.87	43.26
3	14.91	43.29	14.82	43.14	14.88	43.10	14.89	43.17	14.87	43.26
4	14.89	43.29	14.82	43.14	14.88	43.10	14.89	43.17	14.87	43.26
5	14.89	43.30	14.84	43.13	14.88	43.13	14.89	43.17	14.87	43.27
6	14.89	43.30	14.84	43.16	14.88	43.12	14.89	43.17	14.87	43.27
7	14.89	43.30	14.83	43.15	14.88	43.10	14.88	43.20	14.87	43.28
Average	14.91	43.29	14.83	43.13	14.87	43.10	14.89	43.17	14.87	43.27

Notes : (1) The output periods in this table have been corrected using the following relationship as proposed in Campbell Scientific Inc., (2006b) to take into account temperature effect:

$\tau_{corr} = \tau_{uncorr} + (20 - T_{soil}) * (0.526 - 0.052 * \tau_{uncorr} + 0.00136 * \tau_{uncorr}^2)$

where τ_{corr} is the corrected output period in μsec, τ_{uncorr} is the uncorrected output period, and T_{soil} is the soil temperature in °C.

(2) The soil temperature during testing was about 19°C.

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Table 4 - Verification of Suction for 229 HD Sensors Immersed in Tap Water

Record No.	Suction (kPa)																	
	HD-1			HD-2			HD-3			HD-4			HD-5			HD-6		
	OAP (2009)	Fisher (2000)	Graeme Campbell & Asso. Pty Ltd (2006)	OAP (2009)	Fisher (2000)	Graeme Campbell & Asso. Pty Ltd (2006)	OAP (2009)	Fisher (2000)	Graeme Campbell & Asso. Pty Ltd (2006)	OAP (2009)	Fisher (2000)	Graeme Campbell & Asso. Pty Ltd (2006)	OAP (2009)	Fisher (2000)	Graeme Campbell & Asso. Pty Ltd (2006)	OAP (2009)	Fisher (2000)	Graeme Campbell & Asso. Pty Ltd (2006)
1	12.86	2.62	2.36	12.58	2.55	2.29	12.72	2.58	2.33	12.72	2.58	2.33	12.14	2.44	2.18	12.99	2.65	2.40
2	13.01	2.66	2.40	12.58	2.55	2.29	12.58	2.55	2.29	12.72	2.58	2.33	12.43	2.51	2.25	12.84	2.62	2.36
3	13.01	2.66	2.40	12.43	2.51	2.25	12.86	2.62	2.36	12.72	2.58	2.33	12.43	2.51	2.25	13.14	2.69	2.44
4	12.72	2.58	2.33	12.43	2.51	2.25	12.86	2.62	2.36	12.86	2.62	2.36	12.58	2.55	2.29	12.99	2.65	2.40
5	12.72	2.58	2.33	12.43	2.51	2.25	12.86	2.62	2.36	12.58	2.55	2.29	12.14	2.44	2.18	12.84	2.62	2.36
6	13.01	2.66	2.40	12.43	2.51	2.25	13.01	2.66	2.40	12.72	2.58	2.33	12.14	2.44	2.18	12.99	2.65	2.40
7	12.86	2.62	2.36	12.58	2.55	2.29	13.01	2.66	2.40	12.58	2.55	2.29	12.30	2.48	2.22	12.99	2.65	2.40
Ave.	12.88	2.63	2.37	12.49	2.53	2.27	12.84	2.62	2.36	12.70	2.58	2.32	12.31	2.48	2.22	12.97	2.65	2.39

Notes : The above values were evaluated from the individual measurements of temperature rise, based on the following empirical relationships:

(a) OAP (2009)
average of (i) $s = 4.2168\, e^{1.4172\Delta T}$, (ii) $s = 5.0627\, e^{1.3978\Delta T}$, and (iii) $s = 4.6418\, e^{1.4049\Delta T}$,

(b) Fisher (2000)
$s = 0.717\, e^{1.788\Delta T}$, and

(c) Graeme Campbell & Associates Pty Ltd (2006)
average of (i) $s = 0.5e^{1.99\Delta T}$, (ii) $s = 0.81\, e^{2.11\Delta T}$, and (iii) $s = 0.32\, e^{1.88\Delta T}$,

where s is the suction (kPa) and ΔT is the temperature rise (°C), which is corrected using the procedures established by Flint *et al* (2002).

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Table 5 - Verification of Suction for Watermark 200 GM Sensors Immersed in Tap Water

Record No.	Suction (kPa)																	
	GB-1			GB-2			GB-3			GB-4			GB-5			GB-6		
	Camp. Sc., Inc. (2009a)	Irrometer Chart# 3 (EME Sys., 2002)	Eldredge et al (1993)	Camp. Sc., Inc. (2009a)	Irrometer Chart# 3 (EME Sys., 2002)	Eldredge et al (1993)	Camp. Sc., Inc. (2009a)	Irrometer Chart# 3 (EME Sys., 2002)	Eldredge et al (1993)	Camp. Sc., Inc. (2009a)	Irrometer Chart# 3 (EME Sys., 2002)	Eldredge et al (1993)	Camp. Sc., Inc. (2009a)	Irrometer Chart# 3 (EME Sys., 2002)	Eldredge et al (1993)	Camp. Sc., Inc. (2009a)	Irrometer Chart# 3 (EME Sys., 2002)	Eldredge et al (1993)
1	0.38	4.06	6.85	0.30	3.99	6.79	-0.02	3.66	6.54	0.74	4.42	7.14	0.49	4.17	6.94	0.34	4.02	6.82
2	0.38	4.06	6.85	0.24	3.93	6.75	-0.02	3.66	6.54	0.74	4.42	7.13	0.48	4.16	6.93	0.34	4.02	6.82
3	0.38	4.06	6.85	0.24	3.93	6.75	-0.04	3.65	6.53	0.74	4.42	7.13	0.48	4.17	6.93	0.35	4.03	6.83
4	0.38	4.06	6.85	0.24	3.92	6.74	-0.07	3.62	6.50	0.74	4.43	7.13	0.49	4.17	6.94	0.36	4.05	6.84
5	0.33	4.02	6.82	0.21	3.90	6.72	-0.11	3.58	6.47	0.73	4.42	7.13	0.47	4.15	6.92	0.38	4.06	6.85
6	0.31	4.00	6.80	0.21	3.90	6.72	-0.13	3.56	6.46	0.74	4.42	7.13	0.47	4.16	6.93	0.37	4.06	6.85
7	0.30	3.98	6.79	0.21	3.89	6.72	-0.13	3.55	6.45	0.74	4.42	7.13	0.48	4.17	6.93	0.37	4.06	6.85
Average	0.35	4.03	6.83	0.24	3.92	6.74	-0.07	3.61	6.50	0.74	4.42	7.13	0.48	4.16	6.93	0.36	4.04	6.84

Notes : The above values were evaluated from the individual measurements of electrical resistance, based on the following empirical relationships:

(a) Campbell Scientific Inc. (2009a)
average value of $s = 7.407*R_{21}-3.704$,

(b) Irrometer Chart #3 (EME Systems, 2002)
$s = 20*(R*(1 + 0.018*(T-24) - 0.55))$, and

(c) Eldredge et al (1993)
$s = 6.44 + (4.196*R-2.098)/(1-0.013*T)$,

where s is the suction (kPa), T is temperature (°C), and R is electrical resistance (kΩ). R_{21} is equal to $R/(1-(0.018*(T-21))$,which is to take account of temperature effect with respect to a reference temperature of 21°C. The temperature during the measurements was at about 18.6°C.

Table 6 - Summary of Physical Properties of Soil Samples A, D and E and Test Moisture Content (Phase I Tests)

Soil Sample No.	Percentage Passing by Weight		Specific Gravity	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index	Standard Proctor Max. Dry Density (Mg/m^3)	Optimum Moisture Content (%)	Test Moisture Content (%)
	63 µm	2 mm							
A ("medium-grained soil")	28	77	2.6	52	29	23	1.79	15	7.3 10.3 12.6 13.7 14.9 16.2 17.6 18.9
D ("fine-grained soil")	48	87	2.64	41	25	16	1.56	19	11.9 13.8 15.6 16.5 19.0 20.4 22.0
E ("coarse-grained soil")	14	60	2.61	23.6	Non plastic	-	2.12	7.8	3.3 4.0 4.9 6.0 6.9

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Table 7 - Monitoring of Moisture Content of Soil Specimens in Control Boxes for Sample A (Phase I Tests)

Box 1		Box 2		Box 3		Box 4		Box 5		Box 11		Box 12		Box 13	
Date	MC (%)	Date	MC (%)	Date	MC (%)	Date	MC (%)	Date	MC (%)	Date	MC (%)	Date	MC (%)	Date	MC (%)
12.3.09	18.87	12.3.09	7.31	19.3.09	16.19	12.3.09	12.64	12.3.09	10.26	11.5.09	13.67	11.5.09	14.92	18.5.09	17.57
28.4.09	18.76	5.5.09	7.04	28.4.09	16.19	30.4.09	12.61	5.5.09	9.99	19.5.09	13.63	18.5.09	14.81	27.5.09	17.48
25.5.09	18.72	13.8.09	7.01	27.5.09	16.23	9.6.09	12.83	4.6.09	10.01	9.6.09	13.67	11.6.09	14.89	3.6.09	17.31
8.6.09	18.38			15.6.09	16.01	29.6.09	12.73	18.6.09	10.18	18.6.09	13.75	6.7.09	14.75	26.6.09	17.71
3.7.09	18.50			13.7.09	15.86	22.7.09	12.78	15.7.09	10.01	29.7.09	13.74	21.7.09	14.80	20.7.09	17.20
27.7.09	18.66			23.7.09	16.09	29.7.09	12.80	10.8.09	10.06	6.8.09	13.78	28.7.09	15.04	27.7.09	17.57
15.3.10	18.54			23.3.10	16.09	5.1.10	12.55			20.8.09	13.73	6.8.09	14.95	12.8.09	17.62
						26.1.10	12.58			27.8.09	13.78	12.8.09	14.87	17.8.09	17.35
						2.2.10	12.5			8.9.09	13.83	25.8.09	14.85	25.08.09	17.57
						9.2.10	12.41			23.9.09	13.86	15.9.09	14.75	1.9.09	17.7
						5.3.10	12.58			15.3.10	13.84	8.10.09	15.05	14.12.09	17.6
												20.10.09	14.90	4.1.10	17.24
												10.11.09	14.79	18.1.10	17.57
												18.11.09	14.84	24.2.10	17.36
												30.11.09	14.65	19.3.10	17.55
												15.3.10	14.65		
Min.MC (%)	18.38		7.01		15.86		12.41		9.99		13.63		14.65		17.20
Max.MC (%)	18.87		7.31		16.23		12.83		10.26		13.86		15.05		17.62
Diff.MC (%)	0.49		0.3		0.37		0.42		0.27		0.23		0.4		0.42

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Table 8 - Monitoring of Moisture Content of Soil Specimens in Control Boxes for Sample D (Phase I Tests)

Box 6		Box 7		Box 8		Box 9		Box 10		Box 18		Box 21	
Date	MC (%)	Date	MC (%)	Date	MC (%)	Date	MC (%)	Date	MC (%)	Date	MC (%)	Date	MC (%)
12.3.09	21.97	12.3.09	18.99	12.3.09	15.62	19.3.09	13.77	25.3.09	11.86	29.6.09	16.51	24.8.09	20.35
4.5.09	21.83	11.5.09	18.79	13.5.09	15.26	19.5.09	13.63	19.5.09	11.86	8.7.09	16.45	8.9.09	20.36
9.9.09	21.86	28.8.09	18.74	9.9.09	15.41					9.9.09	16.56	8.10.09	20.27
21.4.10	21.80	21.4.10	18.63	21.4.10	15.48					21.4.10	16.46	21.4.10	20.20
Min.MC (%)	21.80		18.63		15.26		13.63		11.86		16.45		20.20
Max.MC (%)	21.97		18.99		15.62		13.77		11.86		16.56		20.36
Diff.MC (%)	0.47		0.36		0.36		0.14		0		0.11		0.16

Table 9 - Monitoring of Moisture Content of Soil Specimens in Control Boxes for Sample E (Phase I Tests)

Box 14		Box 15		Box 16		Box 19		Box 20	
Date	MC (%)	Date	MC (%)	Date	MC (%)	Date	MC (%)	Date	MC (%)
8.6.09	6.89	8.6.09	6.01	17.6.09	4.03	26.6.09	4.85	2.7.09	3.25
18.6.09	6.61	22.6.09	5.81	30.6.09	3.99	8.7.09	4.75	16.7.09	3.29
9.9.09	6.75	9.9.09	5.88	9.9.09	4.06	9.9.09	4.81	9.9.09	3.30
21.4.10	6.65	21.4.10	5.94	21.4.10	3.98	21.4.10	4.68	21.4.10	3.28
Min.MC (%)	6.61		5.81		3.98		4.68		3.25
Max.MC (%)	6.89		6.01		4.06		4.85		3.30
Diff.MC (%)	0.28		0.2		0.08		0.17		0.05

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Table 10 - Temperature Measurement from Different Soil Specimens for Sample A (Phase I Tests)

Date	Time (hrs)	Temperature (°C)										
		Box 1 (18.9% MC)	Box 2 (7.3% MC)	Box 3 (16.2% MC)	Box 4 (12.6% MC)	Box 5 (10.3% MC)	Box 11 (10.3% Mc)	Box 12 (10.3% MC)	Box 13 (10.3% MC)	Min.MC (%)	Max.MC (%)	Diff.MC (%)
20.4.09	18:00	19.0	-	-	-	-				19.0	19.0	0.0
24.4.09	16:00	19.0	19.0	19.0	19.1	-				19.0	19.1	0.1
27.4.09	10:00	19.3	19.3	19.3	19.3	-				19.3	19.3	0.0
27.4.09	16:00	19.3	19.3	19.3	19.4	-				19.3	19.4	0.1
28.4.09	10:00	19.5	19.5	19.5	19.5	-				19.5	19.5	0.0
29.4.09	16:00	19.4	19.4	-	19.5	19.4				19.4	19.5	0.1
30.4.09	10:00	19.6	19.6	-	19.5	19.6				19.5	19.6	0.1
30.4.09	16:00	19.5	19.5	-	-	19.5				19.5	19.5	0.0
4.5.09	16:00	19.4	19.4	-	-	19.4	-	-	-	19.4	19.4	0
5.5.09	10:00	19.4	-	-	-	19.4	-	-	-	19.4	19.4	0
14.5.09	16:00	-	-	-	-	-	19.6	19.7	-	19.6	19.7	0.1
15.5.09	10:00	-	-	-	-	-	19.6	19.6	-	19.6	19.6	0
21.5.09	16:00	20.0	-	-	-	-	-	-	20.1	20.0	20.1	0.1
22.5.09	10:00	19.9	-	19.9	-	-	-	-	19.9	19.9	19.9	0
2.6.09	10:00	-	-	-	19.5	19.5	19.4	19.5	19.4	19.4	19.5	0.1
2.6.09	16:00	-	-	-	19.5	19.4	19.4	19.5	19.5	19.4	19.5	0.1
4.6.09	16:00	-	-	-	19.8	-	19.8	19.8	-	19.8	19.8	0
5.6.09	16:00	19.9	-	-	20.0	-	20.0	20.0	-	19.9	20	0.1
8.6.09	16:00	-	-	20.0	19.9	-	19.9	20.0	-	19.9	20	0.1
10.6.09	16:00	-	-	20.2	-	20.1	-	20.1	-	20.1	20.2	0.1
11.6.09	10:00	-	-	19.8	-	19.7	-	19.8	-	19.7	19.8	0.1
12.6.09	16:00	-	-	20.3	-	20.3	20.3	20.3	-	20.3	20.3	0
15.6.09	16:00	-	-	20.0	-	20.0	20.0	20.0	-	20.0	20.0	0
16.6.09	10:00	-	-	-	-	20.1	20.1	20.1	-	20.1	20.1	0
26.6.09	10:00	-	-	19.7	19.7	19.7	-	19.6	19.7	19.6	19.7	0.1
29.6.09	10:00	-	-	20.5	20.5	20.4	-	20.4	20.5	20.4	20.5	0.1
2.7.09	16:00	19.9	-	20.0	-	20.0	-	20.0	-	19.9	20	0.1
3.7.09	16:00	-	-	19.7	-	19.8	-	19.7	-	19.7	19.8	0.1
10.7.09	16:00	-	-	20.0	20.1	20.0	-	20.0	-	20.0	20.1	0.1
14.7.09	16:00	-	-	-	20.5	20.6	-	20.5	-	20.5	20.6	0.1
15.7.09	10:00	-	-	-	20.3	20.4	20.3	20.3	-	20.3	20.4	0.1
22.7.09	16:00	-	-	20.0	19.9	-	19.9	-	-	19.9	20	0.1
23.7.09	10:00	-	-	-	19.9	-	19.9	-	-	19.9	19.9	0
24.7.09	10:00	20.0	-	-	20.1	-	20.0	-	20.1	20.0	20.1	0.1
31.7.09	10:00	-	-	-	-	19.2	19.2	19.3	-	19.2	19.3	0.1
4.8.09	10:00	-	-	-	-	-	19	18.9	-	18.9	19	0.1
12.8.09	10:00	-	19.3	-	-	-	19.2	-	-	19.2	19.3	0.1
19.8.09	16:00	-	-	-	-	-	20.0	20.1	20.1	20.0	20.1	0.1
31.8.09	10:00	-	-	-	-	-	20.0	20.1	20.1	20	20.1	0.1
4.9.09	10:00	-	-	-	-	-	19.9	20.0	-	19.9	20.0	0.1
14.9.09	16:00	-	-	-	-	-	19.3	19.3	-	19.3	19.3	0
21.9.09	16:00	-	-	-	-	-	19.6	-	-	19.6	19.6	0
30.9.09	16:00	-	-	-	-	-	-	19.4	-	19.4	19.4	0
7.10.09	10:00	-	-	-	-	-	-	19.3	-	19.3	19.3	0
24.11.09	10:00	-	-	-	-	-	-	19.8	-	19.8	19.8	0
18.12.09	16:00	-	-	-	-	-	-	-	19.5	19.5	19.5	0
22.1.10	10:00	-	-	-	19.8	-	-	-	-	19.8	19.8	0
9.2.10	16:00	-	-	-	20.0	-	-	-	-	20.0	20.0	0
23.2.10	16:00	-	-	-	-	-	-	-	19.9	19.9	19.9	0
26.3.10	16:00	19.9	19.9	19.8	19.9	19.9	19.8	19.9	19.9	19.8	19.9	0.1
29.3.10	10:00	19.4	19.4	19.3	19.4	19.3	19.3	19.3	19.4	19.3	19.4	0.1
Min.		19.0	19.0	19.0	19.1	19.2	19.2	18.9	19.4			
Max.		20.0	20.0	20.3	20.5	20.6	20.3	20.5	20.5			
Diff.		1	1	0.7	1.4	1.4	1.1	1.6	1.1			

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Table 11 - Temperature Measurement from Different Soil Specimens for Sample D (Phase I Tests)

Date	Time (hrs)	Temperature (°C)									
		Box 6 (MC of 18.9%)	Box 7 (MC of 7.3%)	Box 8 (MC of 16.2%)	Box 9 (MC of 12.6%)	Box 10 (MC of 10.3%)	Box 18 (MC of 10.3%)	Box 21 (MC of 10.3%)	Min.MC (%)	Max.MC (%)	Diff.MC (%)
30.4.09	10:00	19.6	-	-	-	-	-	-	19.6	19.6	0
4.5.09	10:00	19.4	-	-	-	-	-	-	19.4	19.4	0
6.5.09	16:00	-	19.3	19.4	-	-	-	-	19.3	19.4	0.1
7.5.09	10:00	-	19.3	19.4	-	-	-	-	19.3	19.4	0.1
7.5.09	16:00	-	19.2	19.3	19.2	-	-	-	19.2	19.3	0.1
8.5.09	10:00	-	19.3	19.4	19.3	-	-	-	19.3	19.4	0.1
11.5.09	10:00	-	19.4	19.4	19.4	19.5	-	-	19.4	19.5	0.1
12.5.09	10:00	-	-	19.6	19.6	19.7	-	-	19.6	19.7	0.1
12.5.09	16:00	-	-	19.7	19.7	19.7	-	-	19.7	19.7	0
13.5.09	10:00	-	-	19.7	19.6	19.7	-	-	19.6	19.7	0.1
14.5.09	10:00	-	-	-	19.6	19.7	-	-	19.6	19.7	0.1
15.5.09	10:00	-	-	-	19.6	19.7	-	-	19.6	19.7	0.1
15.5.09	16:00	-	-	-	19.5	19.6	-	-	19.5	19.6	0.1
18.5.09	10:00	-	-	-	19.3	19.4	-	-	19.3	19.4	0.1
19.5.09	10:00	-	-	-	19.4	19.4	-	-	19.4	19.4	0
2.7.09	16:00	-	-	-	-	-	20.0	-	20.0	20.0	0
7.7.09	10:00	-	-	-	-	-	20.4	-	20.4	20.4	0
8.7.09	10:00	-	-	-	-	-	20.2	-	20.2	20.2	0
26.8.09	16:00	-	-	-	-	-	-	19.8	19.8	19.8	0
27.8.09	10:00	-	-	-	-	-	-	19.9	19.9	19.9	0
28.8.09	10:00	-	-	-	-	-	-	20.1	20.1	20.1	0
31.8.09	16:00	-	-	-	-	-	-	19.8	19.8	19.8	0
1.9.09	10:00	-	-	-	-	-	-	19.6	19.6	19.6	0
2.9.09	10:00	-	-	-	-	-	-	20.1	20.1	20.1	0
3.9.09	10:00	-	-	-	-	-	-	19.6	19.6	19.6	0
4.9.09	10:00	-	-	-	-	-	-	20.0	20.0	20.0	0
4.9.09	16:00	-	-	-	-	-	-	19.9	19.9	19.9	0
27.5.10	10:00	19.4	19.4	19.5	-	-	-	19.5	19.4	19.5	0.1
Max.		19.4	19.2	19.3	19.2	19.4	20.0	19.5			
Min.		19.6	19.4	19.7	19.6	19.7	20.4	20.1			
Diff.		0.2	0.2	0.4	0.4	0.3	0.6	0.6			

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Table 12 - Temperature Measurement from Different Soil Specimens for Sample E (Phase I Tests)

Date	Time (hrs)	Temperature (°C)							
		Box 14 (MC of 6.9%)	Box 15 (MC of 6.0%)	Box 16 (MC of 4.9%)	Box 19 (MC of 4.0%)	Box 20 (MC of 3.3%)	Min.MC (%)	Max.MC (%)	Diff.MC (%)
12.6.09	16:00	20.4	-	-	-	-	20.4	20.4	0
15.6.09	16:00	20.0	19.9	-	-	-	19.9	20.0	0.1
16.6.09	10:00	20.2	20.1	-	-	-	20.1	20.2	0.1
17.6.09	16:00	19.7	19.8	-	-	-	19.7	19.8	0.1
18.6.09	10:00	20.3	20.3	-	-	-	20.3	20.3	0
19.6.09	10:00	-	20.4	-	-	-	20.4	20.4	0
23.6.09	16:00	-	-	20.3	-	-	20.3	20.3	0
24.6.09	10:00	-	-	20.4	-	-	20.4	20.4	0
25.6.09	16:00	-	-	20.1	-	-	20.1	20.1	0
26.6.09	10:00	-	-	19.7	-	-	19.7	19.7	0
29.6.09	16:00	-	-	20.3	-	-	20.3	20.3	0
30.6.09	10:00	-	-	19.9	-	-	19.9	19.9	0
3.7.09	16:00	-	-	-	19.7	-	19.7	19.7	0
6.7.09	10:00	-	-	-	20.1	-	20.1	20.1	0
8.7.09	10:00	-	-	-	20.3	20.2	20.2	20.3	0.1
9.7.09	10:00	-	-	-	-	20.1	20.1	20.1	0
10.7.09	16:00	-	-	-	-	20.0	20.0	20.0	0
13.7.09	16:00	-	-	-	-	20.5	20.5	20.5	0
14.7.09	10:00	-	-	-	-	20.6	20.6	20.6	0
15.7.09	16:00	-	-	-	-	20.3	20.3	20.3	0
16.7.09	10:00	-	-	-	-	20.1	20.1	20.1	0
31.5.10	16:00	19.8	19.9	19.9	19.8	19.8	19.8	19.9	0.1
Max.		19.7	19.8	19.7	20.3	19.8			
Min.		20.4	20.4	20.4	19.7	20.6			
Diff.		0.7	0.6	0.7	0.6	0.8			

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Table 13 - Variability of SWT4R Tensiometers (Observations from Soil Sample A) (Phase I Tests)

Moisture Contents of Soil Specimens (%)	Soil Matric Suction (kPa)							
	SWT4R-430	SWT4R-431	SWT4R-432	SWT4R-433	Mean	Max.	Min.	Range/ (% of mean)
7.3	-	unstable	-	-	-	-	-	-
10.3	unstable	unstable	unstable	-	-	-	-	-
12.6	88.24	87.35	85.96	89.99	87.89	89.99	85.96	4.03/(4.6)
13.7	45.67	44.25	45.17	46.81	45.48	46.81	44.25	2.56/(5.6)
14.9	27.95	26.63	26.48	27.44	26.77	27.95	26.48	1.47/(5.4)
16.2	15.11	13.99	14.10	14.84	14.51	15.11	13.99	1.12/(7.7)
17.6	6.46	5.60	6.36	5.81	6.06	6.46	5.60	0.86/(14.2)
18.9	4.23	3.88	4.08	4.51	4.18	4.51	3.88	0.63/(15.1)

Table 14 - Repeatability of SWT4R Tensiometers (Observations from Soil Sample A) (Phase I Tests)

Record No.	Soil Matric Suction (kPa)		
	SWT4R-430 (13.7% MC)	SWT4R-433 (14.9% MC)	SWT4R-432 (17.6% MC)
1	45.67	27.44	6.36
2	43.57	26.28	6.57
3	44.6	26.48	6.38
4	45.76	26.40	6.77
5	43.95	26.05	6.67
Mean	44.70	26.53	6.55
Max.	45.76	27.44	6.77
Min.	43.57	26.05	6.36
Range/ (% of mean)	2.19/(4.9)	1.39/(5.2)	0.41/(6.3)

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Table 15 - Variability of CS605 TDR Probes (Observations from Soil Sample A) (Phase I Tests)

Moisture Contents of Soil Specimens (%)	Dielectric Constant								
	TDR-1	TDR-2	TDR-3	TDR-4	TDR-5	Mean	Max.	Min.	Range/ (% of mean)
7.3	4.25	4.37	4.31	4.26	4.38	4.31	4.38	4.25	0.13/(3)
10.3	4.13	4.16	4.12	4.15	4.17	4.15	4.17	4.12	0.05/(1.2)
12.6	4.52	4.55	4.61	4.65	4.55	4.58	4.65	4.52	0.12/(2.7)
13.7	5.63	5.81	5.62	5.56	5.60	5.65	5.81	5.56	0.25/(4.5)
14.9	5.11	5.19	5.40	5.10	5.31	5.22	5.40	5.10	0.31/(5.9)
16.2	5.06	5.07	5.22	5.11	5.15	5.12	5.22	5.06	0.16/(3.1)
17.6	6.87	6.74	7.20	6.95	6.87	6.93	7.20	6.74	0.46/(6.6)
18.9	6.48	6.30	6.34	6.63	6.33	6.42	6.63	6.30	0.33/(5.2)

Table 16 - Repeatability of CS605 TDR Probes (Observations from Soil Sample A) (Phase I Tests)

Record No.	Dielectric Constant		
	TDR-3 (7.3% MC)	TDR-2 (14.9% MC)	TDR-1 (18.9% MC)
1	4.31	5.19	6.44
2	4.17	5.27	6.32
3	4.31	5.20	6.29
4	4.25	5.21	6.27
5	4.32	5.28	6.4
Mean	4.27	5.23	6.34
Max.	4.32	5.28	6.44
Min.	4.17	5.19	6.27
Range/ (% of mean)	0.15/(3.5)	0.09/(1.7)	0.17/(2.7)

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Table 17 - Variability of CS616 WCR Probes (Observations from Soil Sample A) (Phase I Tests)

Moisture Contents of Soil Specimens (%)	Output Period (μs)								
	WTDR-1	WTDR-2	WTDR-3	WTDR-4	WTDR-5	Mean	Max.	Min.	Range/ (% of mean)
7.3	18.58	18.46	18.47	18.47	18.63	18.52	18.63	18.46	0.17/ (0.9)
10.3	19.52	19.48	19.56	19.77	19.31	19.53	19.77	19.31	0.46/ (2.4)
12.6	22.75	22.69	22.63	22.70	22.57	22.67	22.75	22.57	0.18/ (0.8)
13.7	22.82	22.42	22.65	22.72	22.59	22.64	22.82	22.42	0.40/ (1.8)
14.9	22.82	22.87	23.07	22.76	22.60	22.82	23.07	22.60	0.47/ (2.1)
16.2	23.68	23.43	23.39	23.55	23.38	23.49	23.68	23.38	0.30/ (1.3)
17.6	23.27	23.03	23.10	23.36	23.06	23.16	23.36	23.03	0.33/ (1.4)
18.9	24.73	25.17	24.57	24.62	24.57	24.73	25.17	24.57	0.60/ (2.4)

Table 18 - Repeatability of CS616 WCR Probes (Observations from Soil Sample A) (Phase I Tests)

Record No.	Output Period (μs)		
	WTDR-2 (7.3% MC)	WTDR-4 (14.9% MC)	WTDR-3 (18.9% MC)
1	18.46	22.76	24.57
2	18.45	22.71	24.71
3	18.55	22.62	24.63
4	18.52	22.61	24.70
5	18.41	22.63	24.53
Mean	18.48	22.67	24.63
Max.	18.55	22.76	24.71
Min.	18.41	22.61	24.53
Range/ (% of mean)	0.14/(0.8)	0.15/(0.7)	0.18/(0.7)

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Table 19 - Variability of 229 HD Sensors (Observations from Soil Sample A) (Phase I Tests)

Moisture Contents of Soil Specimens (%)	Temperature Rise (°C)								
	HD-1	HD-2	HD-3	HD-4	HD-5	Mean	Max.	Min.	Range/ (% of mean)
12.6	1.79	1.76	1.71	1.88	1.84	1.80	1.88	1.71	0.17/(9.5)
13.7	1.57	1.50	1.57	1.55	1.54	1.55	1.57	1.50	0.07/(4.5)
14.9	1.39	1.37	1.33	1.41	1.37	1.37	1.41	1.33	0.08/(5.8)
16.2	1.14	1.05	1.08	1.13	1.02	1.08	1.14	1.02	0.12/(11.1)
17.6	0.72	0.71	0.71	0.72	0.75	0.72	0.75	0.71	0.04/(5.5)
18.9	0.73	0.71	0.71	0.72	0.70	0.71	0.73	0.70	0.03/(4.2)

Note: Data for tests on specimens with 7.3% and 10.3% MC were not included as the measured temperatures have reached about 3°C, which is close to the temperature rise limit when the sensors are tested in the dry.

Table 20 - Repeatability of 229 HD Sensors (Observations from Soil Sample A) (Phase I Tests)

Record No.	Temperature Rise (°C)		
	HD-5 (13.7% MC)	HD-4 (14.9% MC)	HD-2 (17.6% MC)
1	1.54	1.41	0.71
2	1.55	1.38	0.71
3	1.54	1.42	0.71
4	1.54	1.37	0.71
5	1.54	1.38	0.73
Mean	1.54	1.39	0.71
Max.	1.55	1.42	0.73
Min.	1.54	1.37	0.71
Range/ (% of mean)	0.01/(0.6)	0.05/(3.6)	0.02/(2.8)

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Table 21 - Variability of Watermark 200 GM Sensors (Observations from Soil Sample A) (Phase I Tests)

Moisture Contents of Soil Specimens (%)	Resistance (kΩ)								
	GB-1	GB-2	GB-3	GB-4	GB-5	Mean	Max.	Min.	Range/ (% of mean)
7.3	-	unstable	-	-	-	-	-	-	-
10.3	unstable	16.61	34.18	16.20	14.09	20.27	34.18 [Note 1]	14.09	20.09/(99.1)
12.6	10.62	10.60	16.40	7.88	10.12	11.12	16.40	7.88	8.52/(76.6)
13.7	7.01	5.08	7.95	6.28	6.18	6.50	7.95	5.08	2.87/(44.3)
14.9	4.11	4.77	5.43	4.59	5.16	4.81	5.43	4.11	1.32/(27.4)
16.2	2.73	2.83	3.2	2.51	2.84	2.82	3.20	2.51	0.69/(24.5)
17.6	0.76	0.56	0.80	0.56	0.58	0.65	0.80	0.56	0.24/(36.3)
18.9	0.57	0.49	0.57	0.60	0.57	0.56	0.60	0.49	0.11/(19.6)

Note: This high value is erroneous. It may be related to the dissolution of the gypsum block within the sensor. This value is ignored, the respective range will become 2.52 kΩ (i.e. 15.6 % of the mean).

Table 22 - Repeatability of Watermark 200 GM Sensors (Observations from Soil Sample A) (Phase I Tests)

Record No.	Resistance (kΩ)		
	GB-5 (17.6 % MC)	GB-4 (14.9 % MC)	GB-2 (13.7 % MC)
1	6.18	4.59	0.56
2	6.83	4.64	0.71
3	7.13	4.82	0.65
4	6.61	4.63	0.84
5	7.23	4.53	0.74
Mean	6.80	4.64	0.70
Max.	7.23	4.82	0.84
Min.	6.18	4.53	0.56
Range/ (% of mean)	1.05/(15.5)	0.29/(6.2)	0.28/(40.0)

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Table 23 - Summary of Test Results (Phase I Tests)

Sensor	Response Time to Reach Stable Reading (min)			Response Time to Reach within ± 10% of the Stable Reading (min)			Variability (Sensor's Reading)	Repeatability (Sensor's Reading)	Accuracy (Measurement of Concern)
	Sample			Sample			Sample		
	A (medium-grained)	D (fine-grained)	E (coarse-grained)	A (medium-grained)	D (fine-grained)	E (coarse-grained)	A (medium-grained)	A (medium-grained)	A (medium-grained)
SWT4R Tensiometer	Above OMC 150 - 550 Below OMC 1000 - 2000	Above OMC 800 - 1000 Below OMC 1000 - 3000	Above OMC NA Below OMC 1500 - 4000	Above OMC 5 - 25 Below OMC 5 - 30	Above OMC 15 - 40 Below OMC 35 - 150	Above OMC NA Below OMC 15 - 65	0.6 kPa to 4 kPa (4% to 15% of the respective mean values)	0.4 kPa to 2 kPa (5% to 6% of the respective mean values)	Soil matric suction: ± 3.5 kPa
TDR Probe (CS605)	Instantaneous	Instantaneous	Instantaneous	Instantaneous	Instantaneous	Instantaneous	Dielectric const.: 0.05 to 0.46 (1% to 7% of the respective mean values)	Dielectric const.: 0.09 to 0.17 (2% to 4% of the respective mean values)	MC: ± 3.4% Soil matric suction: ± 30 kPa
WCR Probe (CS616)	Instantaneous	Instantaneous	Instantaneous	Instantaneous	Instantaneous	Instantaneous	0.17 μs to 0.6 μs (0.8% to 2.4% of the respective mean values)	0.14 μs to 0.18 μs (0.7% to 0.8% of the respective mean values)	MC: ± 2.5% Soil matric suction: ± 40 kPa
HD Sensor (229)	Above OMC 5 - 5100 Below OMC 1500 - 8500	Above OMC 1000 - 1500 Below OMC 2500 - 7000	Above OMC NA Below OMC 2000 - 6500	Above OMC 5 - 3200 Below OMC 700 - 5500	Above OMC 200 - 500 Below OMC 1200 - 4600	Above OMC NA Below OMC 1000 - 2600	0.03°C to 0.17°C (4% to 11% of the respective mean values)	0.01°C to 0.05°C (1% to 4% of the respective mean values)	Soil matric suction: ± 11 kPa
GM Sensor (WM 200)	Above OMC 300 - 22400 Below OMC 3000 - 17000	Above OMC 4500 - 6400 Below OMC 3300 - 14500	Above OMC NA Below OMC 300 - 12000	Above OMC 20 - 14000 Below OMC 1300 - 13000	Above OMC 2100 - 4100 Below OMC 1400 - 8000	Above OMC NA Below OMC 25 - 6400	0.11 kohm to 20.09 kohm (20% to 99% of the respective mean values)	0.29 kohm to 1.05 kohm (6% to 40% of the respective mean values)	Soil matric suction: ± 15 kPa

Notes :
(1) Variability is calculated as the difference of the measured values (range of variation) between individual sensors of the same type at specific moisture contents. In evaluating the variability of GM sensors, the obvious anomalous value of 34.18 kΩ (see Table 21) was ignored.
(2) The accuracy is determined based on 95% confidence levels of standard deviation from the respective empirical relationships established in the present study.

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Table 24 - Merits and Limitations of the Tested Sensors

Sensors	Merits	Limitations
SWT4R Tensiometers	• Provide direct measurement of soil matric suction. • Involve little volume of water flow and hence response time is relatively rapid. • Modest variability in measurements between different sensors. • Good repeatability and reasonable accuracy for soil suction measurement.	• Operate up to a suction value of about 90 kPa only due to water cavitation and possible air trapped in the system during installation. • Require filling and refilling of water in the high air entry filter. • Use of a porous filter may be subject to additional capillary hysteresis during transient state measurements.
CS605 TDR Probes	• Provide instantaneous response. • Require no water transfer to and from the sensor. • Saturation of sensor is not required. • Small variability in dielectric constants measured. • Good repeatability and reasonable accuracy for moisture content measurement.	• Only provide an indirect measurement of soil suction. • Need to establish empirical relationship between soil suction and dielectric constant. • Poor accuracy for soil suction measurement.
CS616 WCR Probes	• Provide instantaneous response. • Require no water transfer to and from the sensor. • Saturation of sensor is not required. • Small variability in output period measured. • Good repeatability and reasonable accuracy for moisture content measurement.	• Only provide an indirect measurement of soil suction. • Need to establish empirical relationship between soil suction and output period. • Poor accuracy for soil suction measurement.
229 HD Sensors	• Able to operate with suction above 90 kPa. • Do not require to fill water in the sensor from time to time (except that saturation of the sensor is needed). • Modest variability in measurements between different sensors.	• Long response time particularly when the soil sample is drier than the OMC. • Only provide an indirect measurement of soil suction. • Need to establish empirical relationship between soil suction and temperature change. • Insensitive at low matric suction (e.g. below 10 kPa). • Use of a porous tip element may be subject to additional capillary hysteresis during transient state measurements.
Watermark GM 200 Sensors	• Able to operate with suctions above 90 kPa. • Do not require to fill water in the sensor from time to time (except that saturation of the sensor is needed).	• Long response time particularly when the soil sample is drier than the OMC. • Need to establish empirical relationship between soil suction and electrical resistance. • Insensitive at low matric suction (e.g. below 5 kPa). • Large sensor-to-sensor variability and poor repeatability in measurement. • Possible ageing due to dissolution of gypsum. • Use of a porous tip element may be subject to additional capillary hysteresis during transient state measurements.
CS210 Enclosure RH Sensors	Not viable for this application due to condensation problem in soil.	

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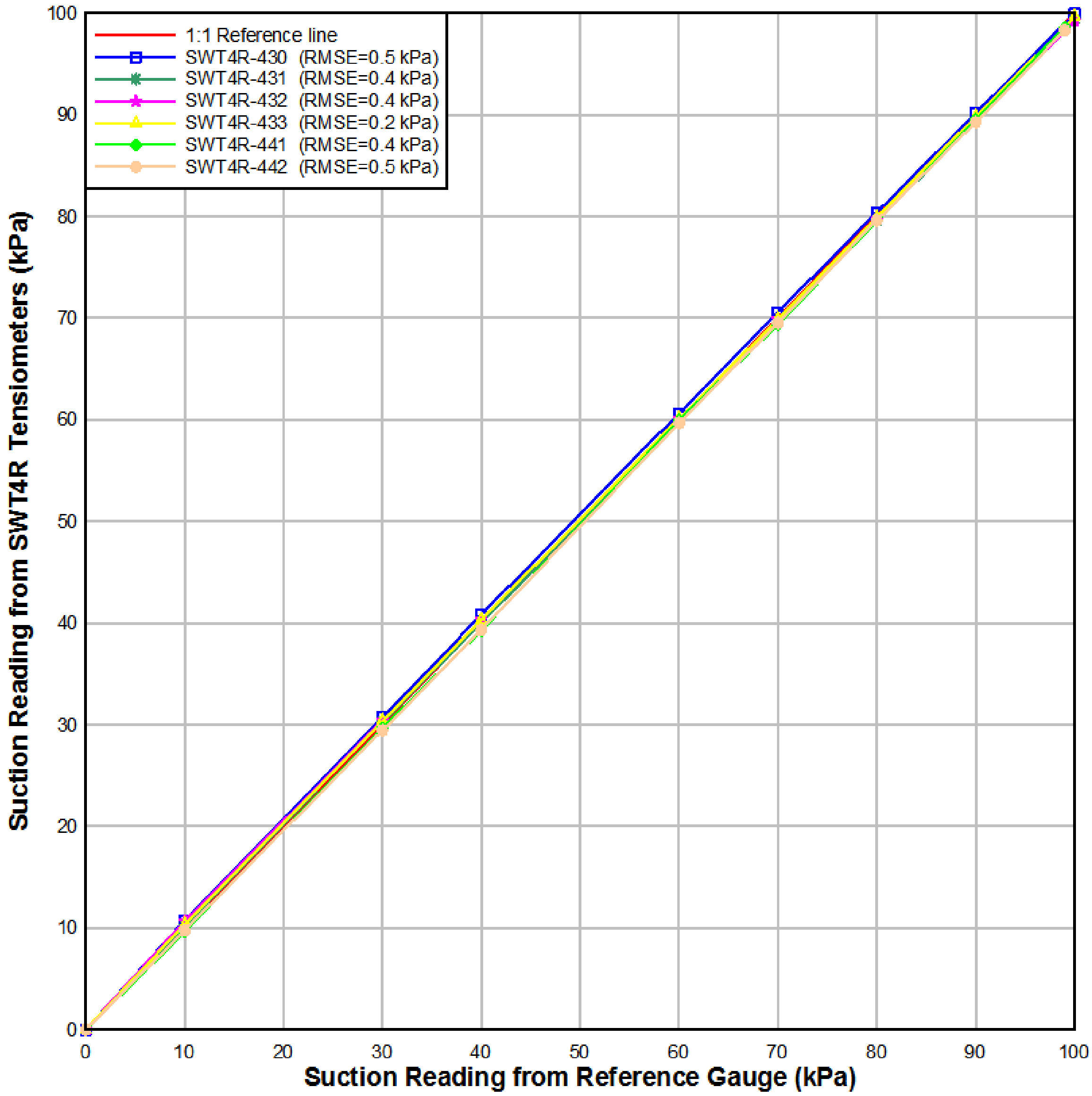

Figure 1 - Verification of SWT4R Tensiometers

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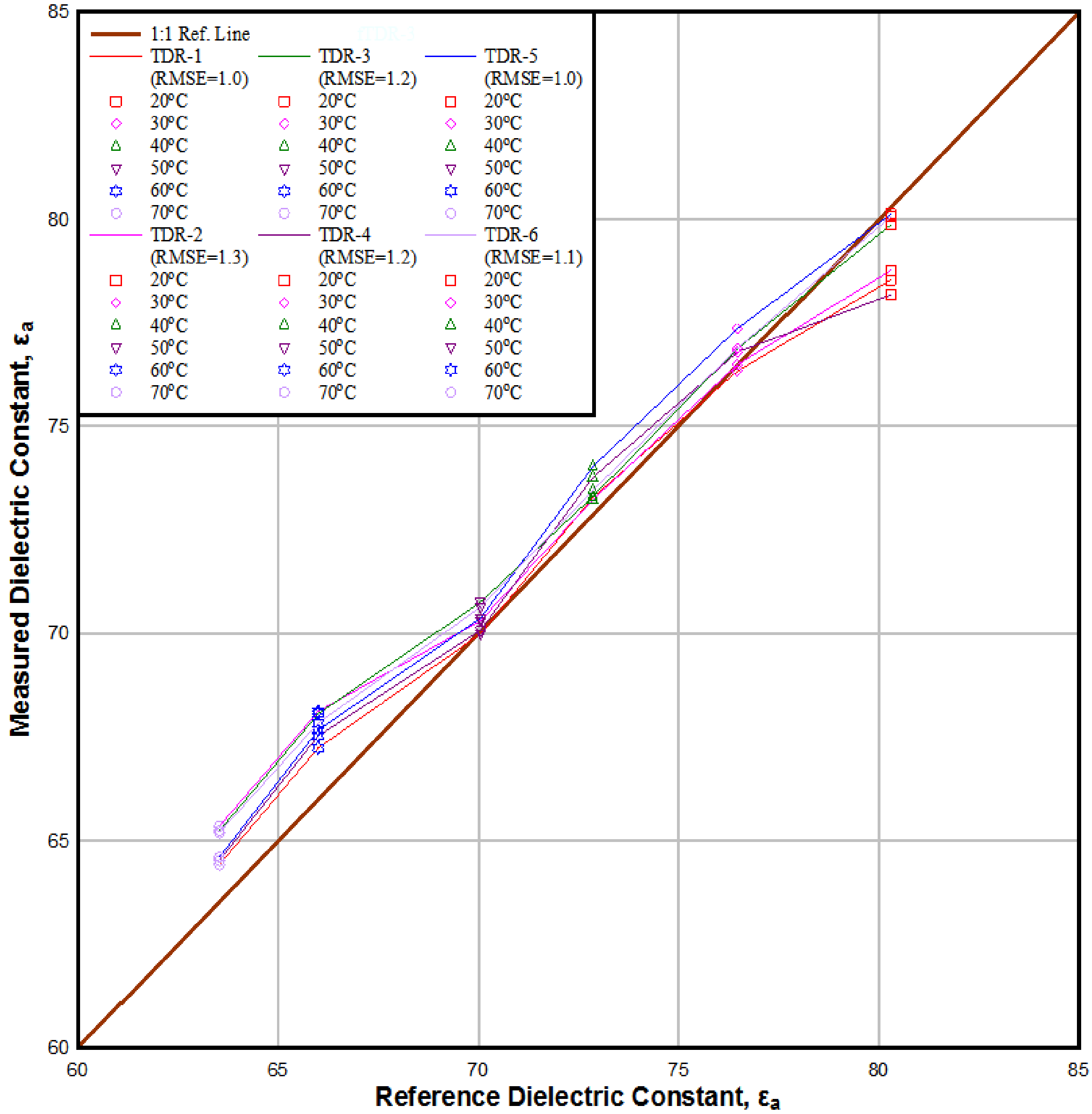

Note: The reference values are the average values based on the estimates/prescribed values by Coym (2004), Meissner & Wentz (2004) and Campbell Scientific Inc. (2009b).

Figure 2 - Verification of CS605 TDR Probes

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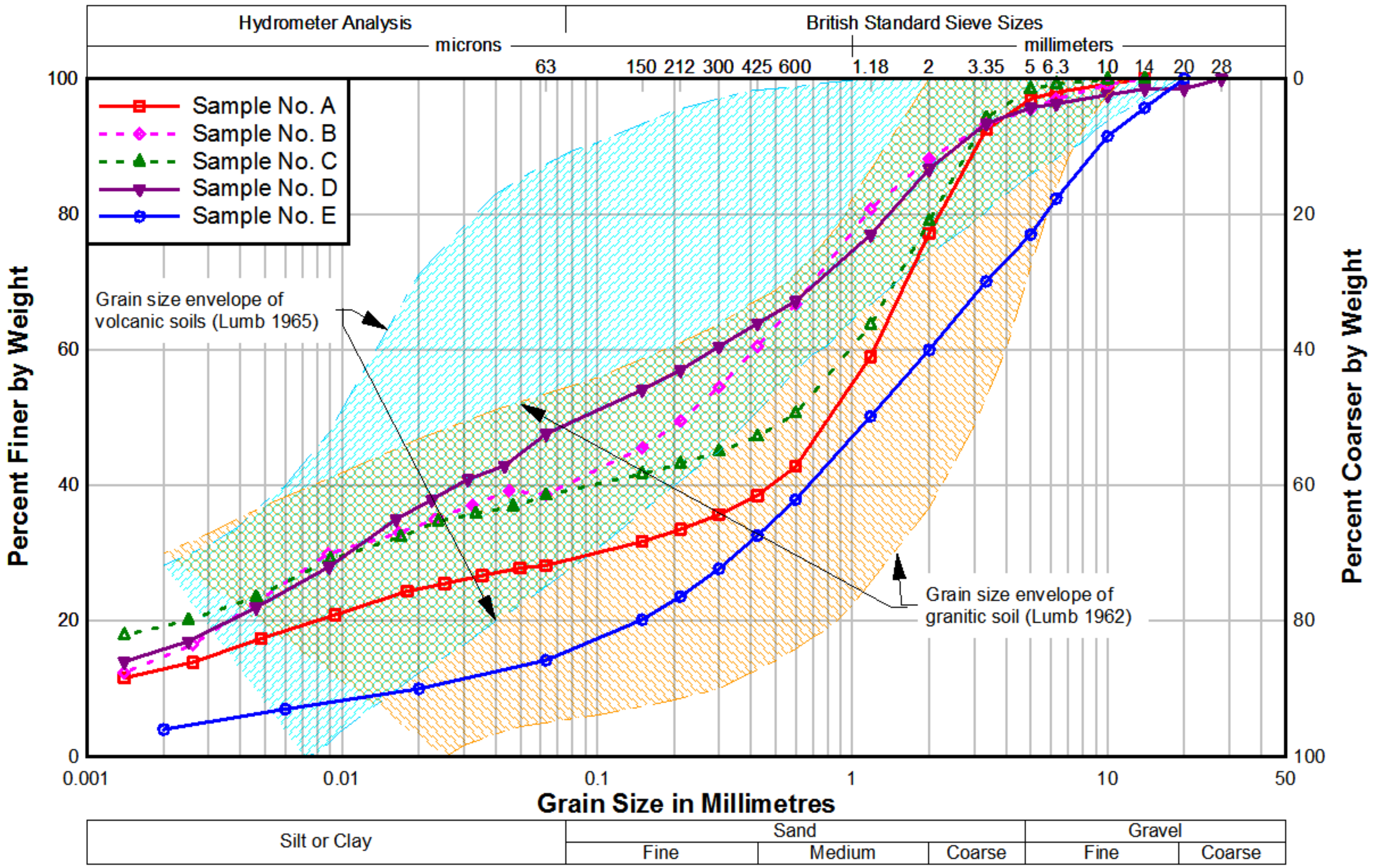

Note: Samples A, B and C (CDG) were obtained from Anderson Road, whereas Soil Sample D (CDV) and Sample E (CDG) were obtained from Lantau Island and Shek O Quarry, respectively. Comparatively, Samples D, A and E, were taken to represent the "fine-grained", "medium-grained" and "coarse-grained" soils respectively for the present study. It should be noted that of 5% fines has been added to Sample E to improve its workability for sample preparation and sensor installation.

Figure 3 - Particle Size Distribution of the Different Soil Samples

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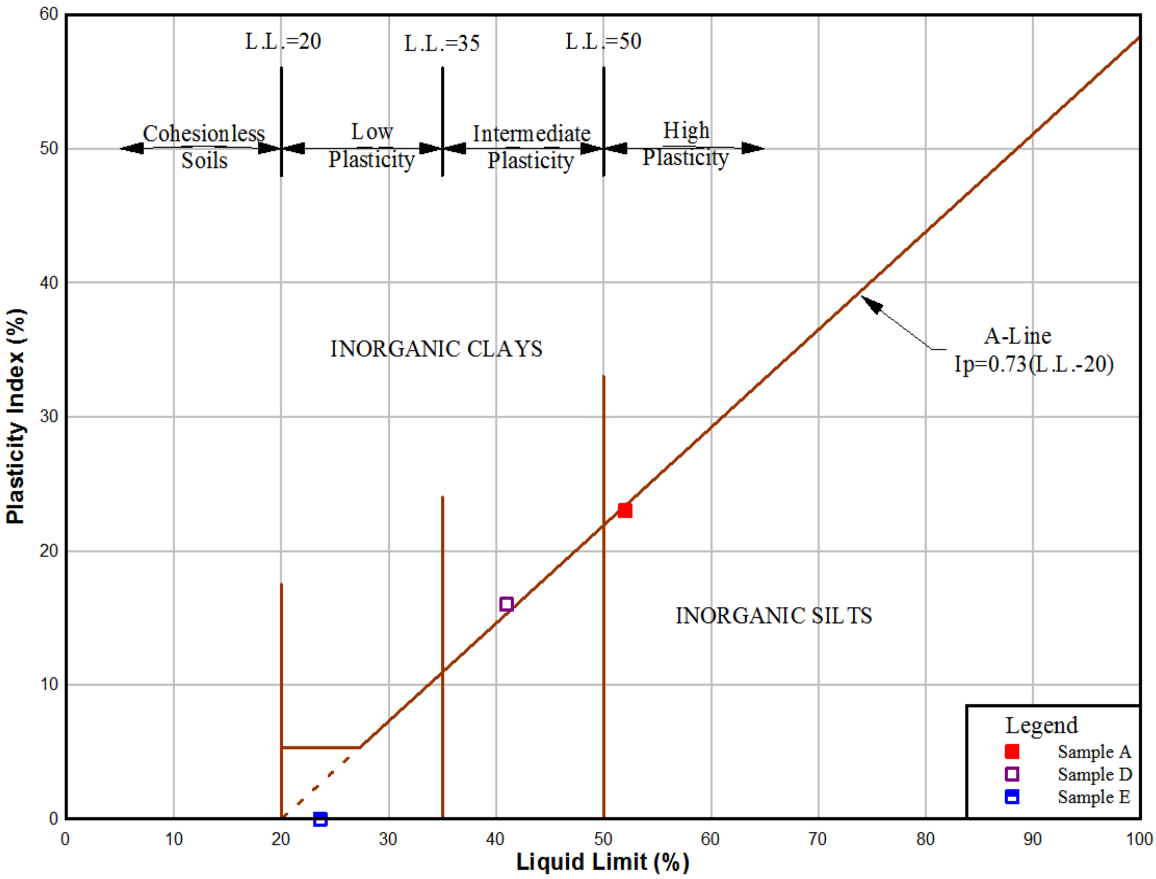

Figure 4 - Plasticity Chart

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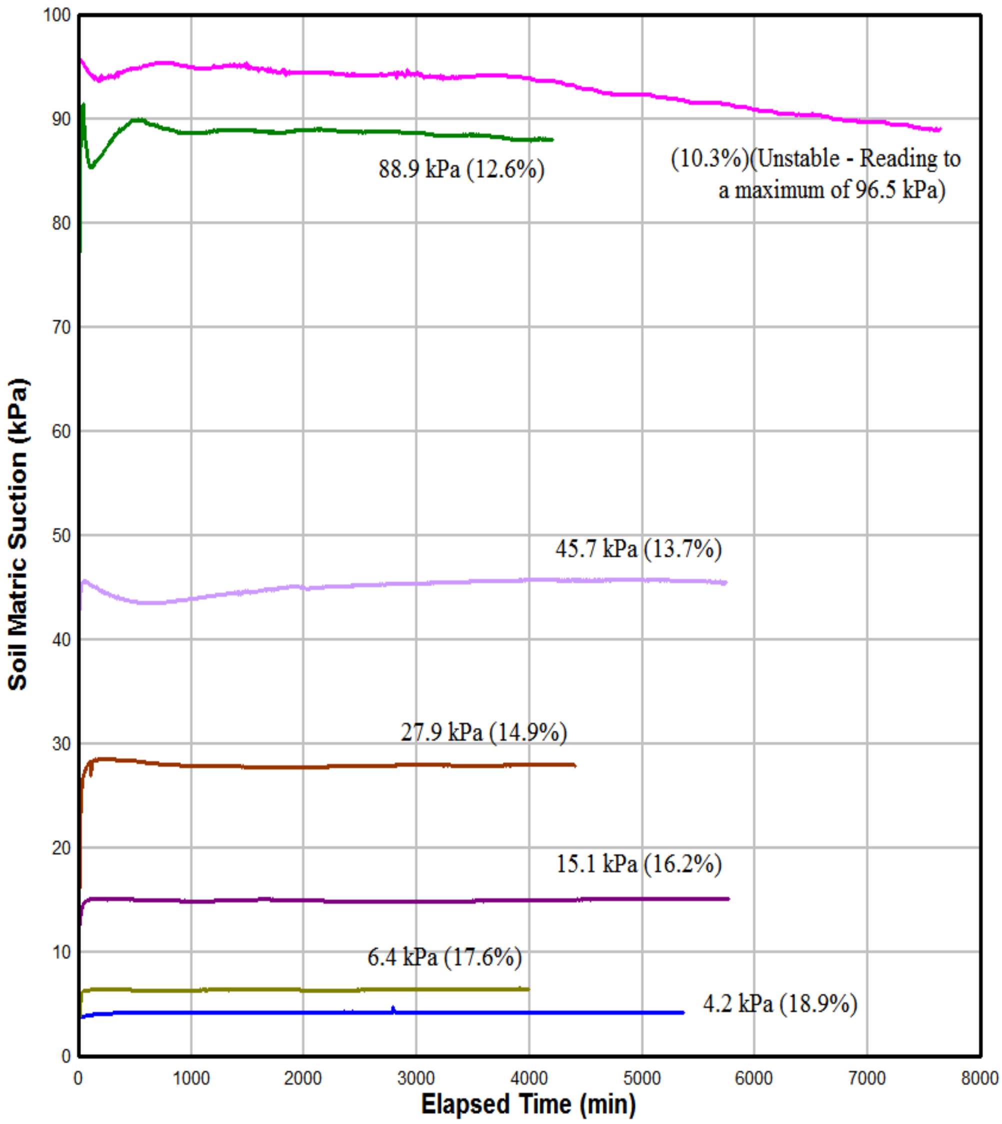

Notes: (1) The optimum moisture content of the soil sample is 15%.
(2) The response time is given below:

Tensiometer No.	Sample Moisture Content (%)	Stable Tensiometer Reading (kPa)	Response Time (min)	Response Time to Reach within ± 10% of the Stable Reading (min)
SWT4R-430	7.3	-	-	-
	10.3	Unstable	Unstable	Unstable
	12.6	88.9	1500	15
	13.7	45.7	2000	10
	14.9	27.9	1000	20
	16.2	15.1	150	20
	17.6	6.4	150	20
	18.9	4.2	150	10

Figure 5 - Readings from Tensiometer No. SWT4R-430 in Soil Sample A

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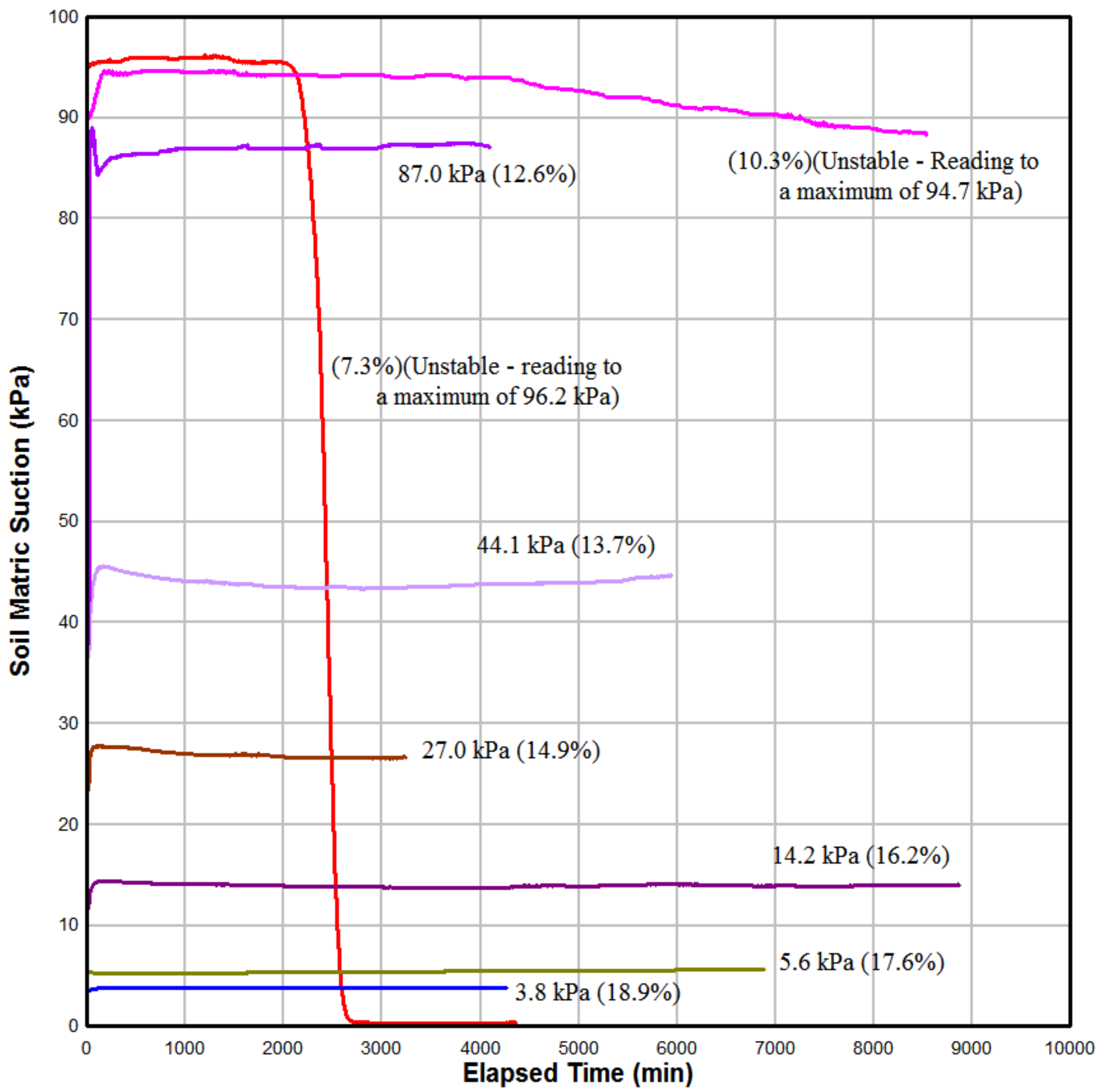

Notes: (1) The optimum moisture content of the soil sample is 15%.
(2) The response time is given below:

Tensiometer No.	Sample Moisture Content (%)	Stable Tensiometer Reading (kPa)	Response Time (min)	Response Time to Reach within ± 10% of the Stable Reading (min)
SWT4R-431	7.3	Unstable	Unstable	Unstable
	10.3	Unstable	Unstable	Unstable
	12.6	87.0	1000	25
	13.7	44.1	1000	25
	14.9	27.0	1000	15
	16.2	14.2	550	25
	17.6	5.6	150	5
	18.9	3.8	200	15

Figure 6 - Readings from Tensiometer No. SWT4R-431 in Soil Sample A

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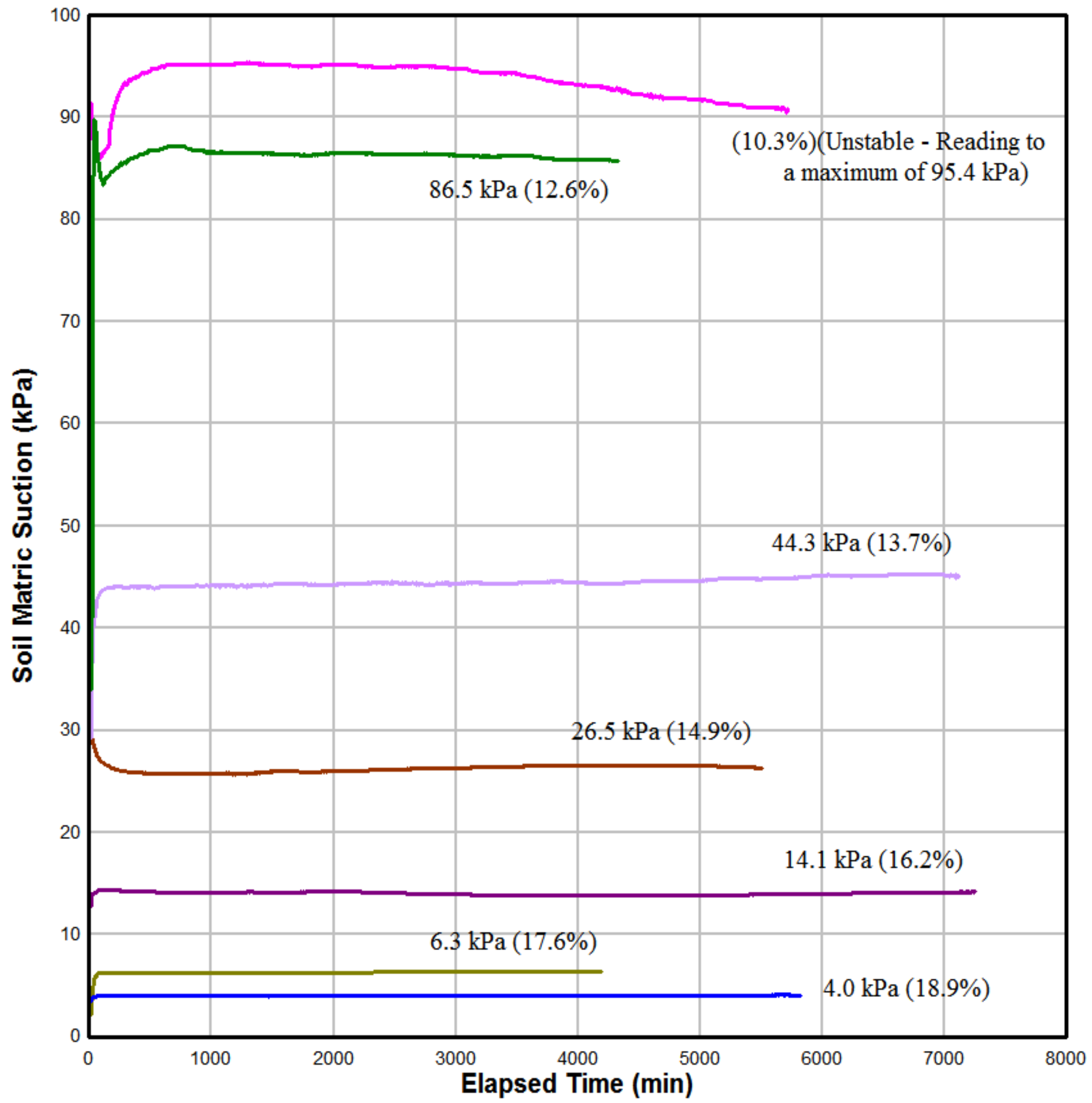

Notes: (1) The optimum moisture content of the soil sample is 15%.
(2) The response time is given below:

Tensiometer No.	Sample Moisture Content (%)	Stable Tensiometer Reading (kPa)	Response Time (min)	Response Time to Reach within ± 10% of the Stable Reading (min)
SWT4R-432	7.3	-	-	-
	10.3	Unstable	Unstable	Unstable
	12.6	86.5	1000	30
	13.7	44.3	2000	30
	14.9	26.5	1000	5
	16.2	14.1	150	10
	17.6	6.3	180	25
	18.9	4.0	200	15

Figure 7 - Readings from Tensiometer No. SWT4R-432 in Soil Sample A

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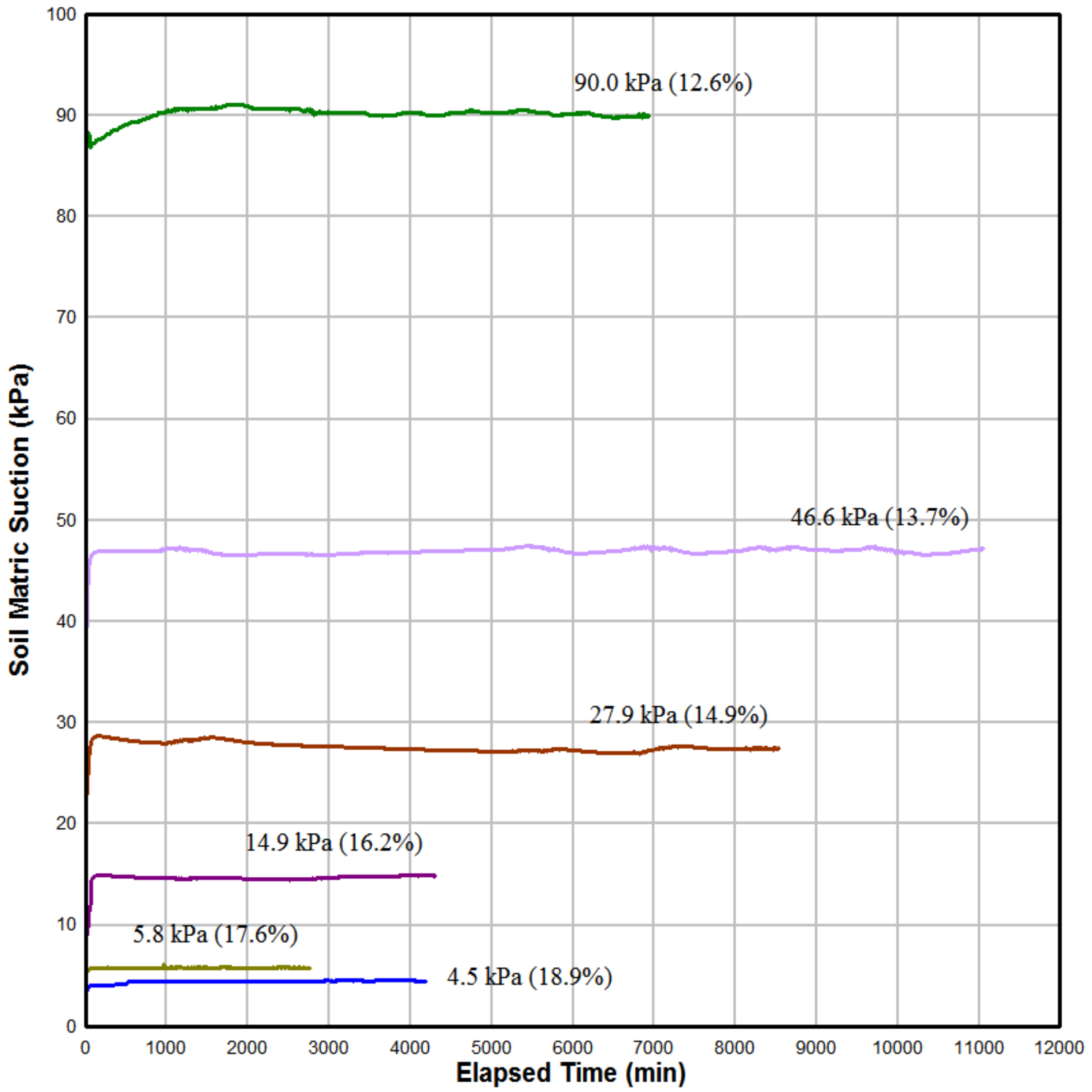

Notes: (1) The optimum moisture content of the soil sample is 15%.
(2) The response time is given below:

Tensiometer No.	Sample Moisture Content (%)	Stable Tensiometer Reading (kPa)	Response Time (min)	Response Time to Reach within ± 10% of the Stable Reading (min)
SWT4R-433	7.3	-	-	-
	10.3	-	-	-
	12.6	90.0	2000	10
	13.7	46.6	2000	20
	14.9	27.9	1000	25
	16.2	14.9	150	25
	17.6	5.8	150	15
	18.9	4.5	550	25

Figure 8 - Readings from Tensiometer No. SWT4R-433 in Soil Sample A

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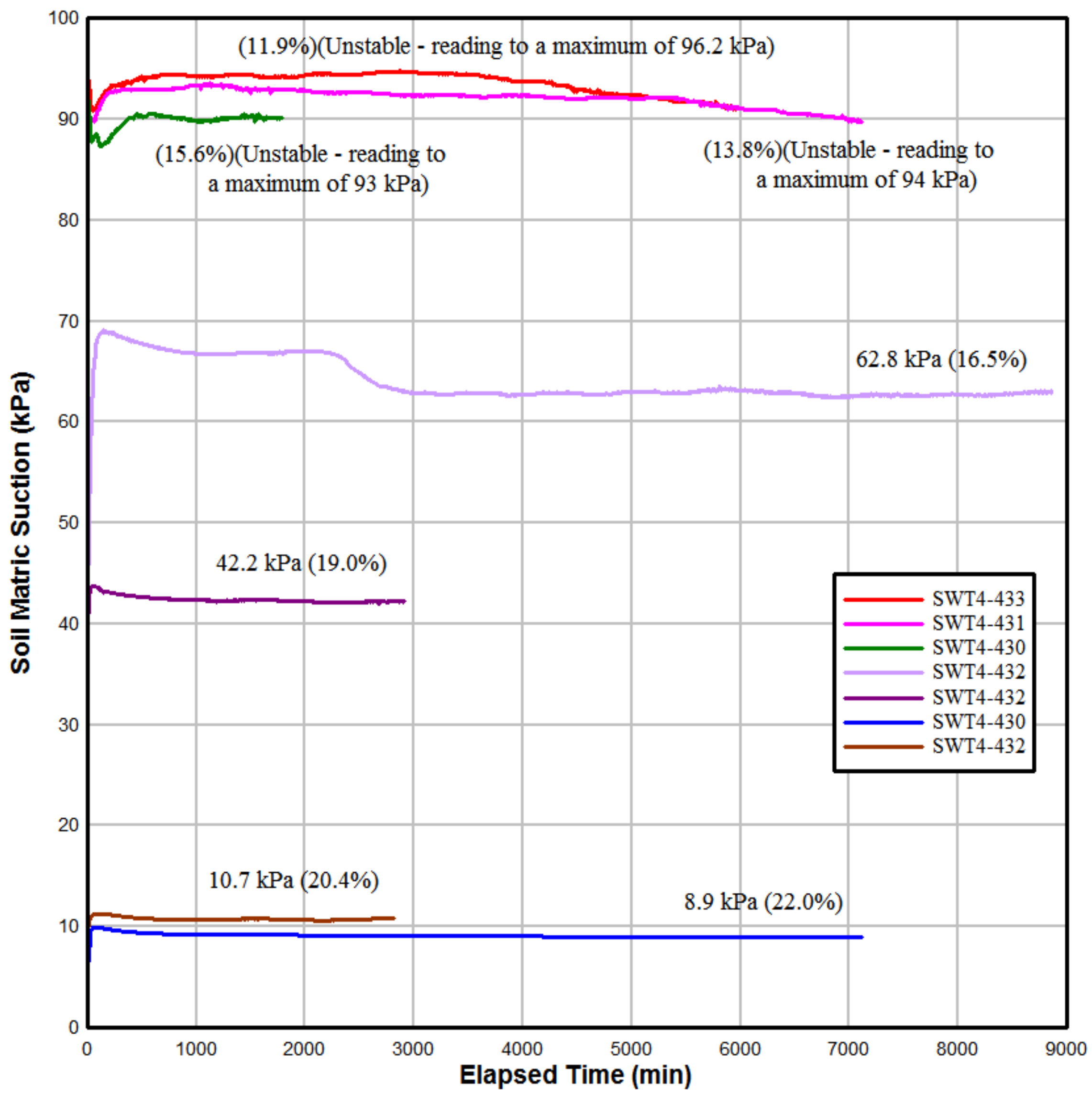

Notes: (1) The optimum moisture content of the soil sample is 19%.
(2) The response time of each tensiometer is given below:

Tensiometer No.	Sample Moisture Content (%)	Stable Tensiometer Reading (kPa)	Response Time (min)	Response Time to Reach within ± 10% of the Stable Reading (min)
SWT4R-433	11.9	Unstable	Unstable	Unstable
SWT4R-431	13.8	Unstable	Unstable	Unstable
SWT4R-430	15.6	Unstable	Unstable	Unstable
SWT4R-432	16.5	62.8	3000	150
SWT4R-432	19.0	42.2	1000	55
SWT4R-432	20.4	10.7	1000	15
SWT4R-430	22.0	8.9	800	40

Figure 9 - Readings from Tensiometers in Soil Sample D

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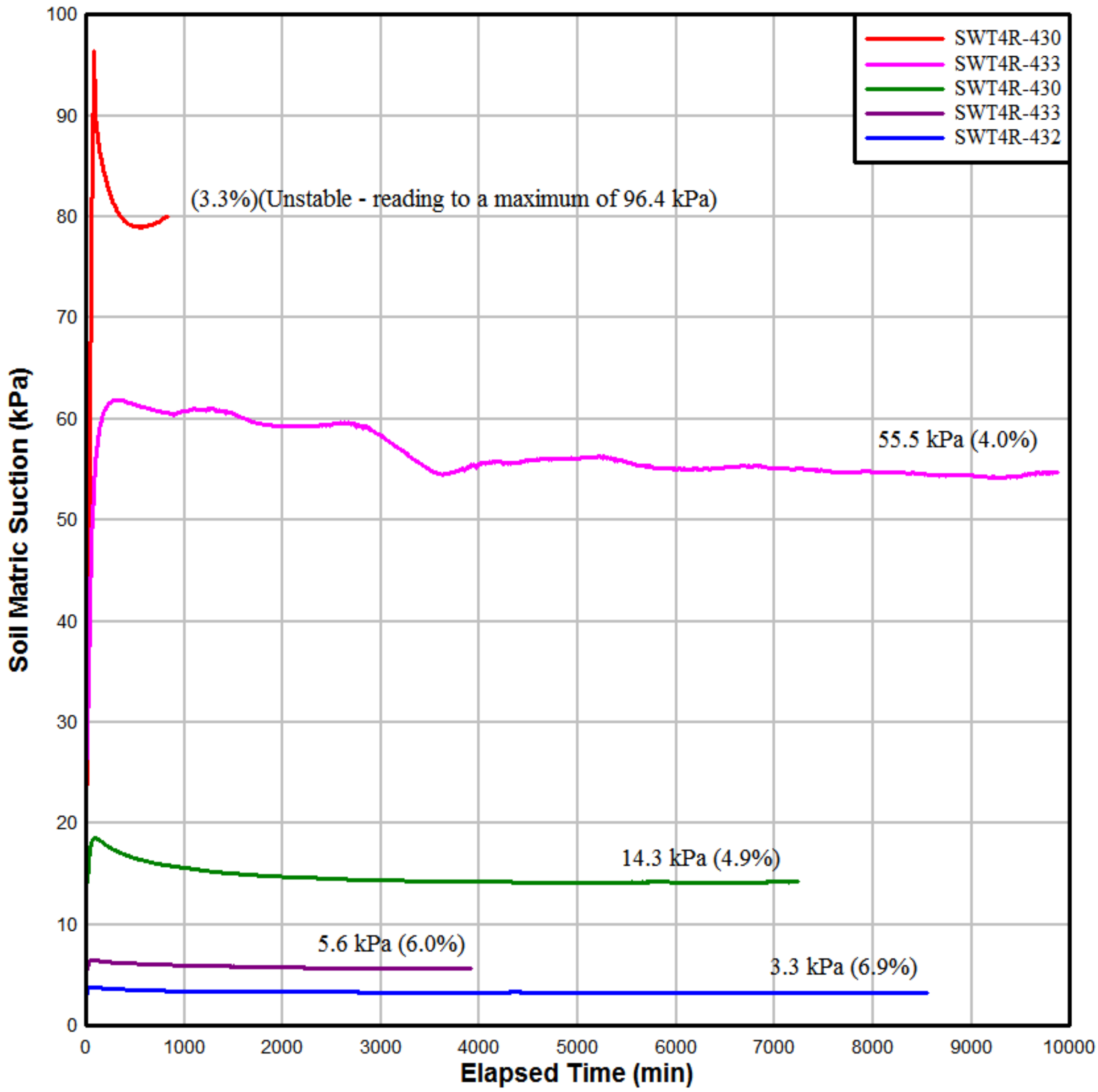

Notes: (1) The optimum moisture content of the soil sample is 19%.
(2) The response time of each tensiometer is given below:

Tensiometer No.	Sample Moisture Content (%)	Stable Tensiometer Reading (kPa)	Response Time (min)	Response Time to Reach within ± 10% of the Stable Reading (min)
SWT4R-430	3.3	Unstable	Unstable	Unstable
SWT4R-433	4.0	55.5	4000	65
SWT4R-430	4.9	14.3	3000	15
SWT4R-433	6.0	5.6	2500	15
SWT4R-432	6.9	3.3	1500	15

Figure 10 - Readings from Tensiometers in Soil Sample E

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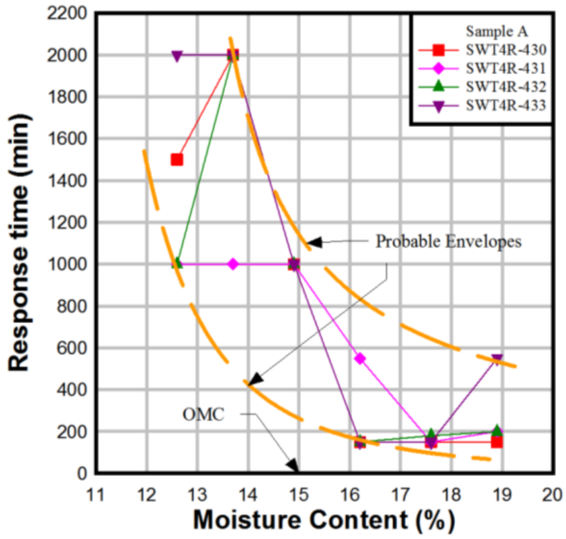
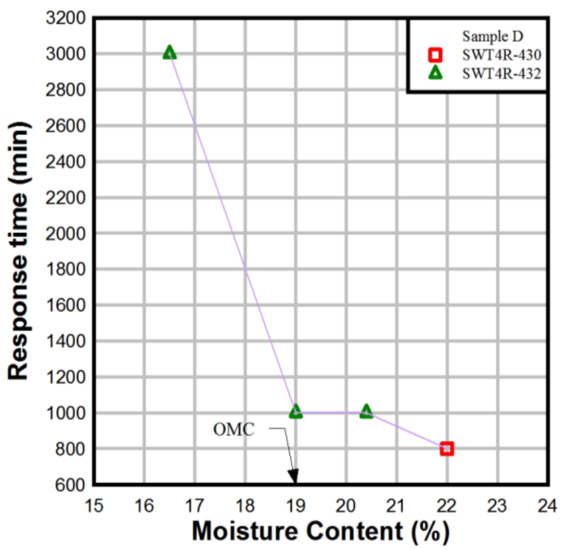
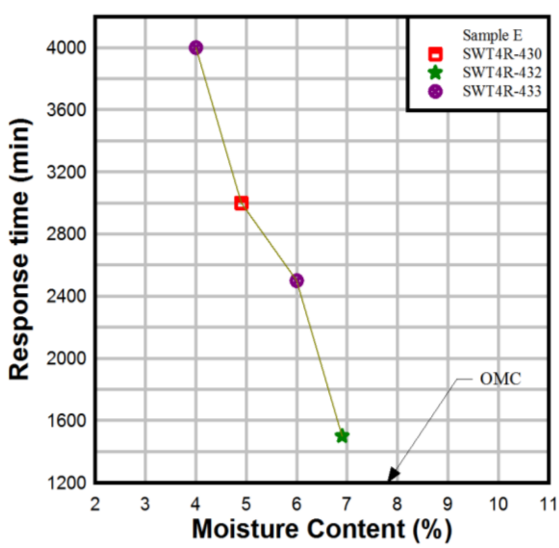


(a) Sample A



(b) Sample D



(c) Sample E

Note: Response time refer to the time when the stable reading was obtained.

Figure 11 - Response Time of Tensiometers in Samples A, D and E

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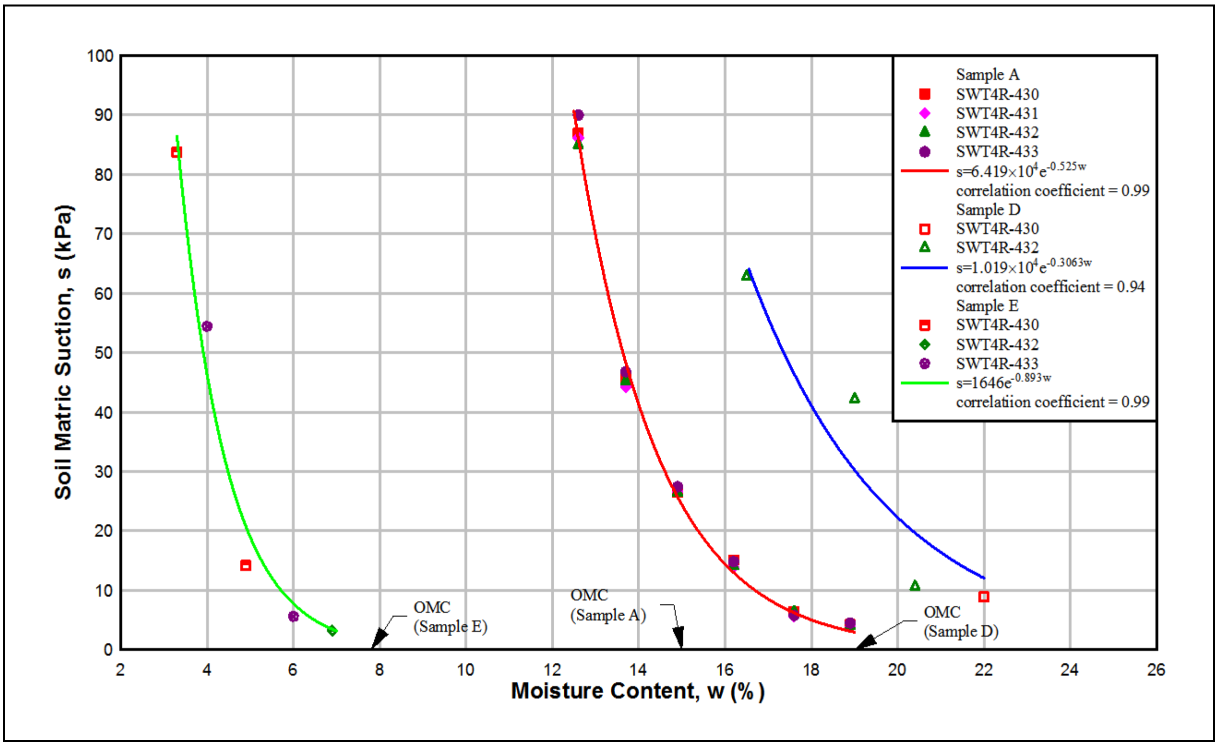
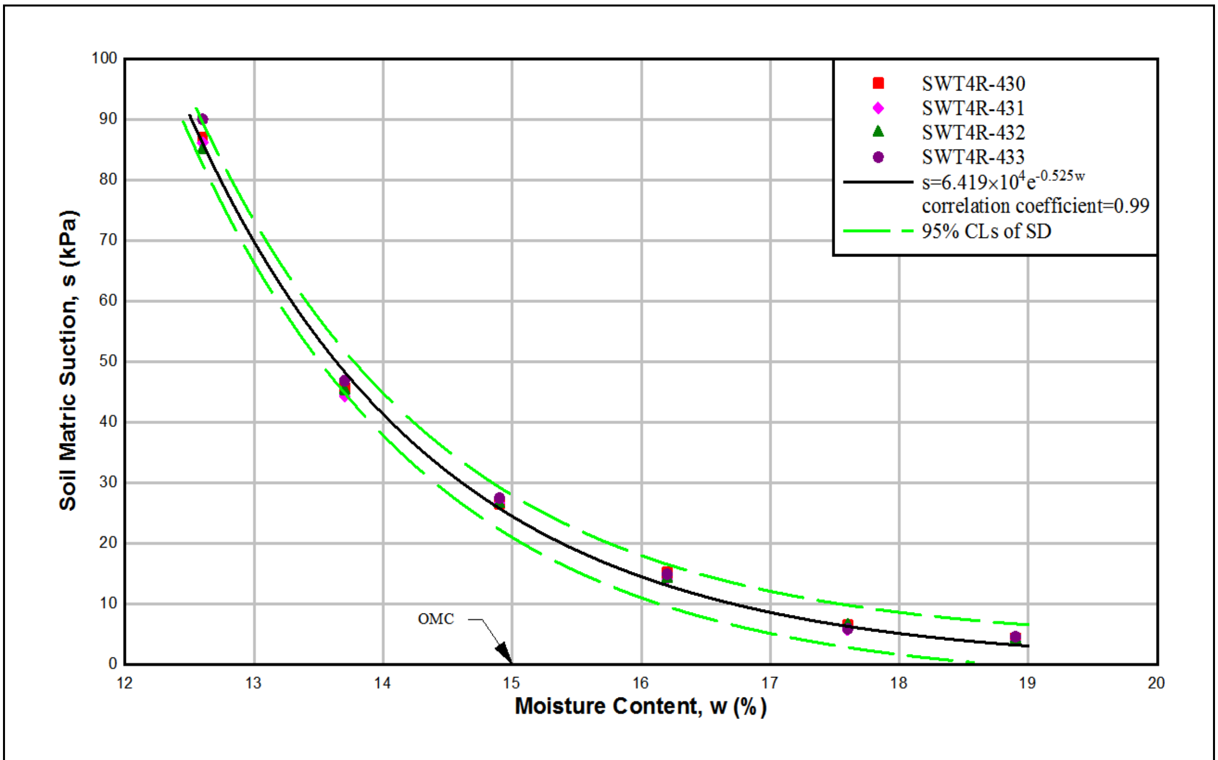


Figure 12 - Relationships between Moisture Content and Soil Matric Suction for Samples A, D and E



Note: "CL" stands for confidence level and "SD" stands for standard deviation.

Figure 13 - Relationship between Moisture Content and Soil Matric Suction for Sample A

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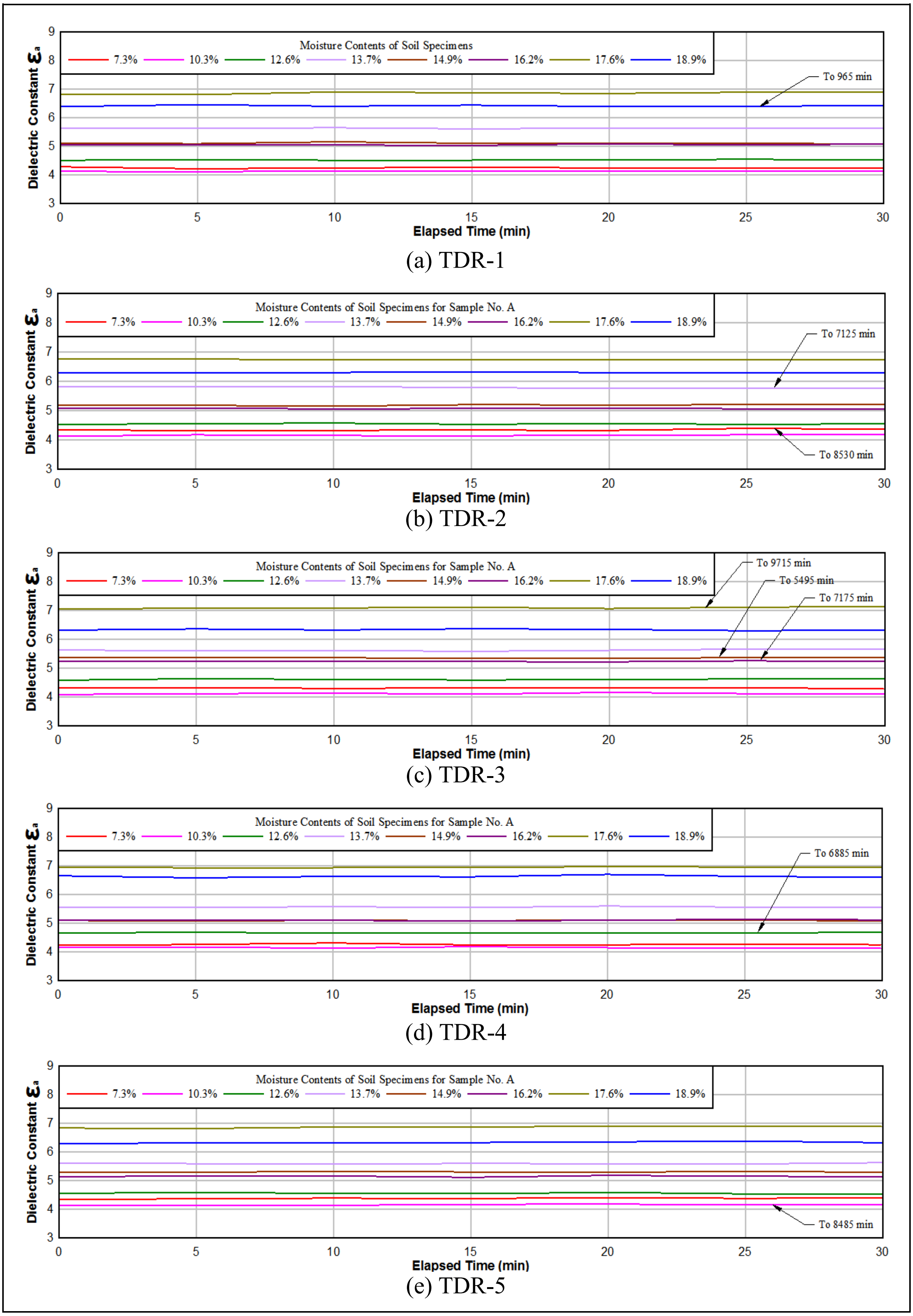

Figure 14 - Dielectric Constants from TDR Probes in Sample A

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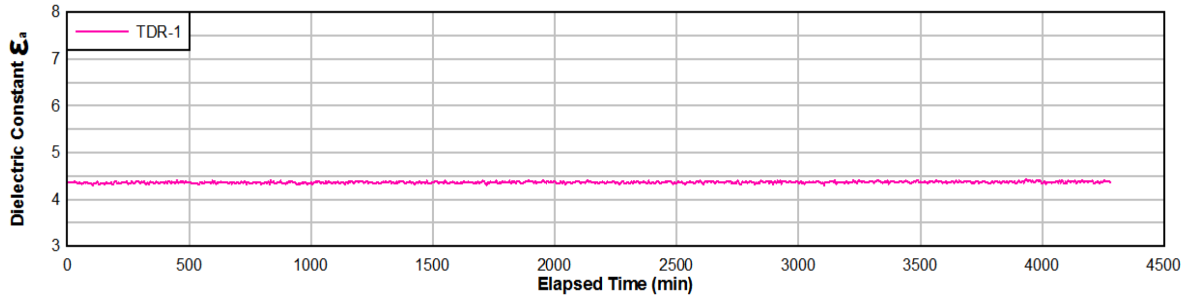
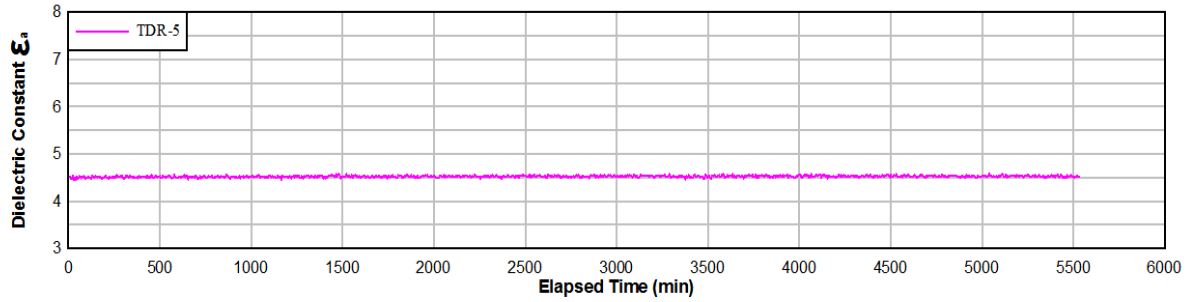
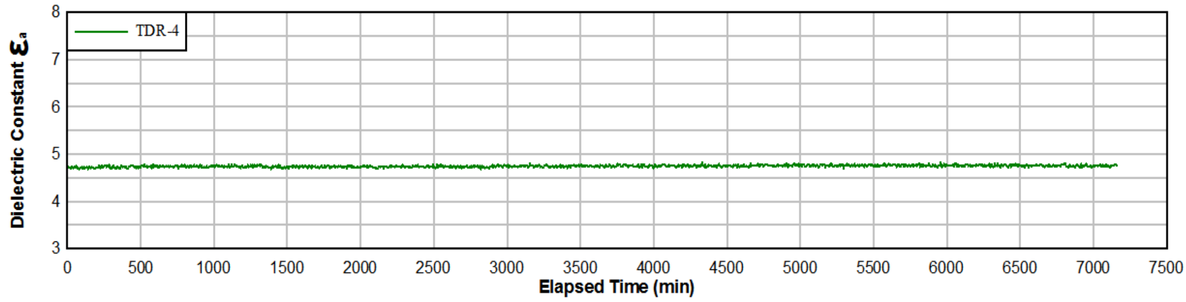


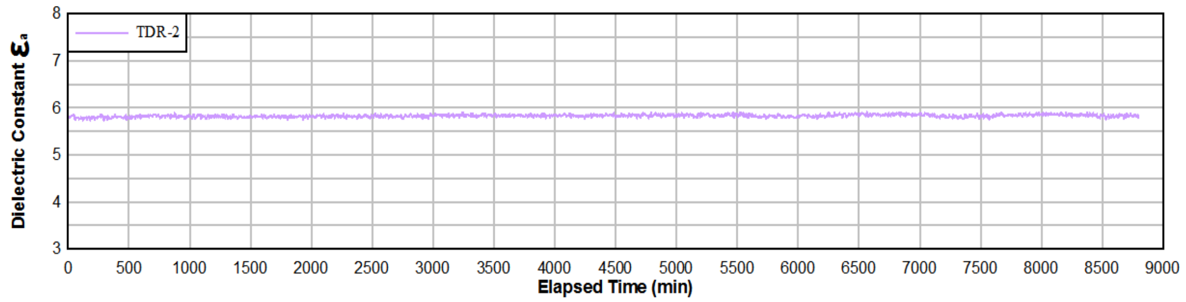
(a) Soil Specimen with Moisture Content of 11.9%



(b) Soil Specimen with Moisture Content of 13.8%



(c) Soil Specimen with Moisture Content of 15.6%



(d) Soil Specimen with Moisture Content of 16.5%

Figure 15 - Dielectric Constants from TDR Probes in Sample D (Sheet 1 of 2)

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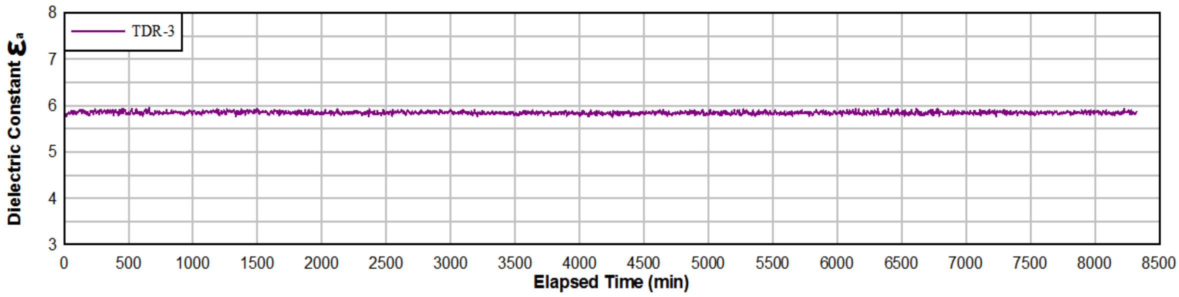
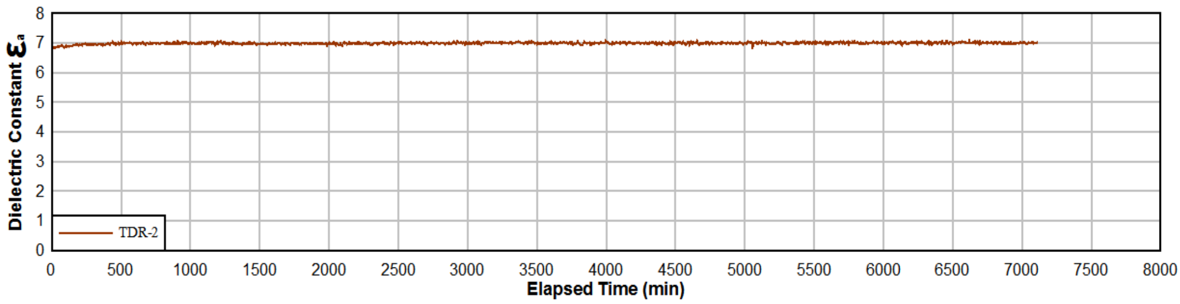
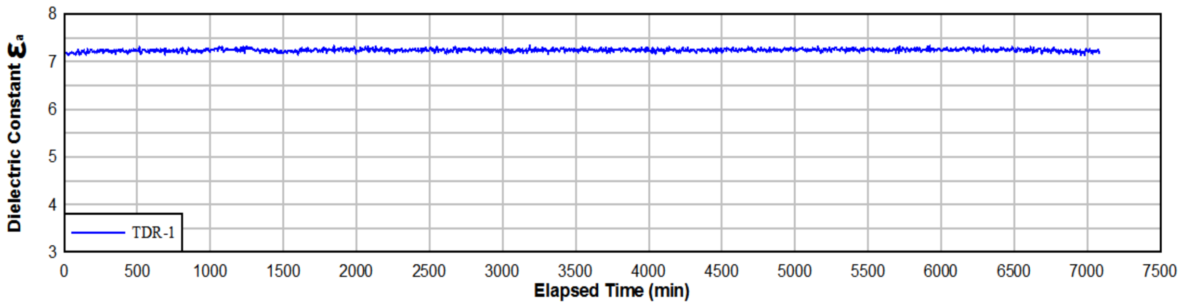


(e) Soil Specimen with Moisture Content of 19.0%



(f) Soil Specimen with Moisture Content of 20.4%



(g) Soil Specimen with Moisture Content of 22.0%

Figure 15 - Dielectric Constants from TDR Probes in Sample D (Sheet 2 of 2)

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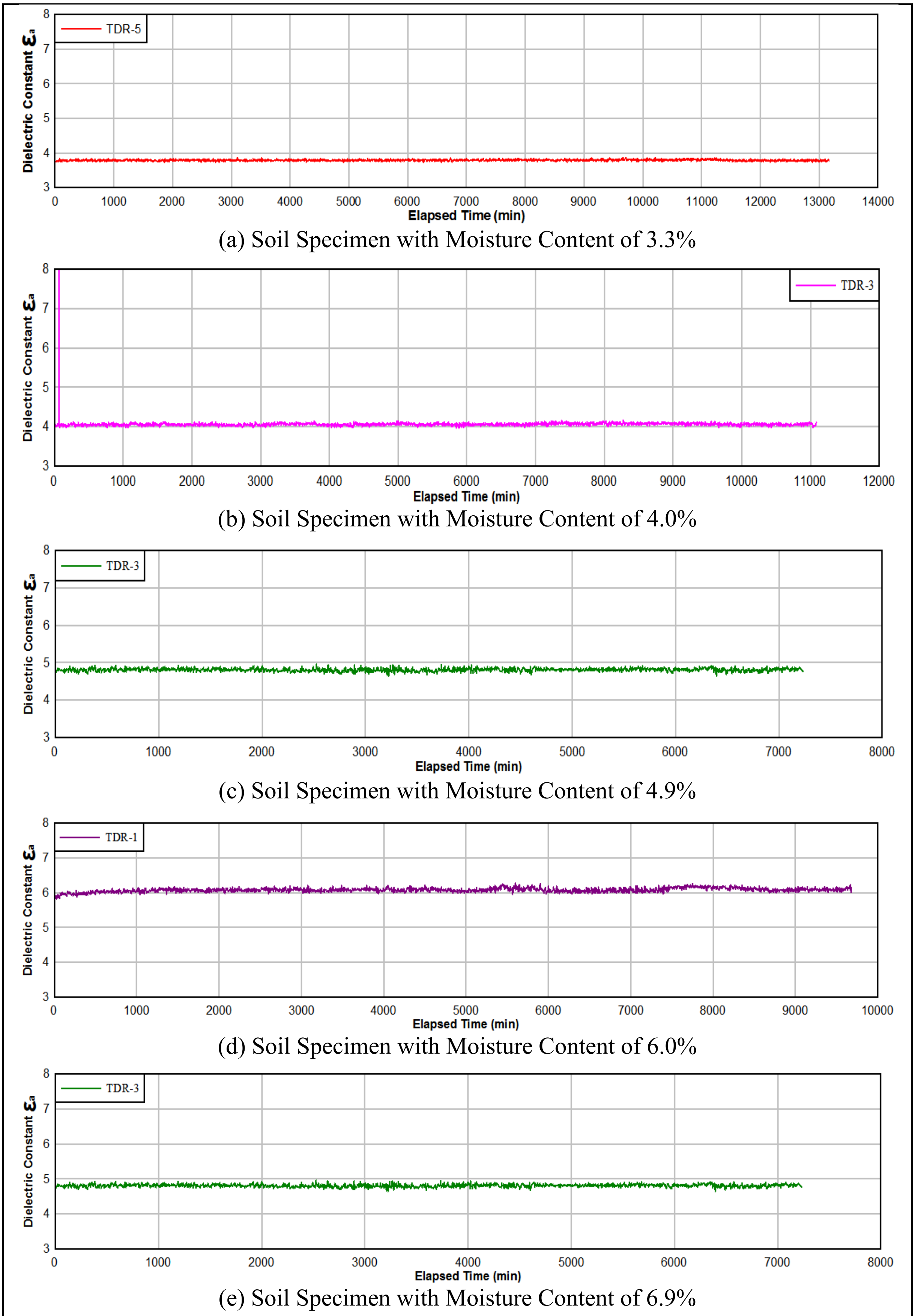

(a) Soil Specimen with Moisture Content of 3.3%

(b) Soil Specimen with Moisture Content of 4.0%

(c) Soil Specimen with Moisture Content of 4.9%

(d) Soil Specimen with Moisture Content of 6.0%

(e) Soil Specimen with Moisture Content of 6.9%

Figure 16 - Dielectric Constants from TDR Probes in Sample E

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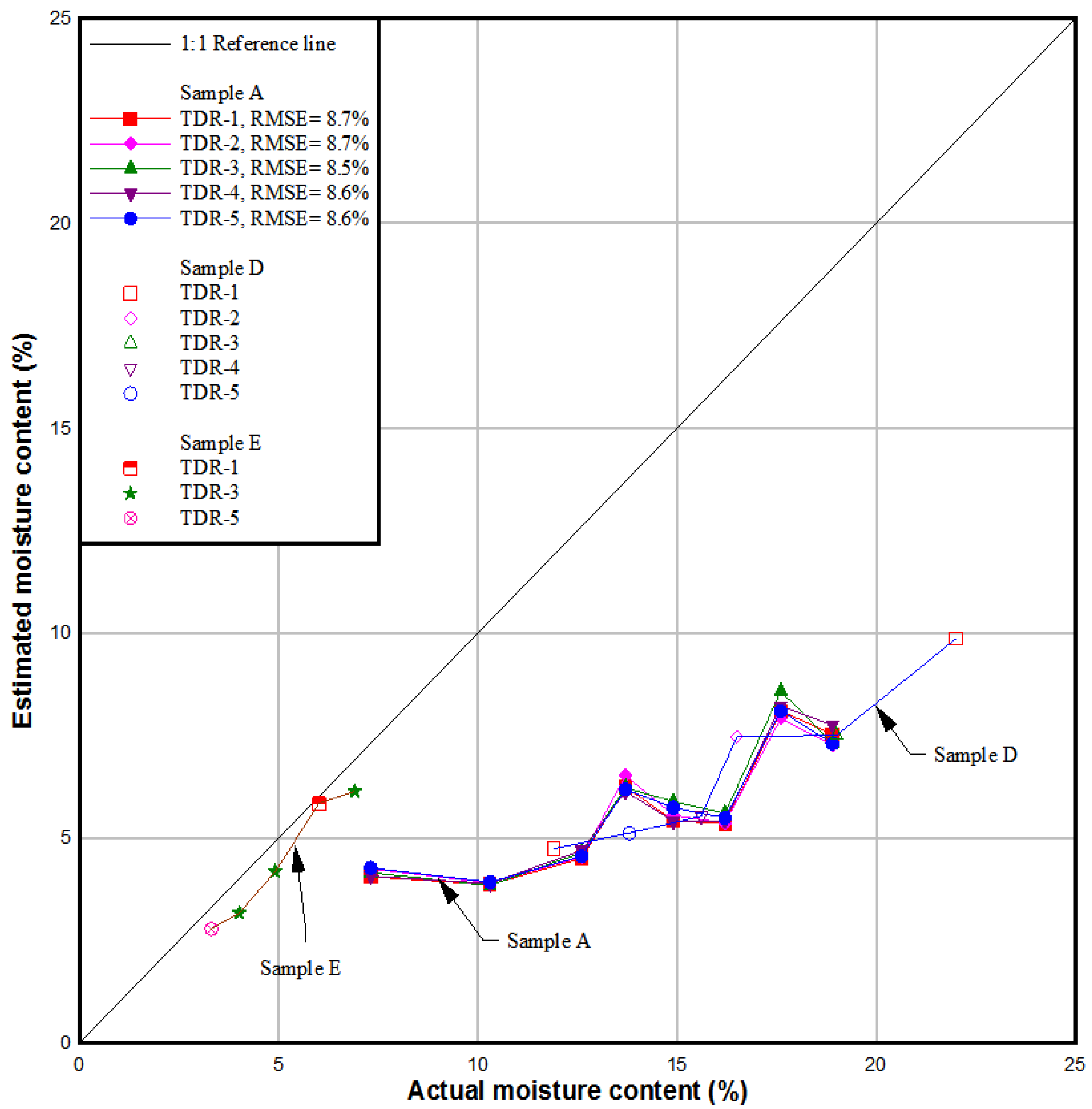

Notes: (1) Moisture contents shown in this figure are gravimetric moisture contents.

(2) The estimated moisture contents were obtained from the following empirical relationship proposed by Topp et al (1980):

$\theta = w\,(\rho_d/\rho_w) = (-530 + 292\varepsilon_a - 5.5\varepsilon_a^2 + 0.043\varepsilon_a^3)/10^4$,

where ε_a is dielectric constant,

θ is volumetric moisture content,

w is gravimetric moisture content,

ρ_d is the dry density of the soil,

ρ_w is the water density.

Figure 17 - Moisture Content Calculated from TDR's Dielectric Constant for Samples A, D and E

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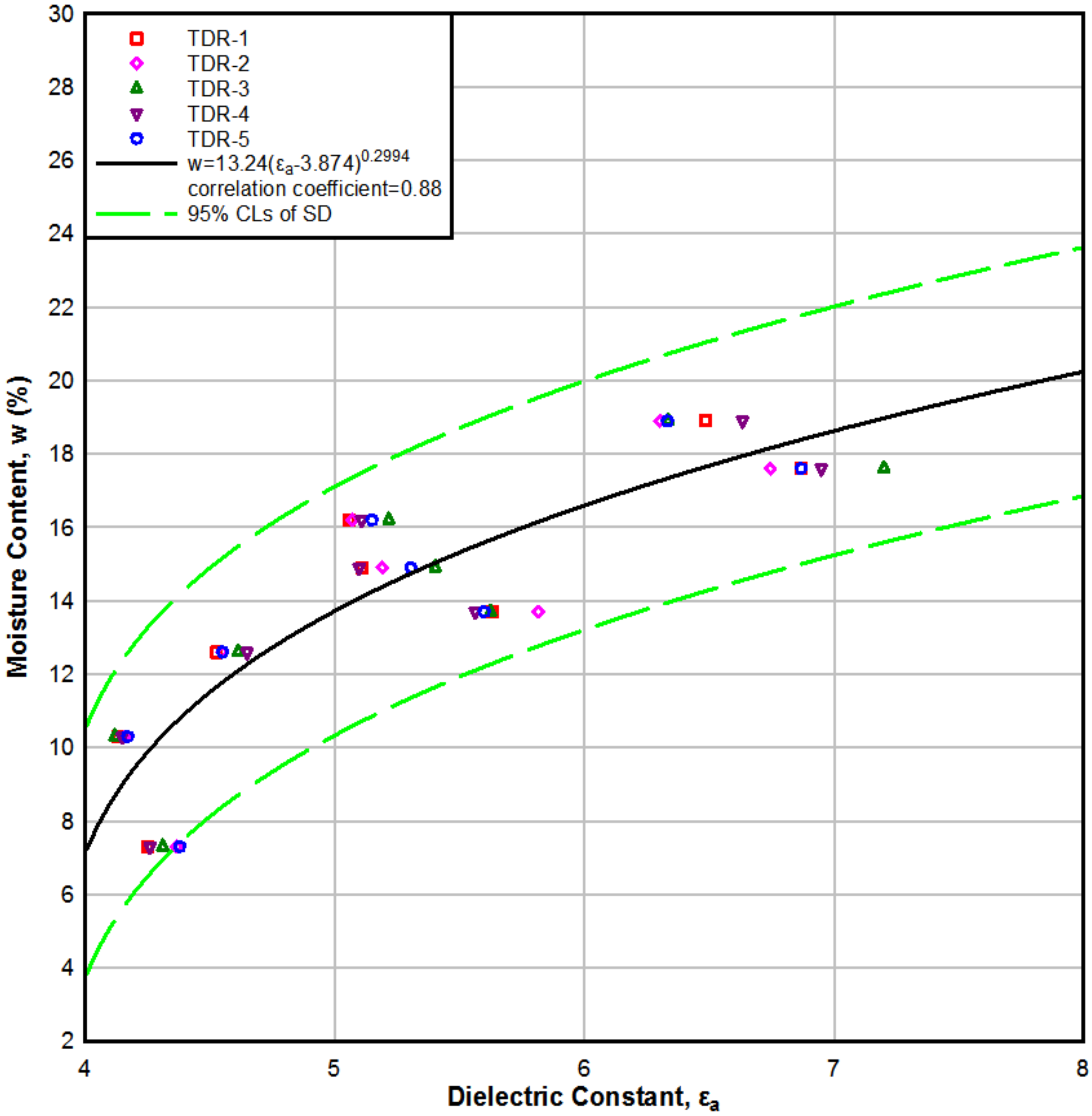

Note: “CL” stands for confidence level and “SD” stands for standard deviation.

Figure 18 - Relationship between TDR’s Dielectric Constant and Moisture Content for Sample A

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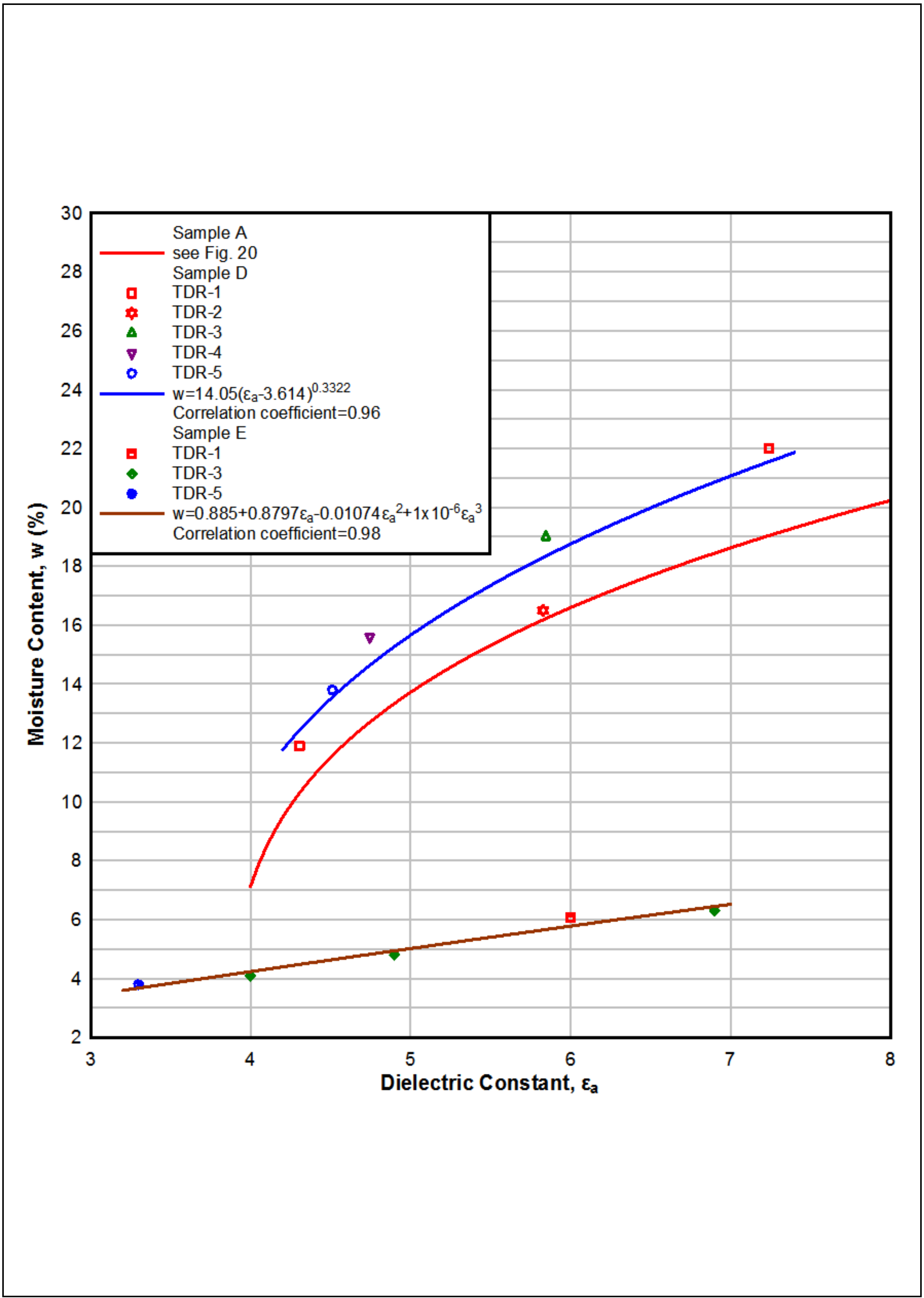

Figure 19 - Relationships between TDR's Dielectric Constant and Moisture Content for Samples A, D and E

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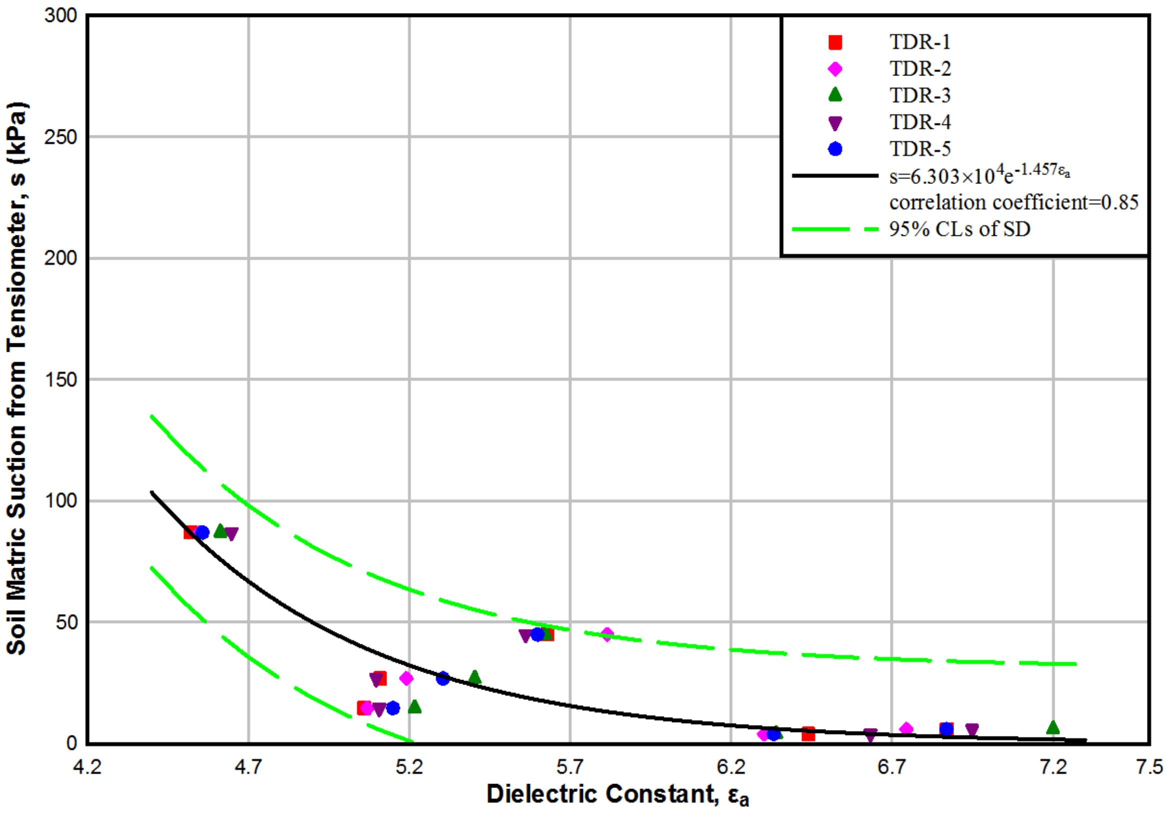

Note: "CL" stands for confidence level and "SD" stands for standard deviation.

Figure 20 - Relationship between TDR's Dielectric Constant and Soil Matric Suction for Sample A

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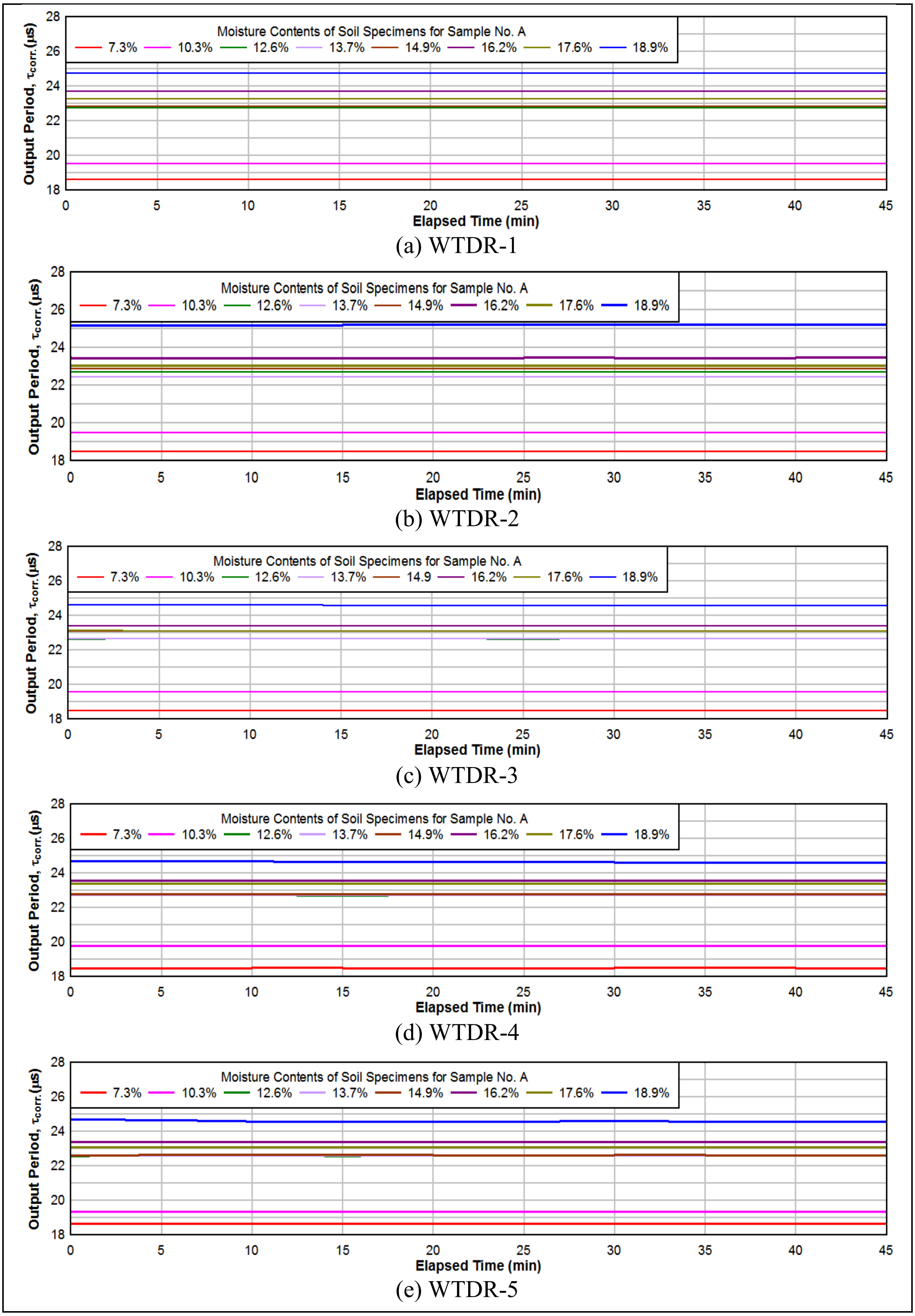

Figure 21 - Output Periods from CS616 WCR Probes in Sample A

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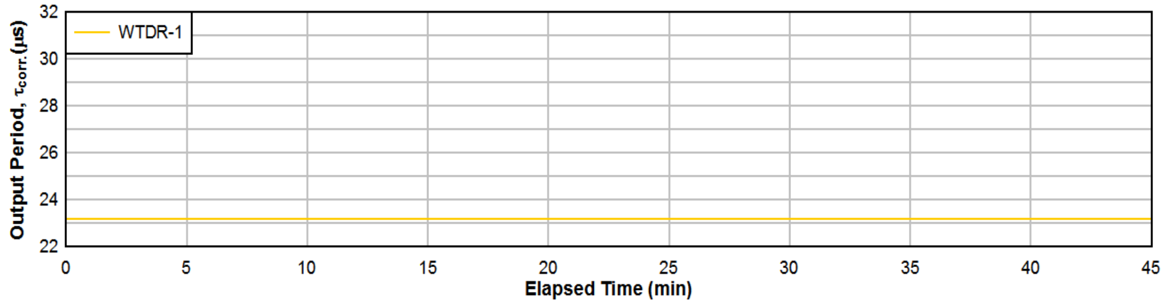
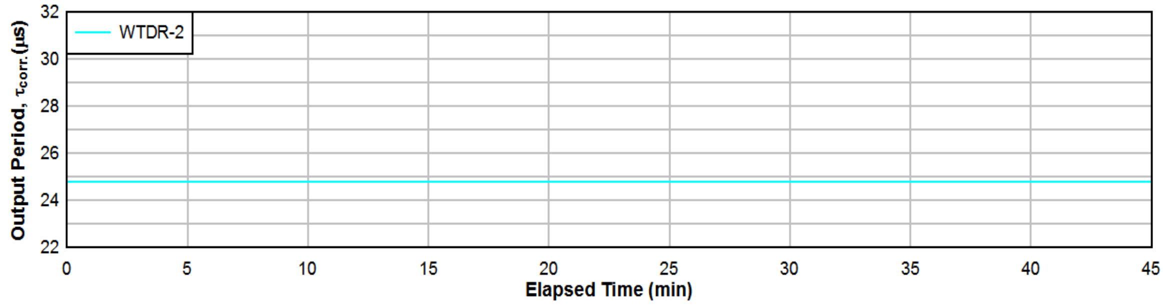
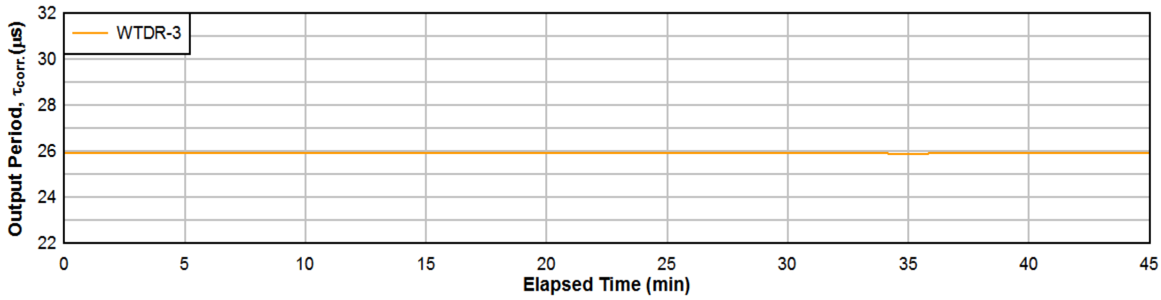


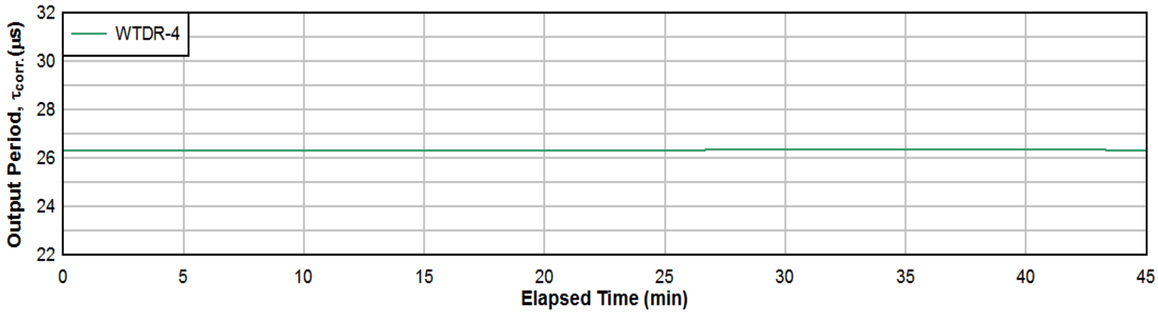
(a) Soil Specimen with Moisture Content of 15.6%



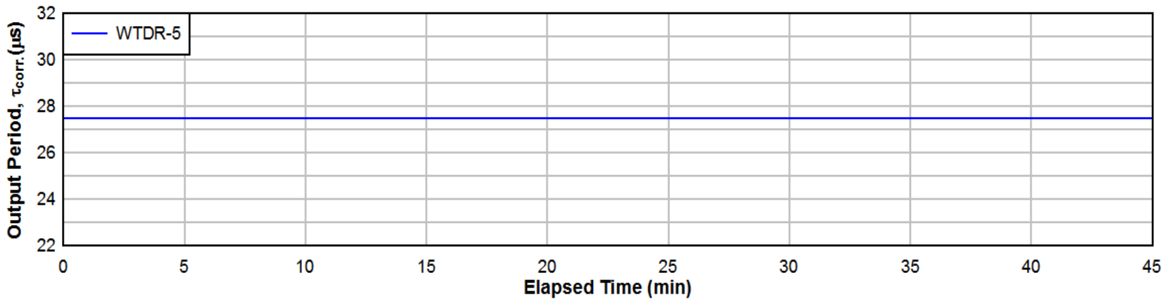
(b) Soil Specimen with Moisture Content of 16.5%



(c) Soil Specimen with Moisture Content of 19.0%



(d) Soil Specimen with Moisture Content of 20.4%



(e) Soil Specimen with Moisture Content of 22.0%

Figure 22 - Output Periods from CS616 WCR Probes in Sample D

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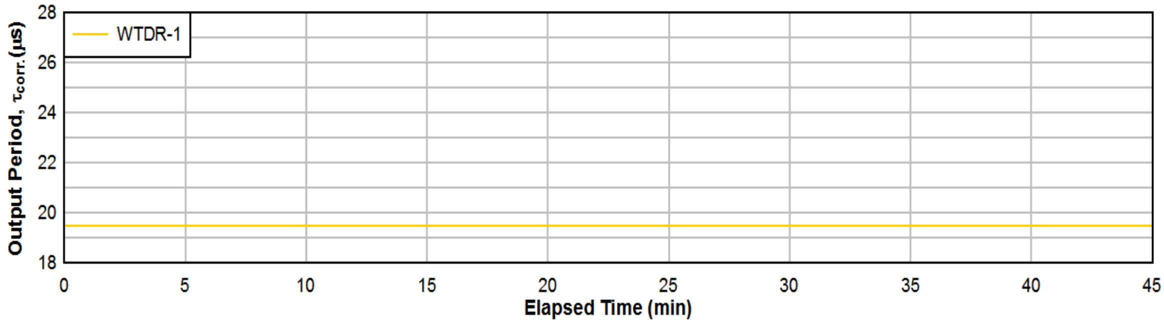
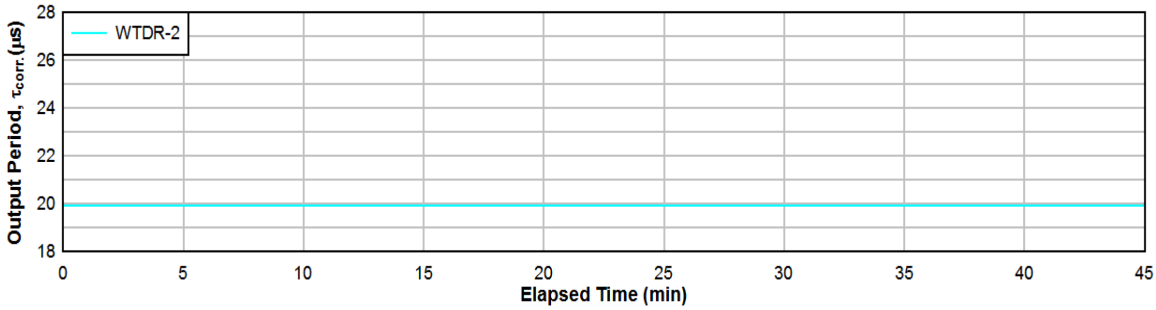
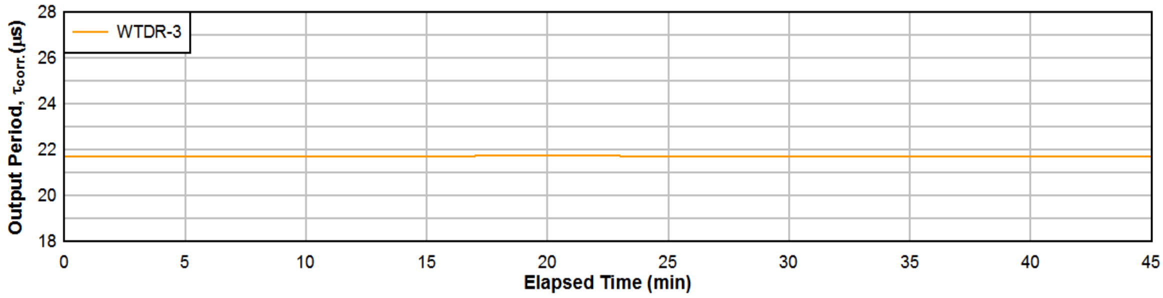


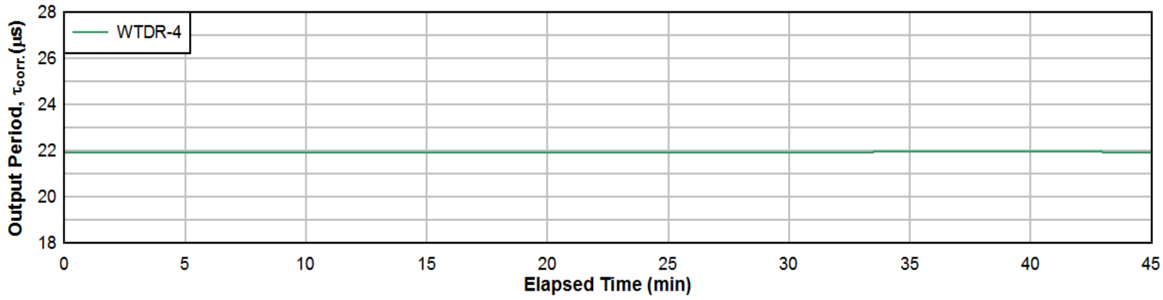
(a) Soil Specimen with Moisture Content of 3.3%



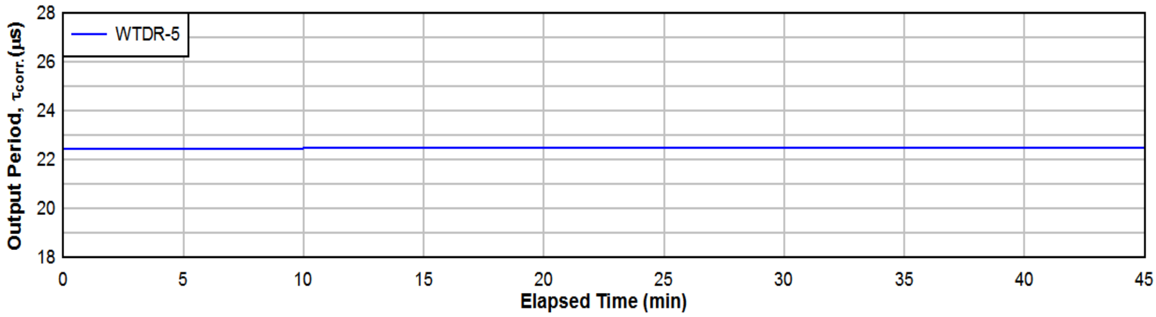
(b) Soil Specimen with Moisture Content of 4.0%



(c) Soil Specimen with Moisture Content of 4.9%



(d) Soil Specimen with Moisture Content of 6.0%



(e) Soil Specimen With Moisture Content of 6.9%

Figure 23 - Output Periods from CS616 WCR Probes in Sample E

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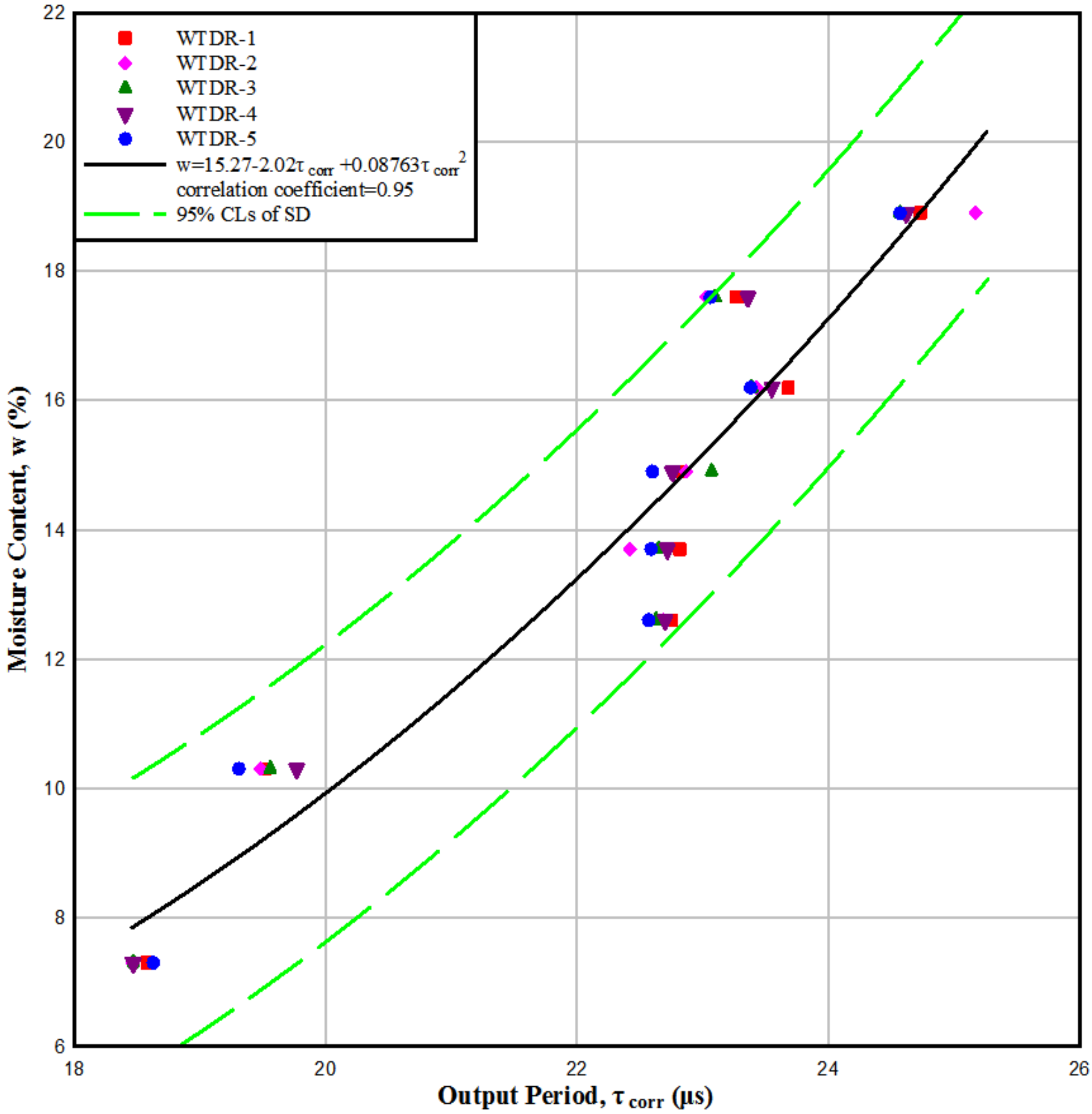

Note: "CL" stands for confidence level and "SD" stands for standard deviation.

Figure 24 - Relationship between Output Period and Moisture Content for Sample A Derived from CS616 WCR Probes

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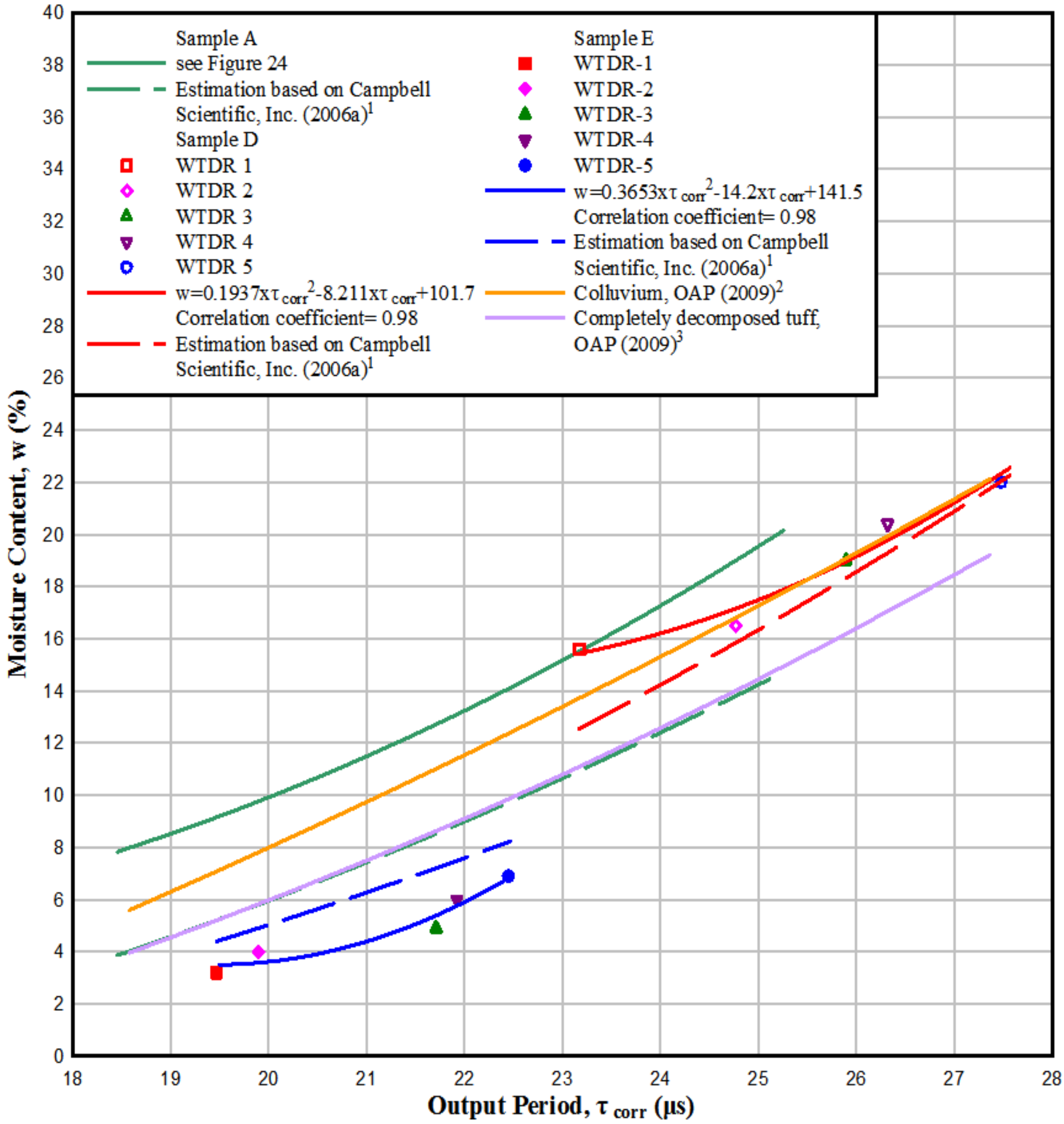

Notes: (1) The estimation (Campbell Scientific, Inc., 2006a) was based on the following relationship : $\theta = w(\rho_d/\rho_w) = 0.0007\,\tau_{corr}^2 - 0.0063\,\tau_{corr} - 0.0663$, where θ is volumetric moisture content, w is gravimetric moisture content, ρ_d is the dry density of the soil (i.e. 1790 kg/m^3 for Sample A, 1560 kg/m^3 for Sample D, and 2120 kg/m^3 for Sample E) and ρ_w is the water density (i.e. 1000 kg/m^3).

(2) The relationship for colluvium (OAP, 2009) is
$\theta = w(\rho_d/\rho_w) = 0.0004\,\tau_{corr}^2 + 0.0099\,\tau_{corr} - 0.2378$, where $(\rho_d/\rho_w) = 1.504$.

(3) The relationship for completely decomposed tuff (OAP, 2009) is
$\theta = w(\rho d/\rho w) = 0.0007\,\tau_{corr}^2 + 0.0044\,\tau_{corr} - 0.0964$, where $(\rho_d/\rho_w) = 1.6$.

Figure 25 - Relationships between Output Period and Moisture Content for Samples A, D and E Derived from CS616 WCR Probes

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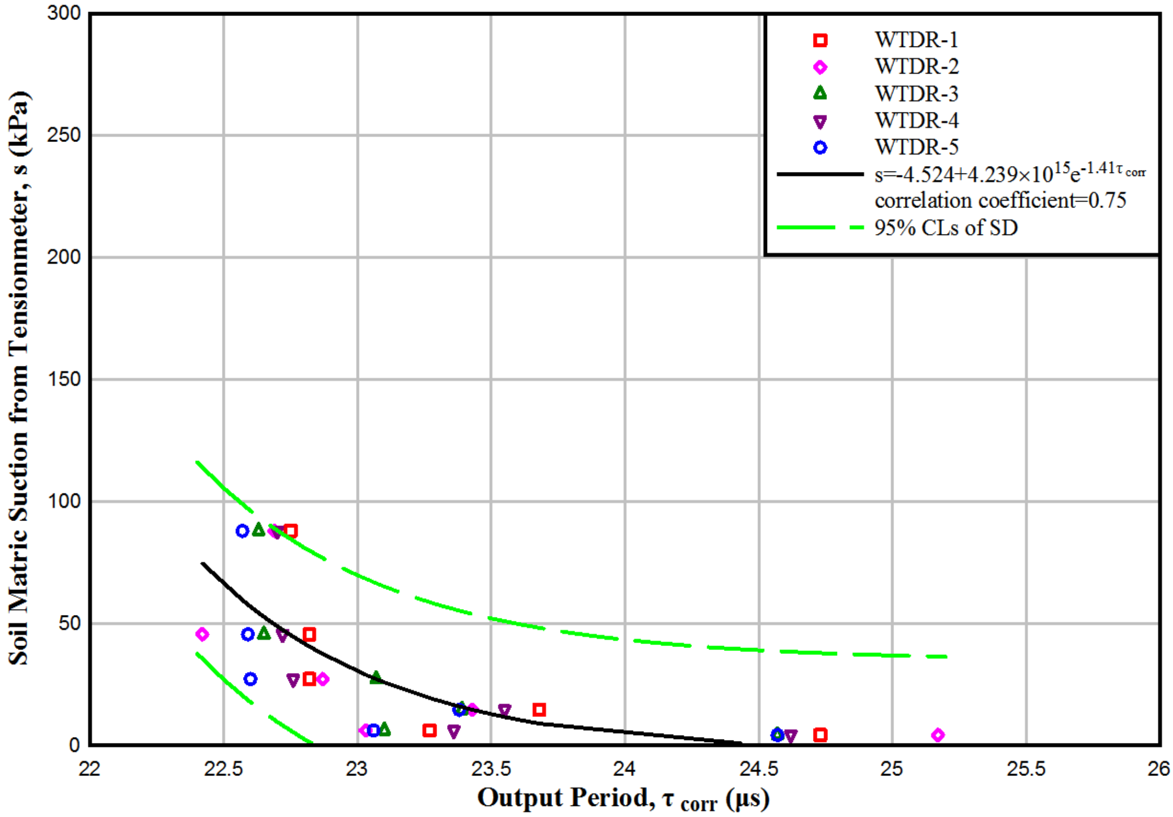

Note: "CL" stands for confidence level and "SD" stands for standard deviation.

Figure 26 - Relationship between Output Period and Soil Matric Suction for Sample A Derived from CS616 WCR Probes

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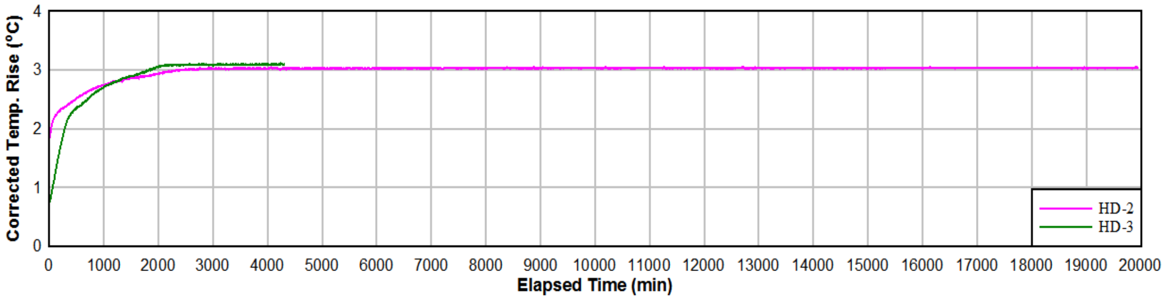
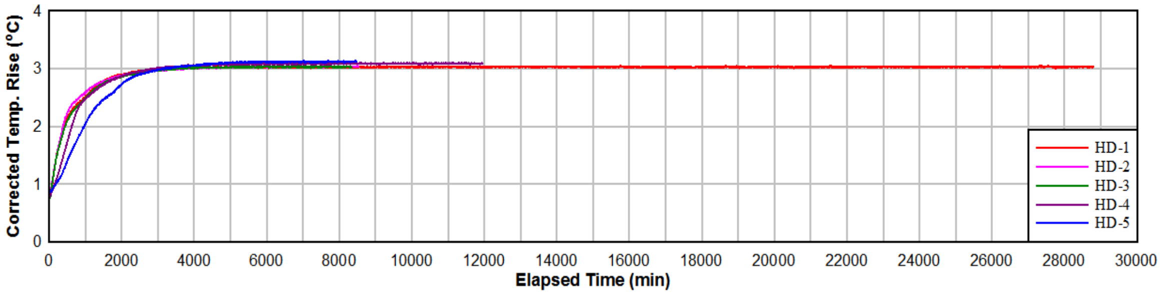
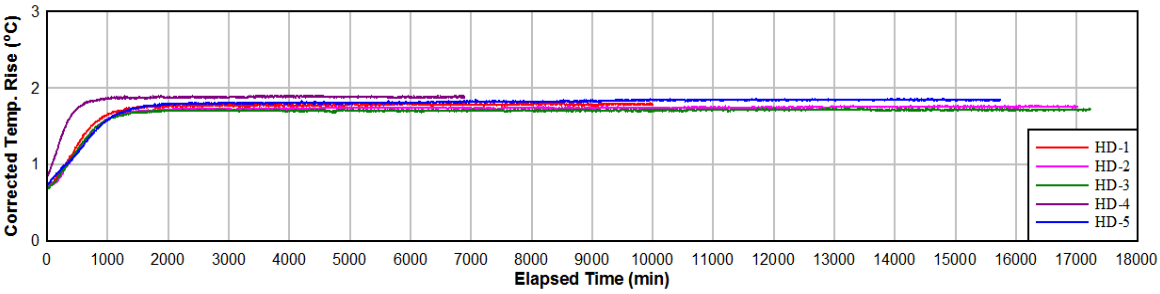


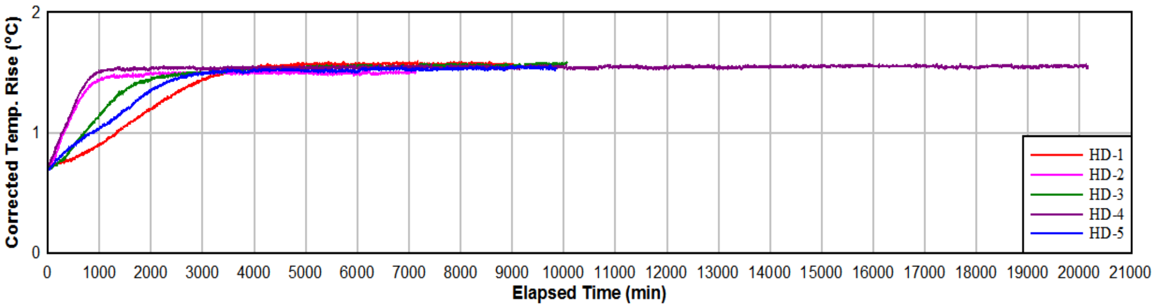
(a) Soil Specimen with Moisture Content of 7.3%



(b) Soil Specimen with Moisture Content of 10.3%



(c) Soil Specimen with Moisture Content of 12.6%



(d) Soil Specimen with Moisture Content of 13.7%

Figure 27 - Readings from 229 HD Sensors in Sample A (Sheet 1 of 2)

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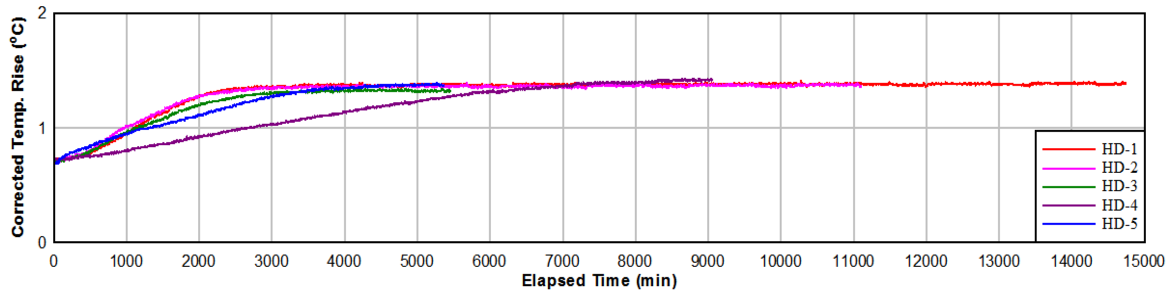
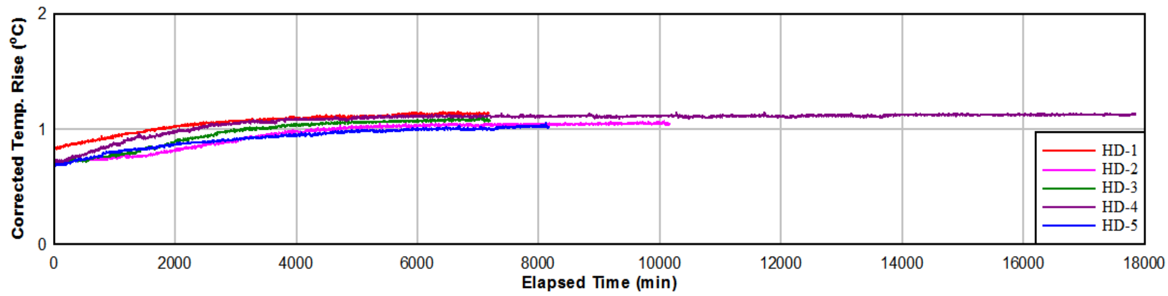
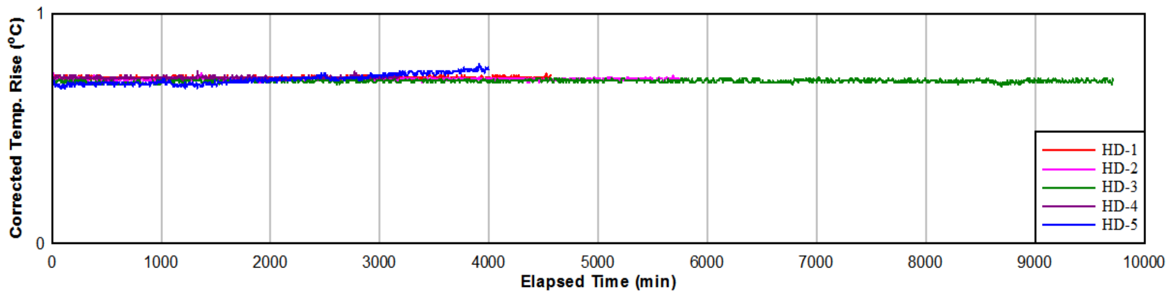


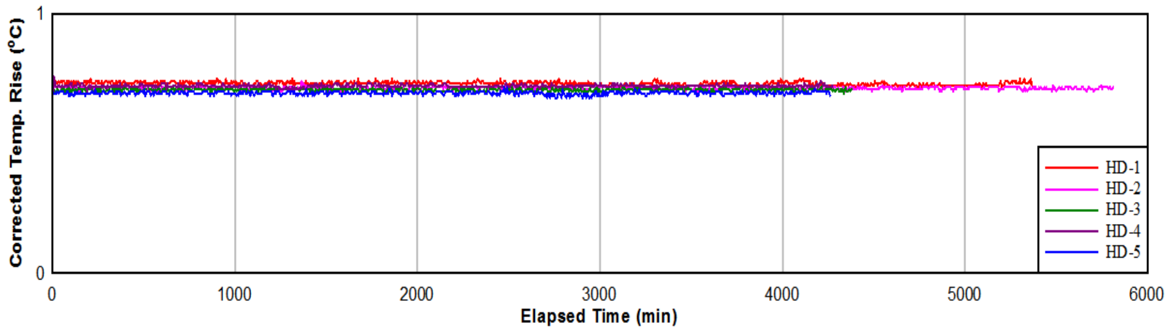
(e) Soil Specimen with Moisture Content of 14.9%



(f) Soil Specimen with Moisture Content of 16.2%



(g) Soil Specimen with Moisture Content of 17.6%



(h) Soil Specimen with Moisture Content of 18.9%

Figure 27 - Readings from 229 HD Sensors in Sample A (Sheet 2 of 2)

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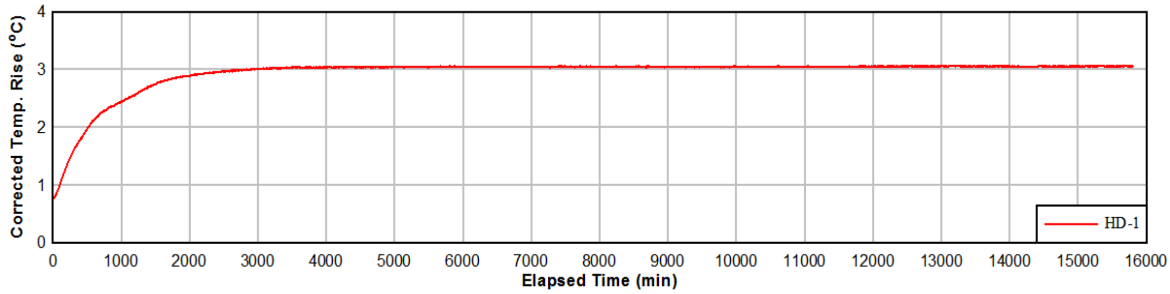
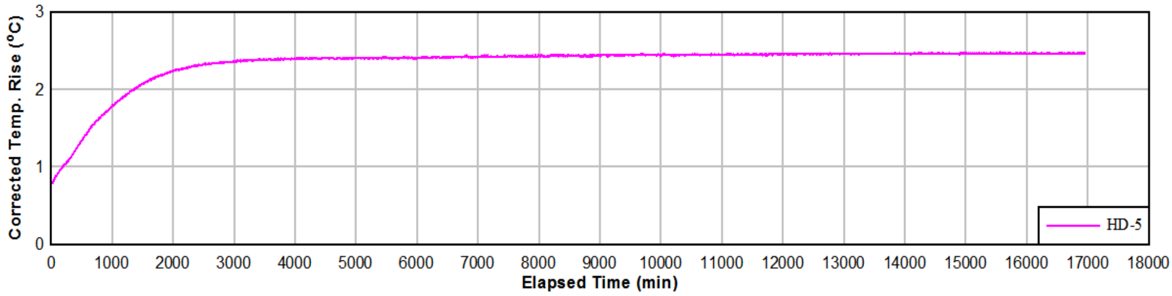
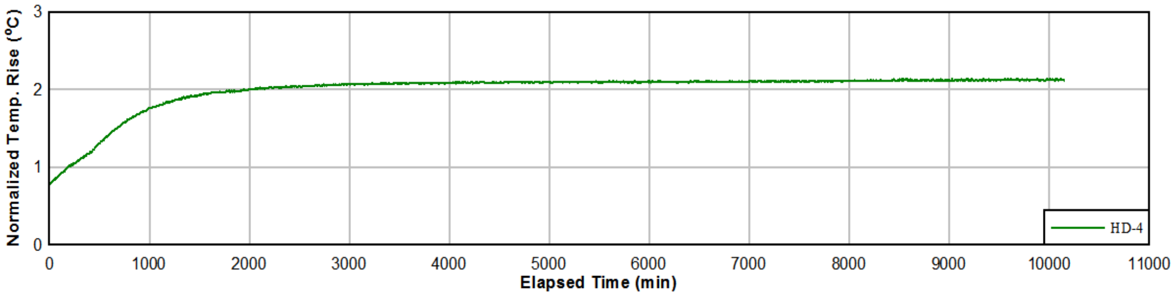


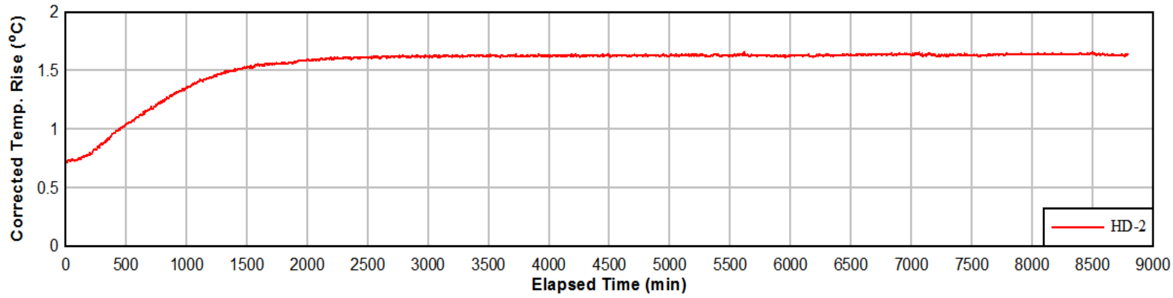
(a) Soil Specimen with Moisture Content of 11.9%



(b) Soil Specimen with Moisture Content of 13.8%



(c) Soil Specimen with Moisture Content of 15.6%



(d) Soil Specimen with Moisture Content of 16.5%

Figure 28 - Readings from 229 HD Sensors in Sample D (Sheet 1 of 2)

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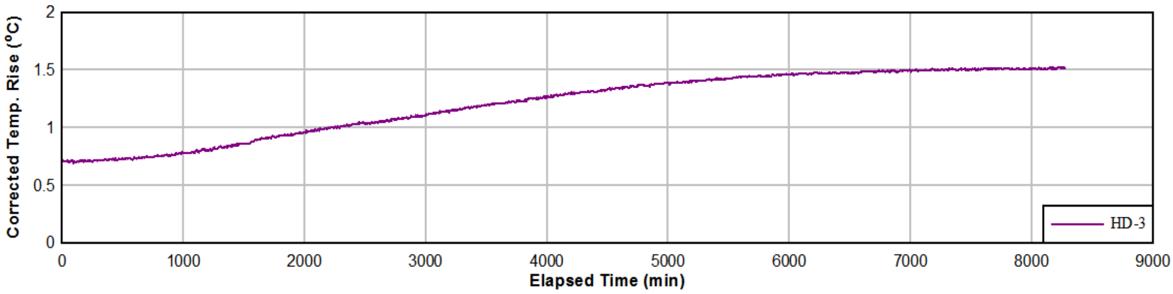
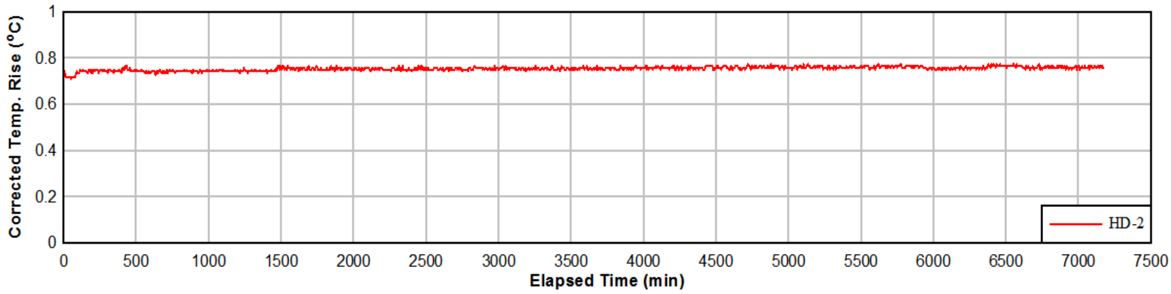
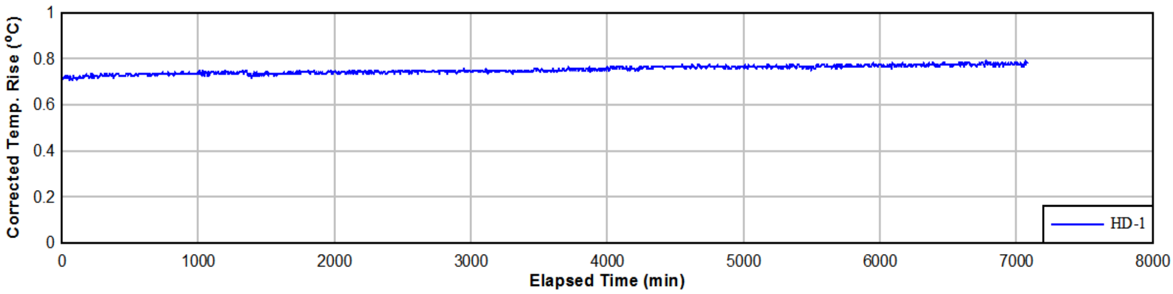


(e) Soil Specimen with Moisture Content of 19.0%



(f) Soil Specimen with Moisture Content of 20.4%



(g) Soil Specimen with Moisture Content of 22.0%

Figure 28 - Readings from 229 HD Sensors in Sample D (Sheet 2 of 2)

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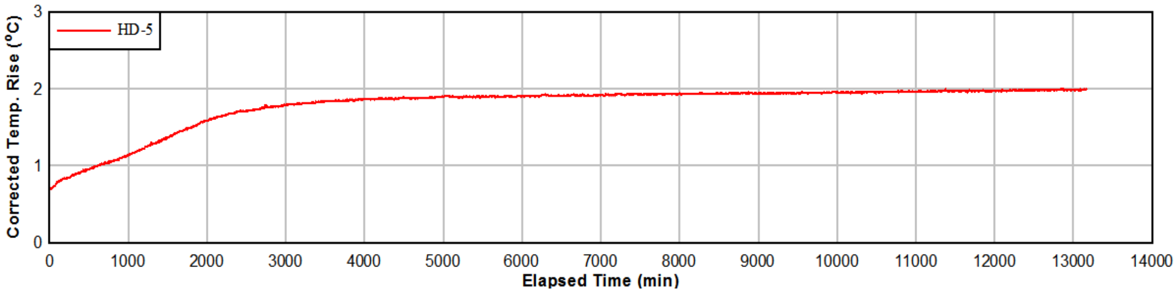
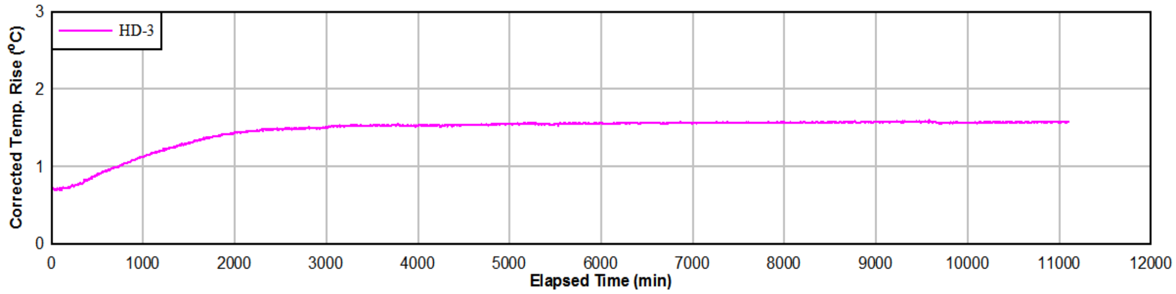
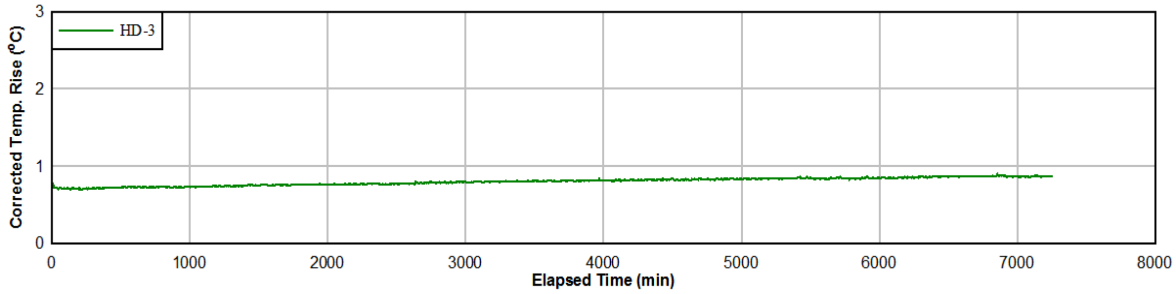


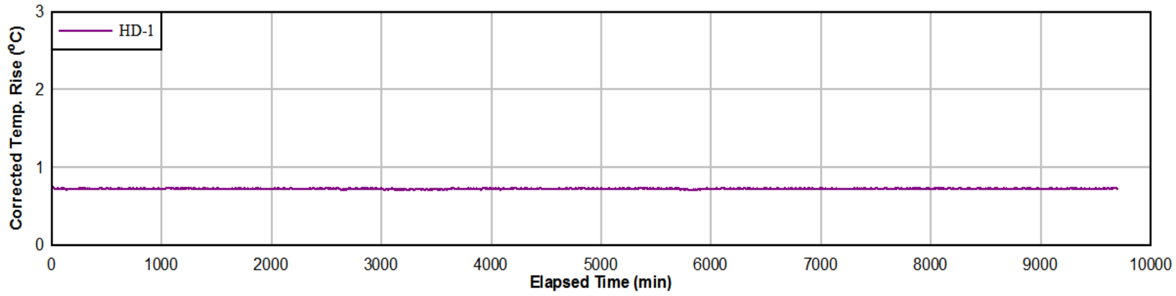
(a) Soil Specimen with Moisture Content of 3.3%



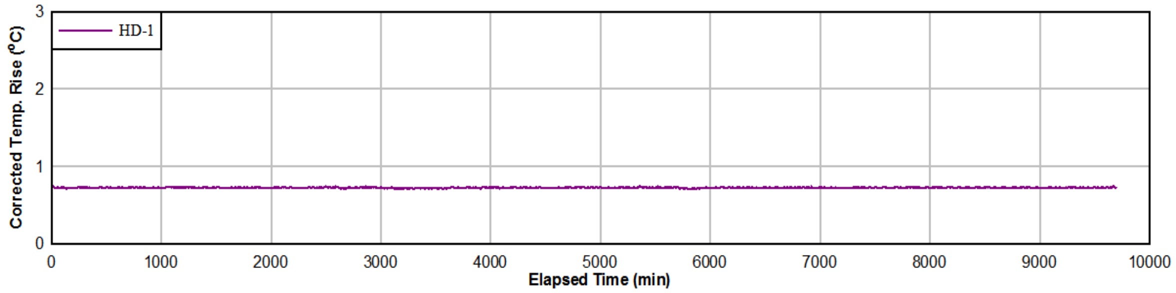
(b) Soil Specimen with Moisture Content of 4.0%



(c) Soil Specimen with Moisture Content of 4.9%



(d) Soil Specimen with Moisture Content of 6.0%



(e) Soil Specimen with Moisture Content of 6.9%

Figure 29 - Readings from 229 HD Sensors in Sample E

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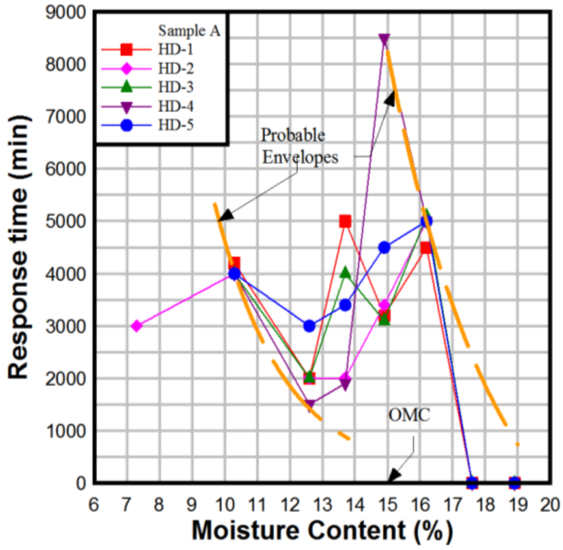
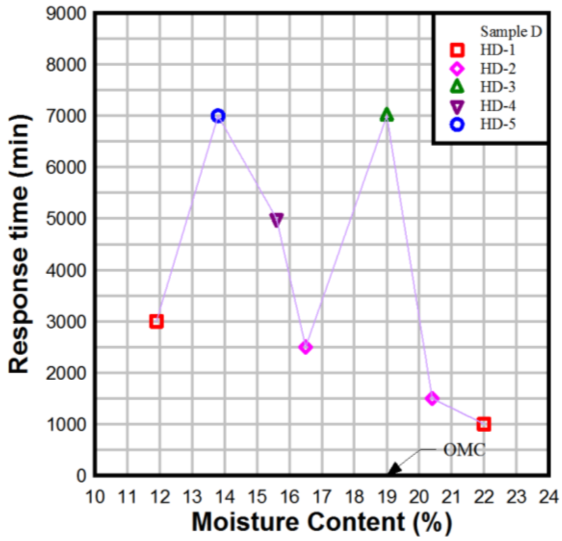
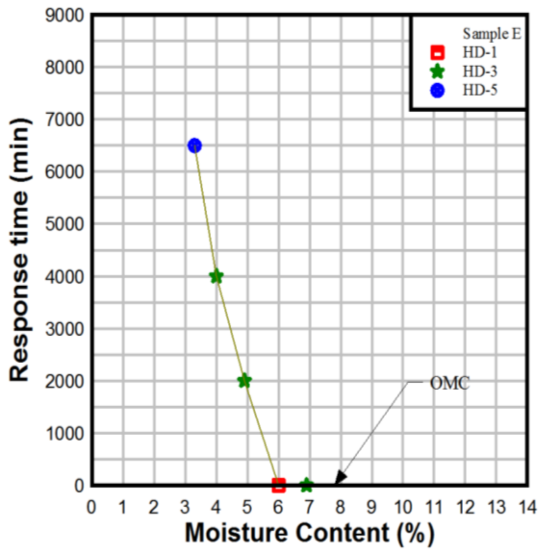


(a) Sample A



(b) Sample D



(c) Sample E

Note: Response time refer to the time when the stable reading was obtained.

Figure 30 - Response Time of 229 HD Sensors in Samples A, D and E

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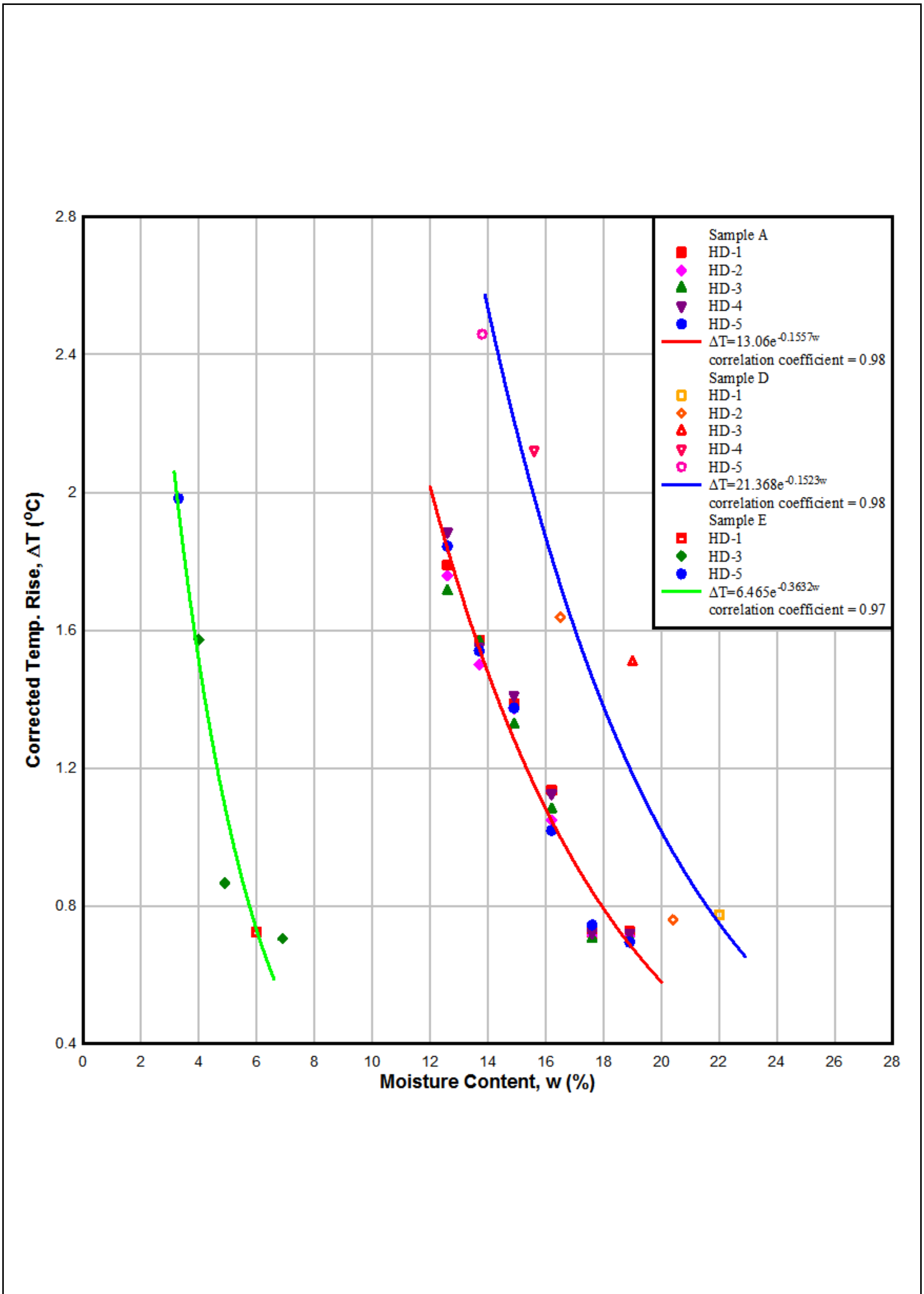

Figure 31 - Relationships between Moisture Content and Temperature Rise for 229 HD Sensors in Samples A, D and E

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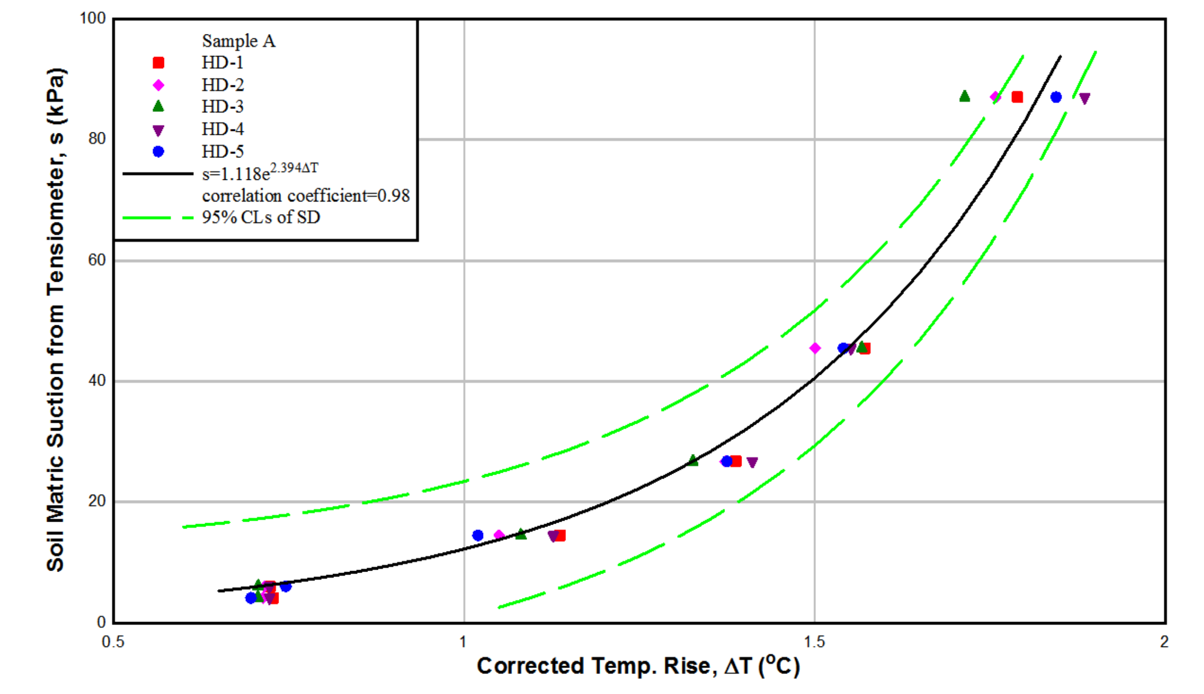

Note: “CL” stands for confidence level and “SD” stands for standard deviation.

Figure 32 - Relationship between Temperature Rise and Soil Matric Suction for 229HD Sensors in Sample A

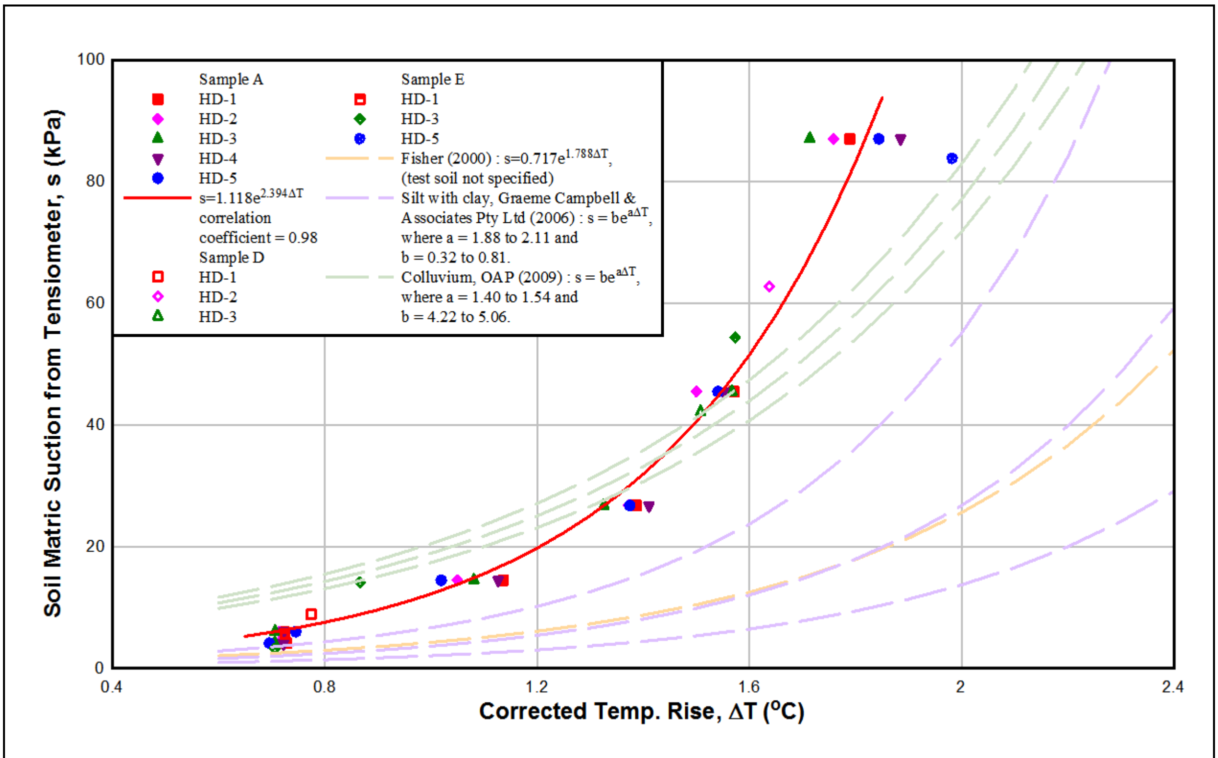

Figure 33 - Comparison of Relationships between Temperature Rise and Soil Matric Suction for 229 HD Sensors in Samples A, D and E

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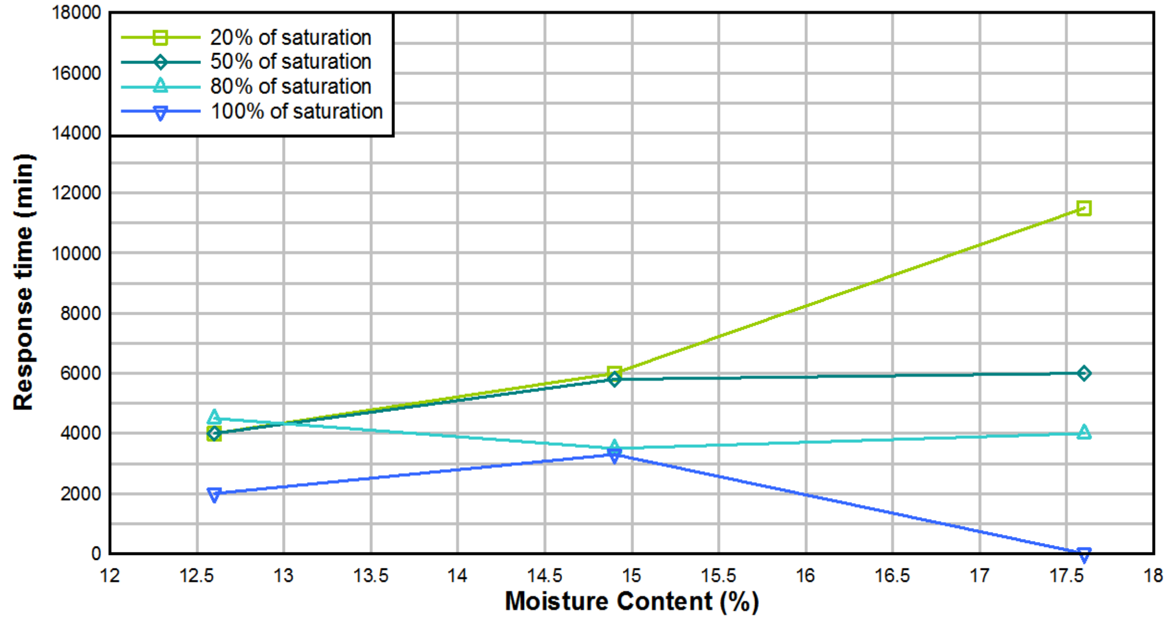
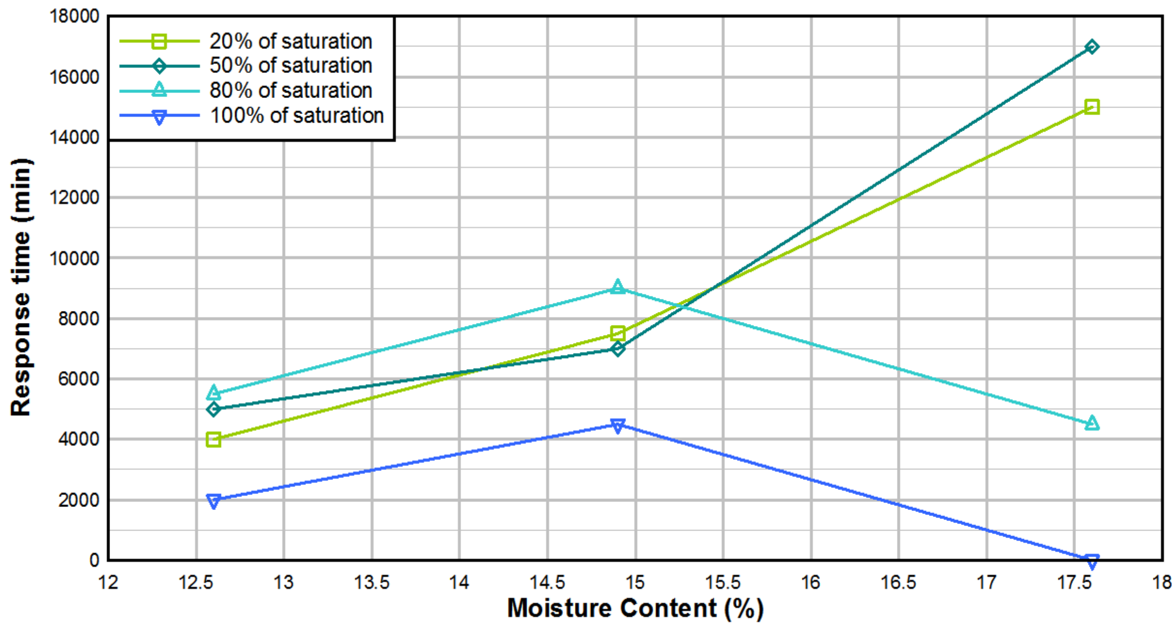


(a) HD1



(b) HD6

Notes: (1) Tests were conducted in Soil Sample A compacted to 85% RC, with different moisture contents (MCs) of 12.6%, 14.9% and 17.6%.
(2) The response time refers to the time when the stable reading was obtained.

Figure 34 - Effect of Saturation on Response Time for 229 HD Sensors

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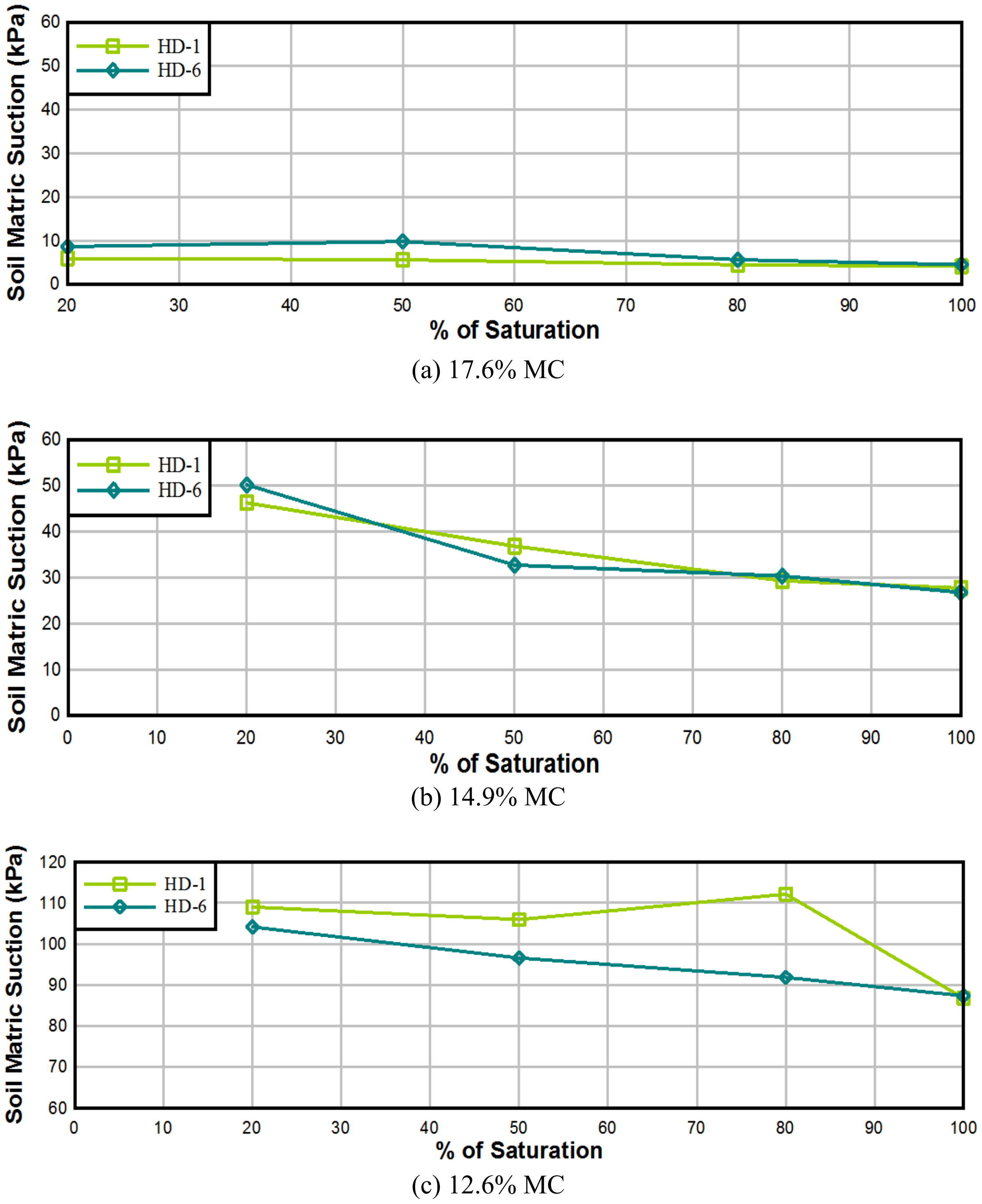

Notes:

(1) Tests were conducted in Soil Sample A compacted to 85% RC, with different moisture contents (MCs) of 12.6%, 14.9% and 17.6%.

(2) The soil matric suctions obtained from Sensors HD-1 and HD-6 are based on the following relationship derived from the Phase I Tests (under steady state conditions):

HD-1: $s = 0.5243e^{2.854\Delta T}$, HD-6: $s = 0.7334e^{2.5156\Delta T}$,

where s = soil matric suction (kPa) and Δ T = corrected temperature rise (°C).

Figure 35 - Effect of Saturation on Soil Matric Suction for 229 HD Sensors

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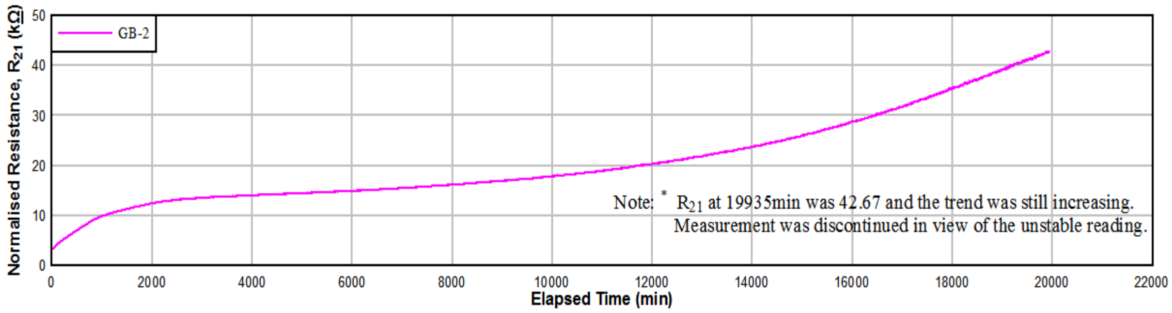
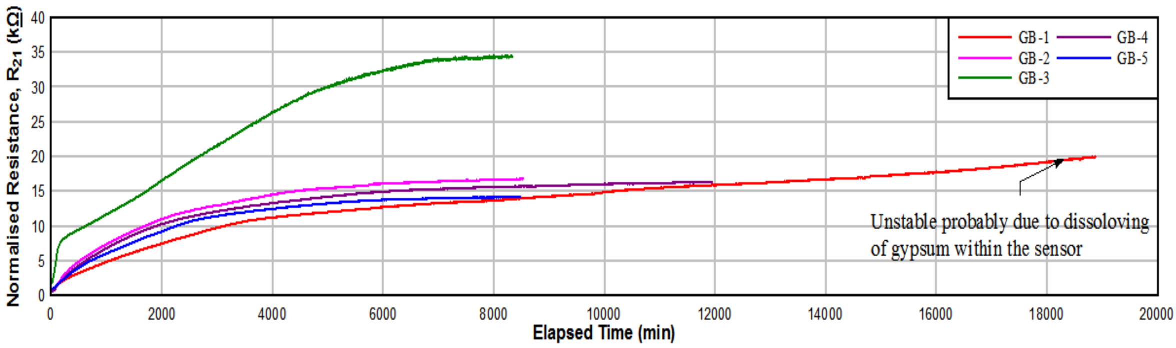
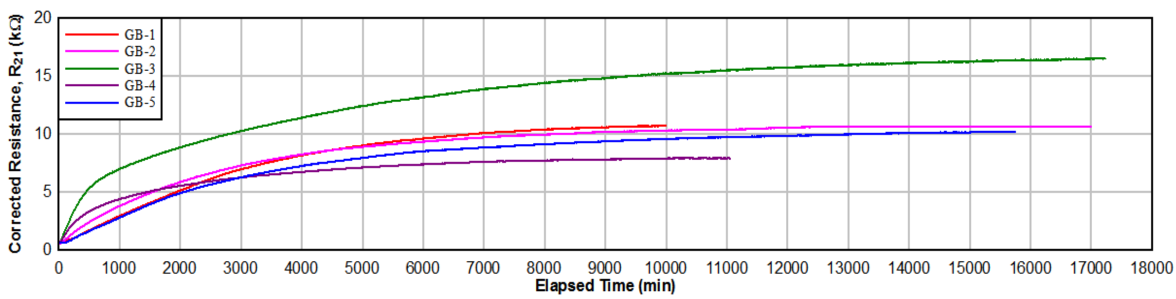


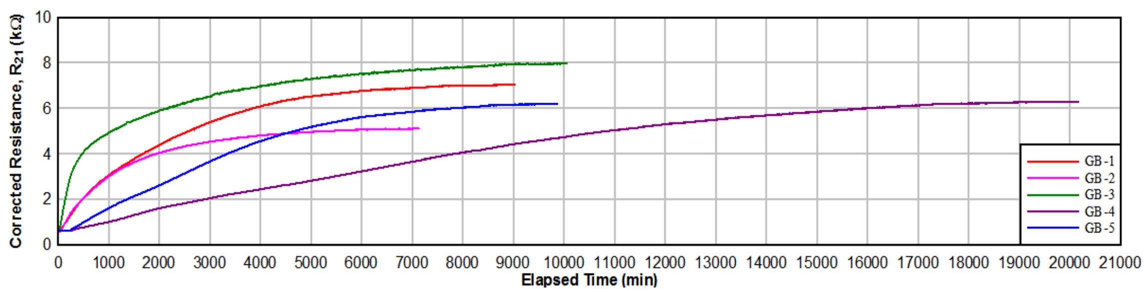
(a) Soil Specimen with Moisture Content of 7.3%



(b) Soil Specimen with Moisture Content of 10.3%



(c) Soil Specimen with Moisture Content of 12.6%



(d) Soil Specimen with Moisture Content of 13.7%

Figure 36 - Readings from Watermark 200 GM Sensors in Sample A (Sheet 1 of 2)

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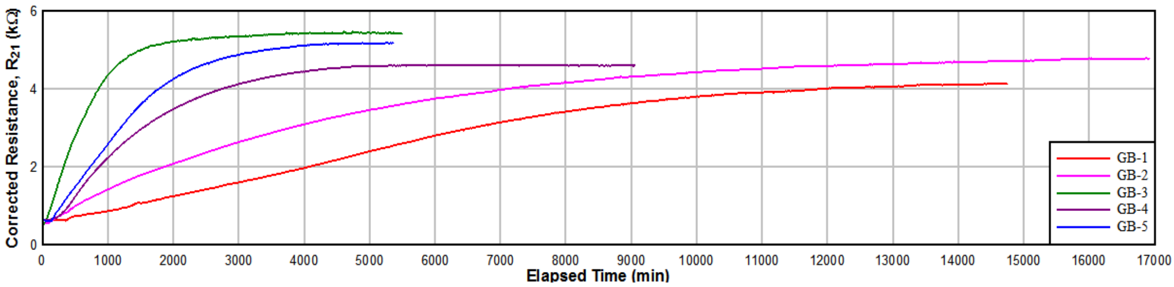
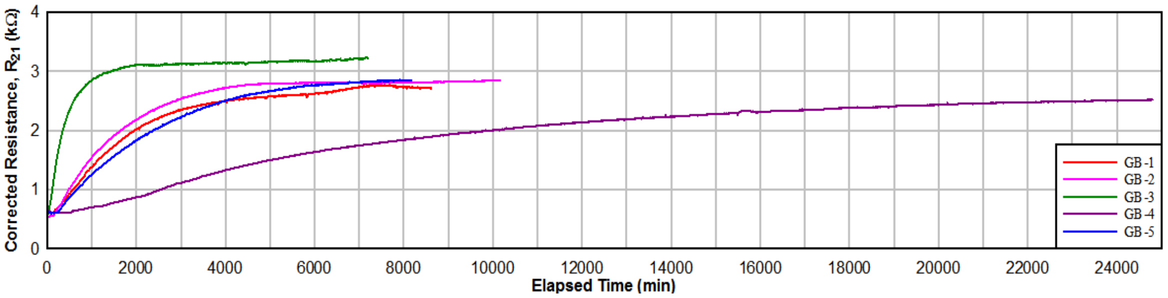
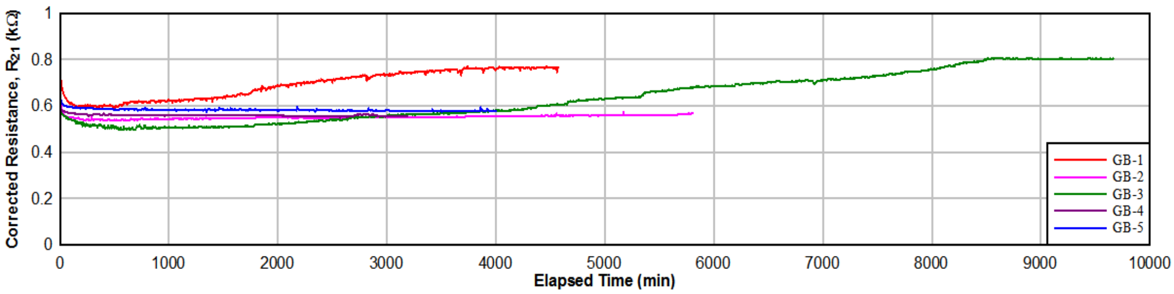


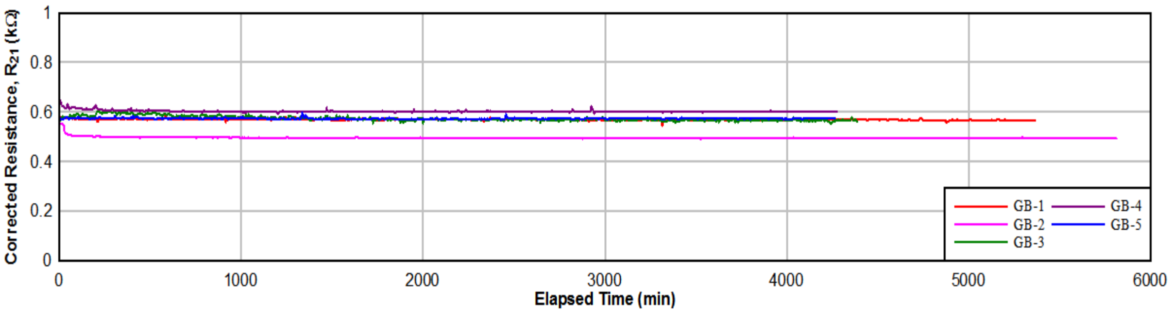
(e) Soil Specimen with Moisture Content of 14.9%



(f) Soil Specimen with Moisture Content of 16.2%



(g) Soil Specimen with Moisture Content of 17.6%



(h) Soil Specimen with Moisture Content of 18.9%

Figure 36 - Readings from Watermark 200 GM Sensors in Sample A (Sheet 2 of 2)

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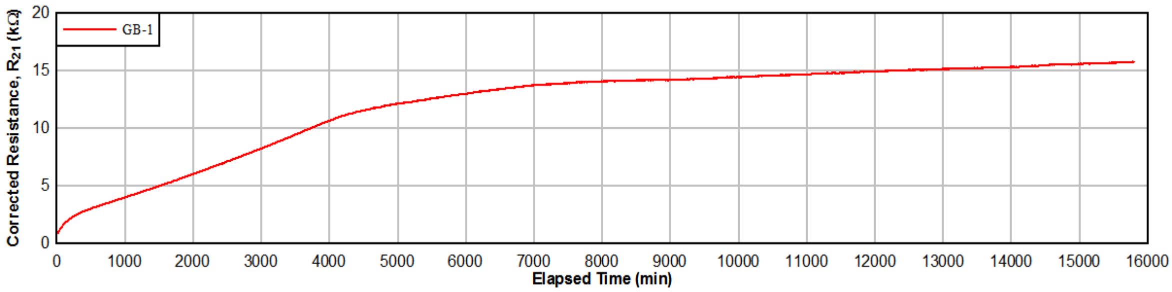
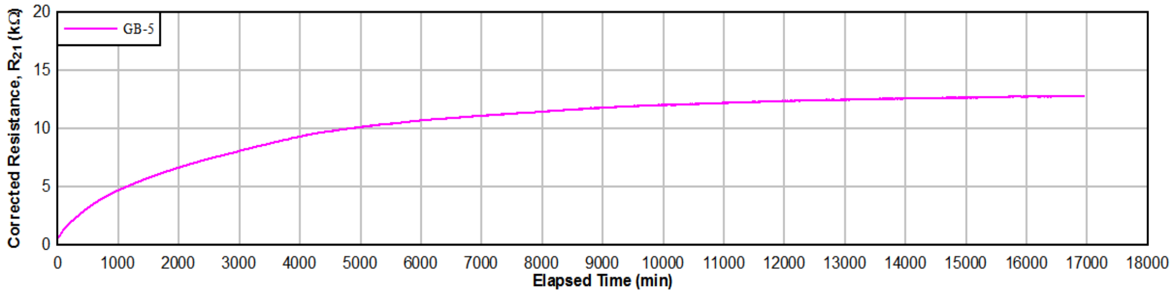
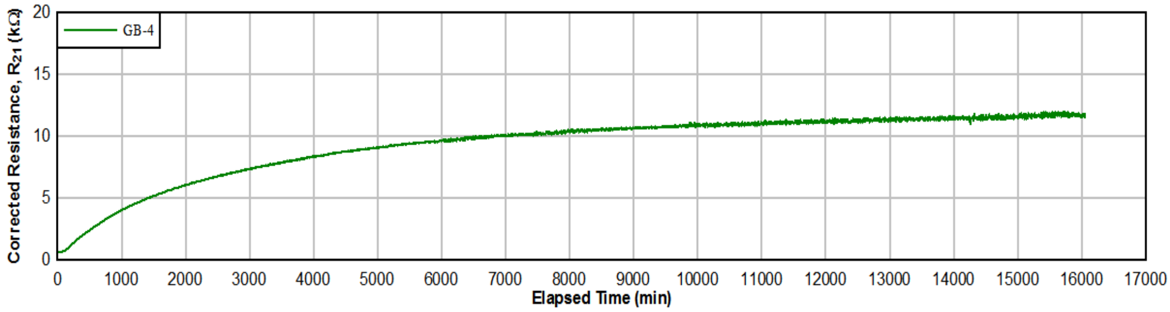


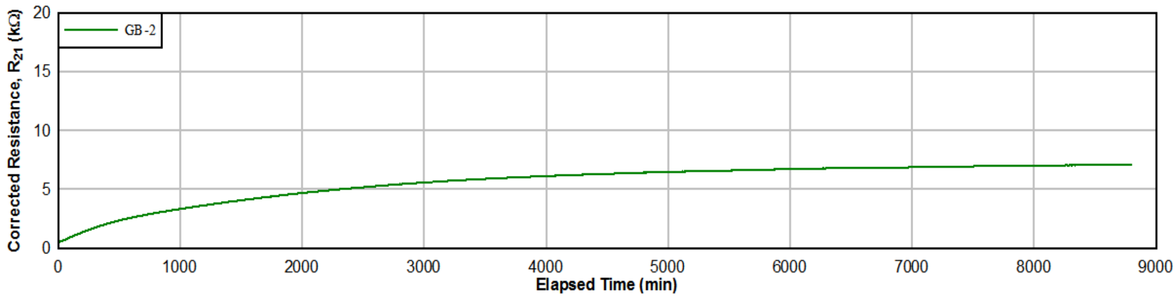
(a) Soil Specimen with Moisture Content of 11.9%



(b) Soil Specimen with Moisture Content of 13.8%



(c) Soil Specimen with Moisture Content of 15.6%



(d) Soil Specimen with Moisture Content of 16.5%

Figure 37 - Readings from Watermark 200 GM Sensors in Sample D (Sheet 1 of 2)

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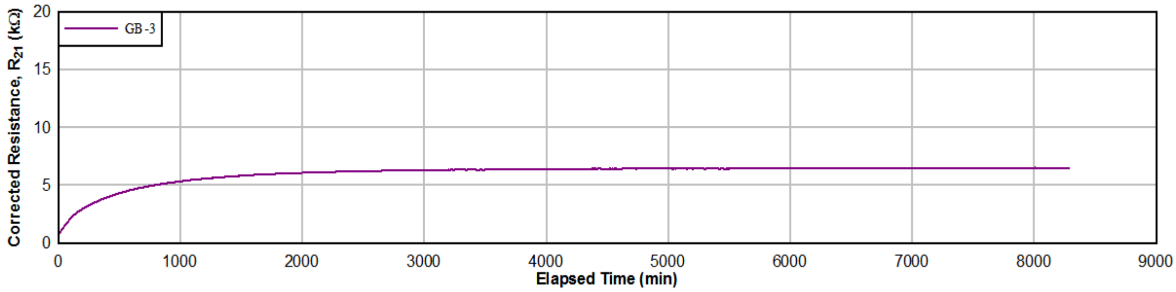
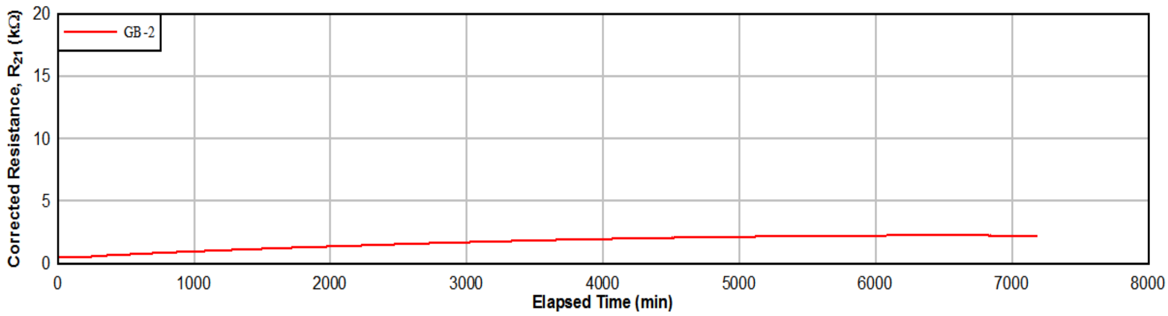
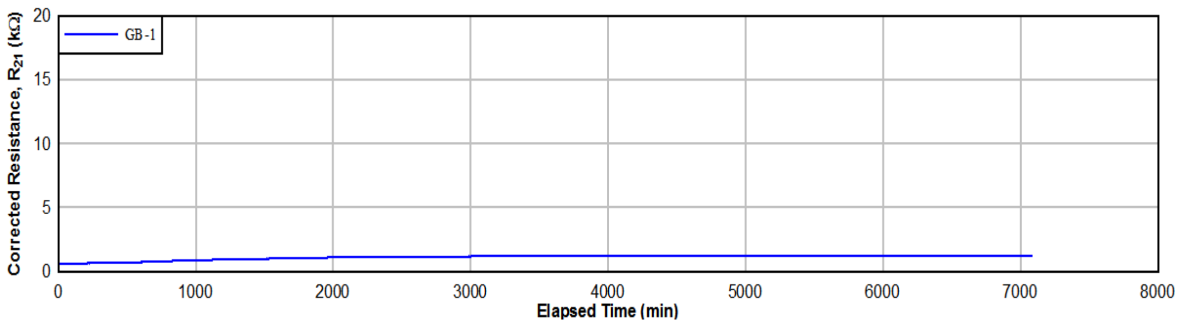


(e) Soil Specimen with Moisture Content of 19.0%



(f) Soil Specimen with Moisture Content of 20.4%



(g) Soil Specimen with Moisture Content of 22.0%

Figure 37 - Readings from Watermark 200 GM Sensors in Sample D (Sheet 2 of 2)

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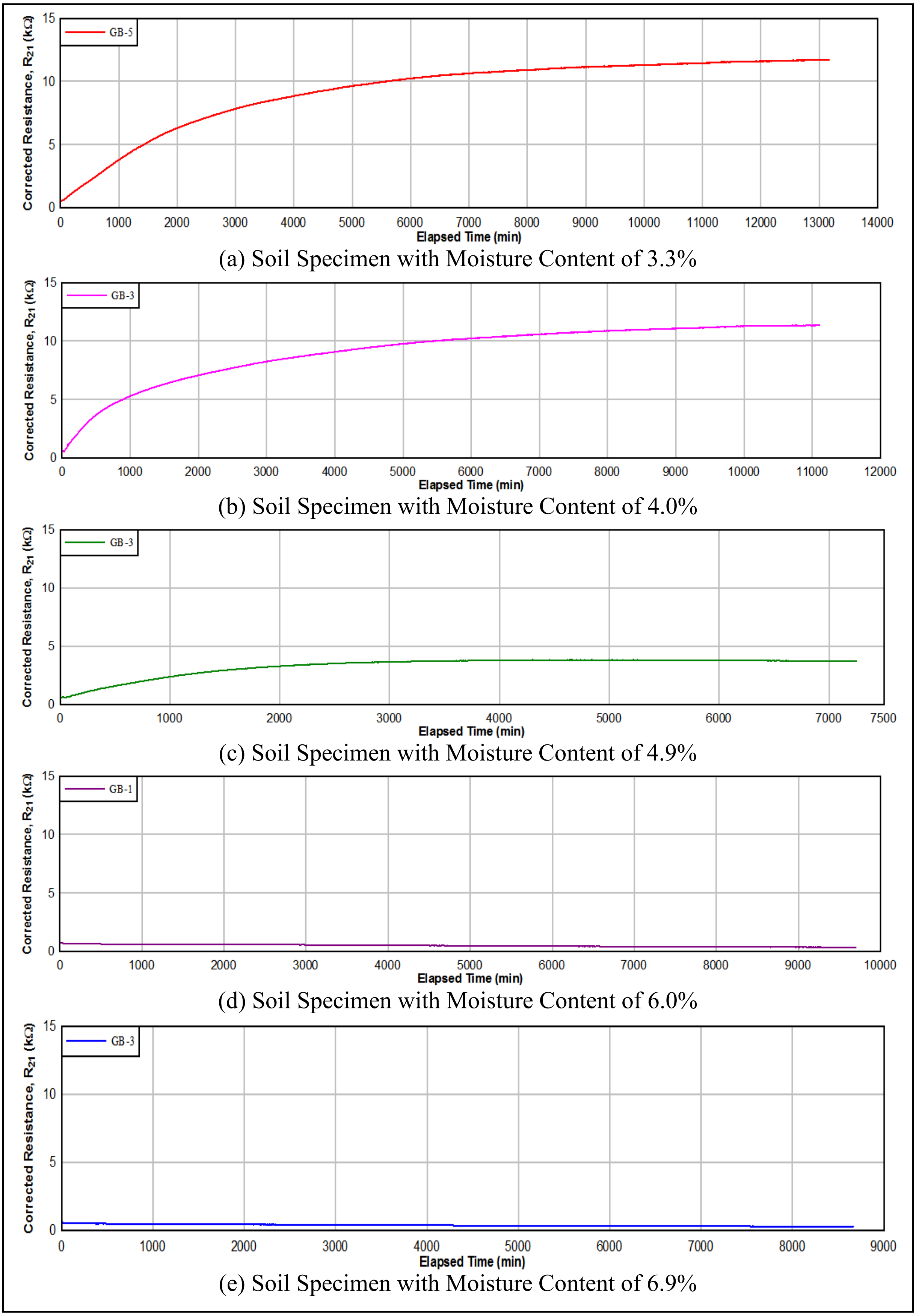

Figure 38 - Readings from Watermark 200 GM Sensors in Sample E

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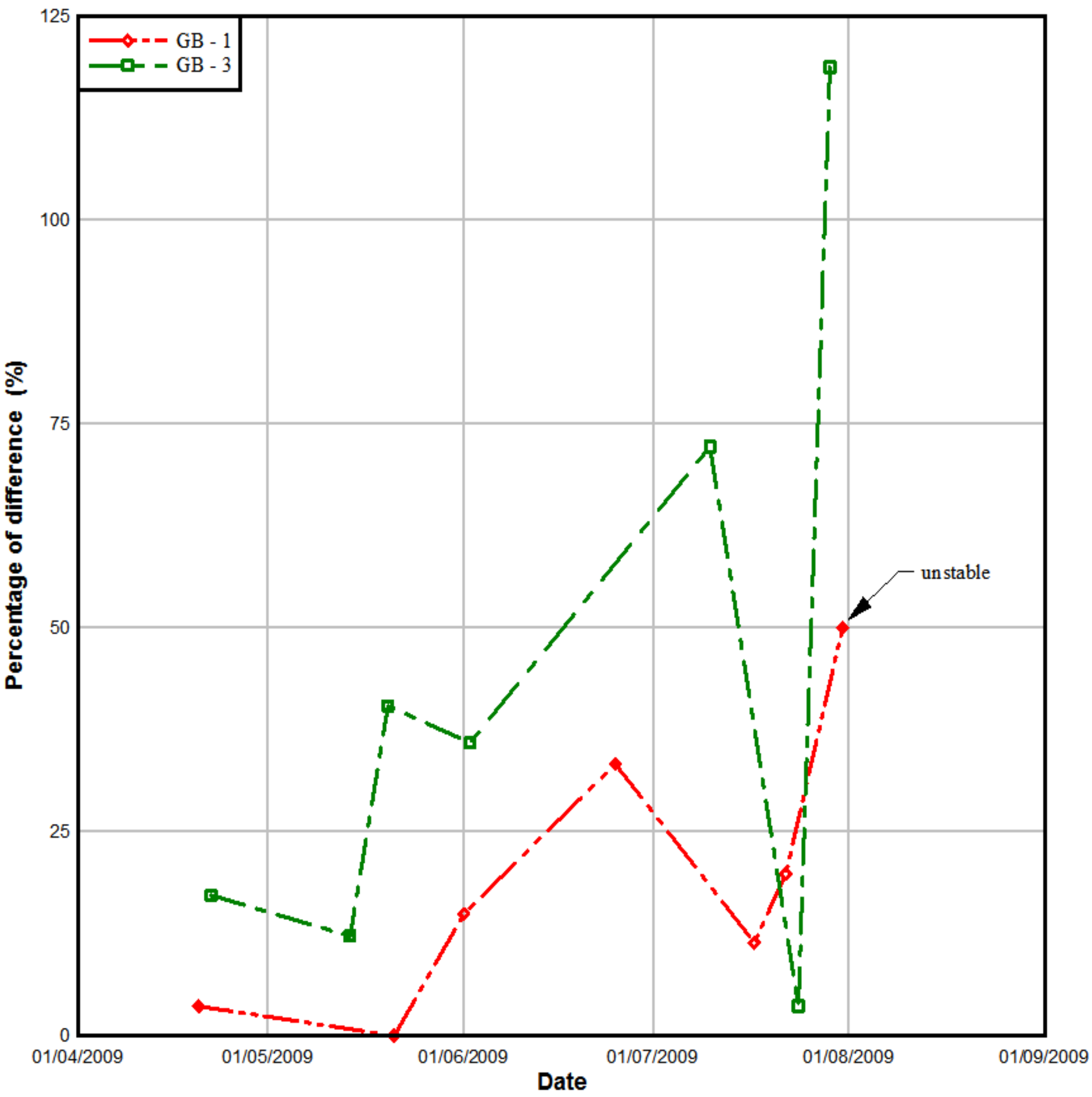

Note: The percentage difference is calculated against the mean value of the measurements from Sensor Nos. GB 2, 4 and 5 in the soil specimens of Sample A.

Figure 39 - Drift of Readings from Watermark 200 GM Sensors

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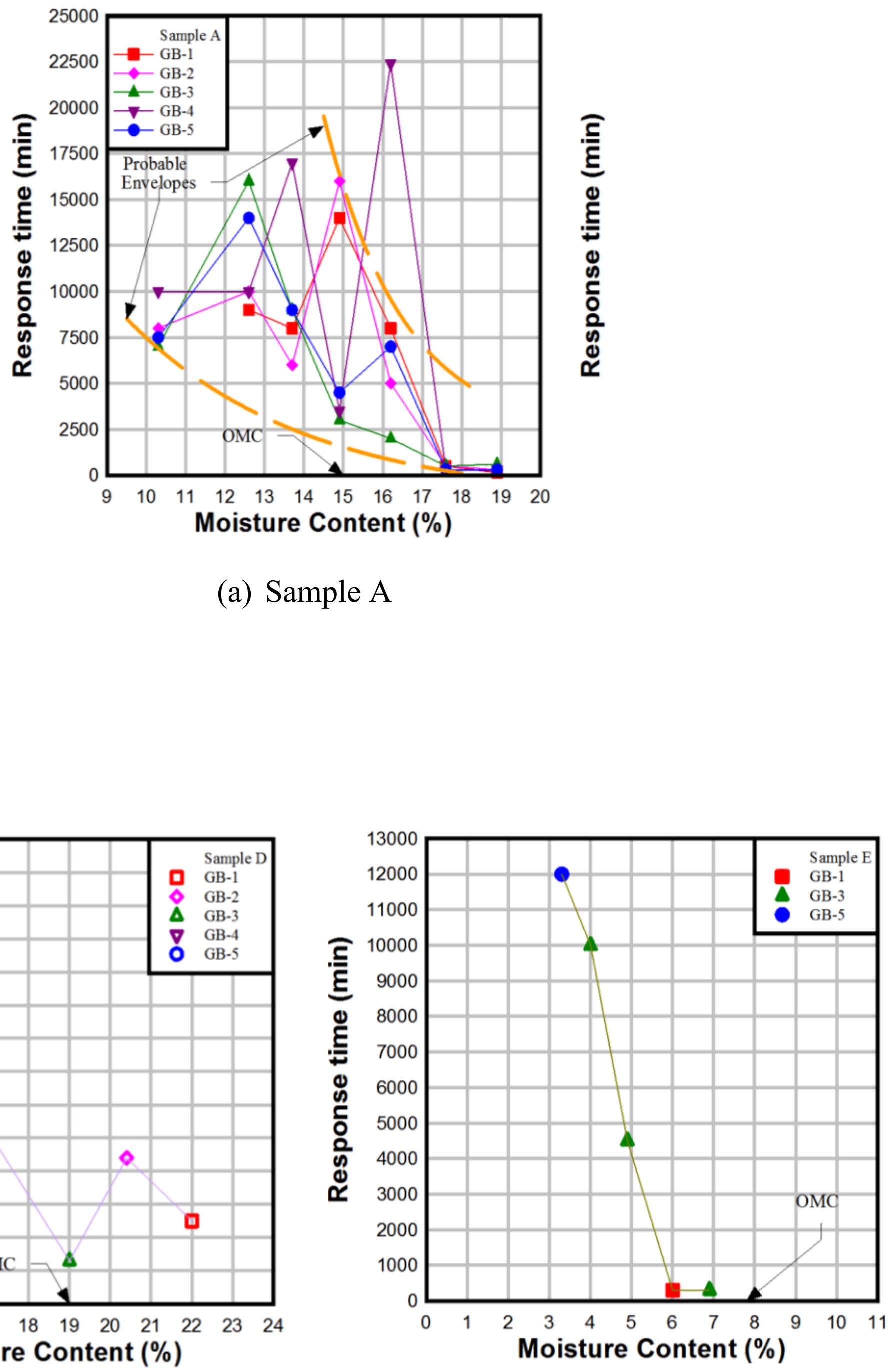

(a) Sample A

(b) Sample D

(c) Sample E

Note: Response time refer to the time when the stable reading was obtained.

Figure 40 - Response Time of Watermark 200 GM Sensors in Samples A, D and E

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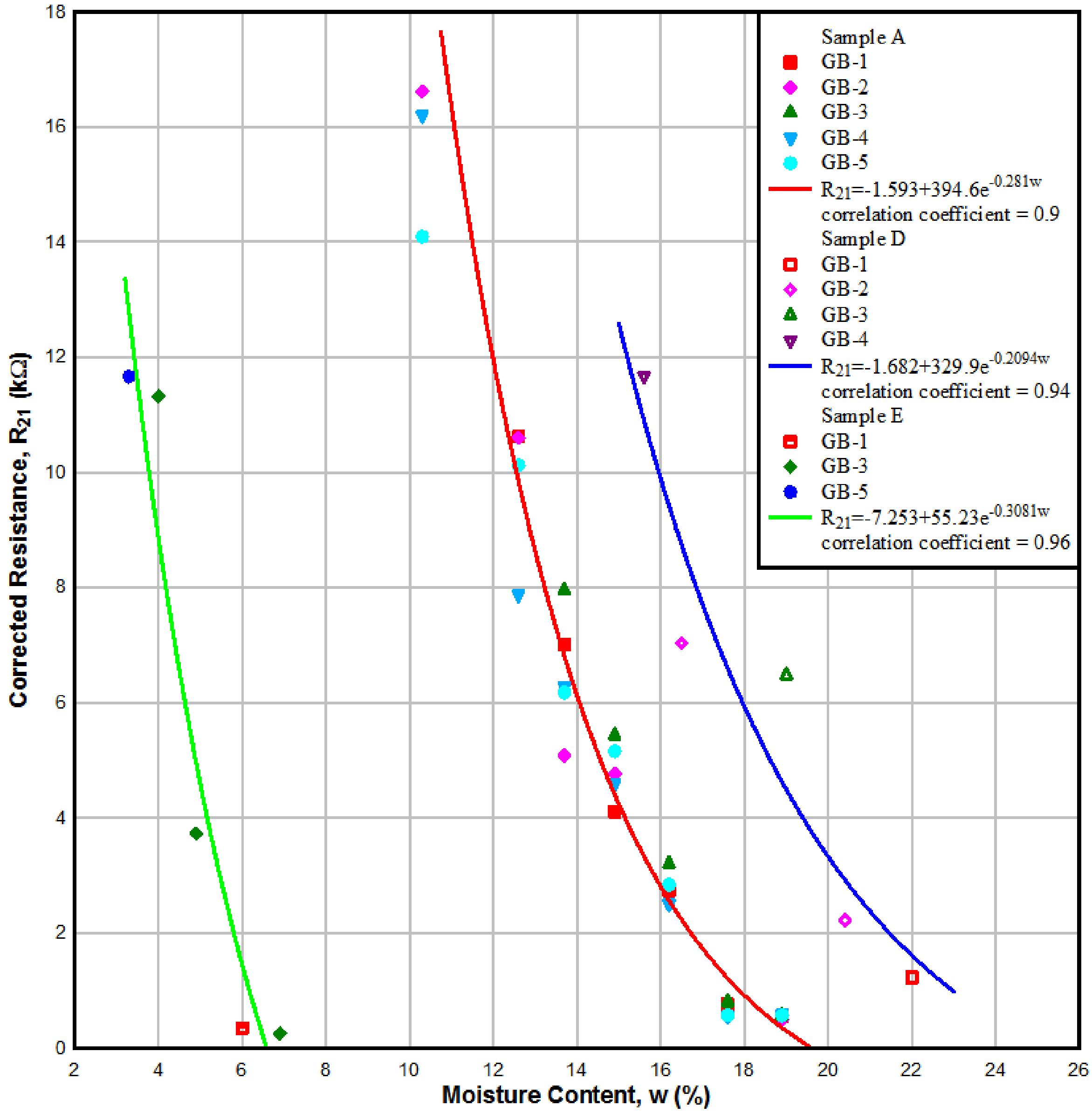

Figure 41 - Relationships between Soil Moisture Content and Electrical Resistance for Watermark 200 GM Sensors in Samples A, D and E

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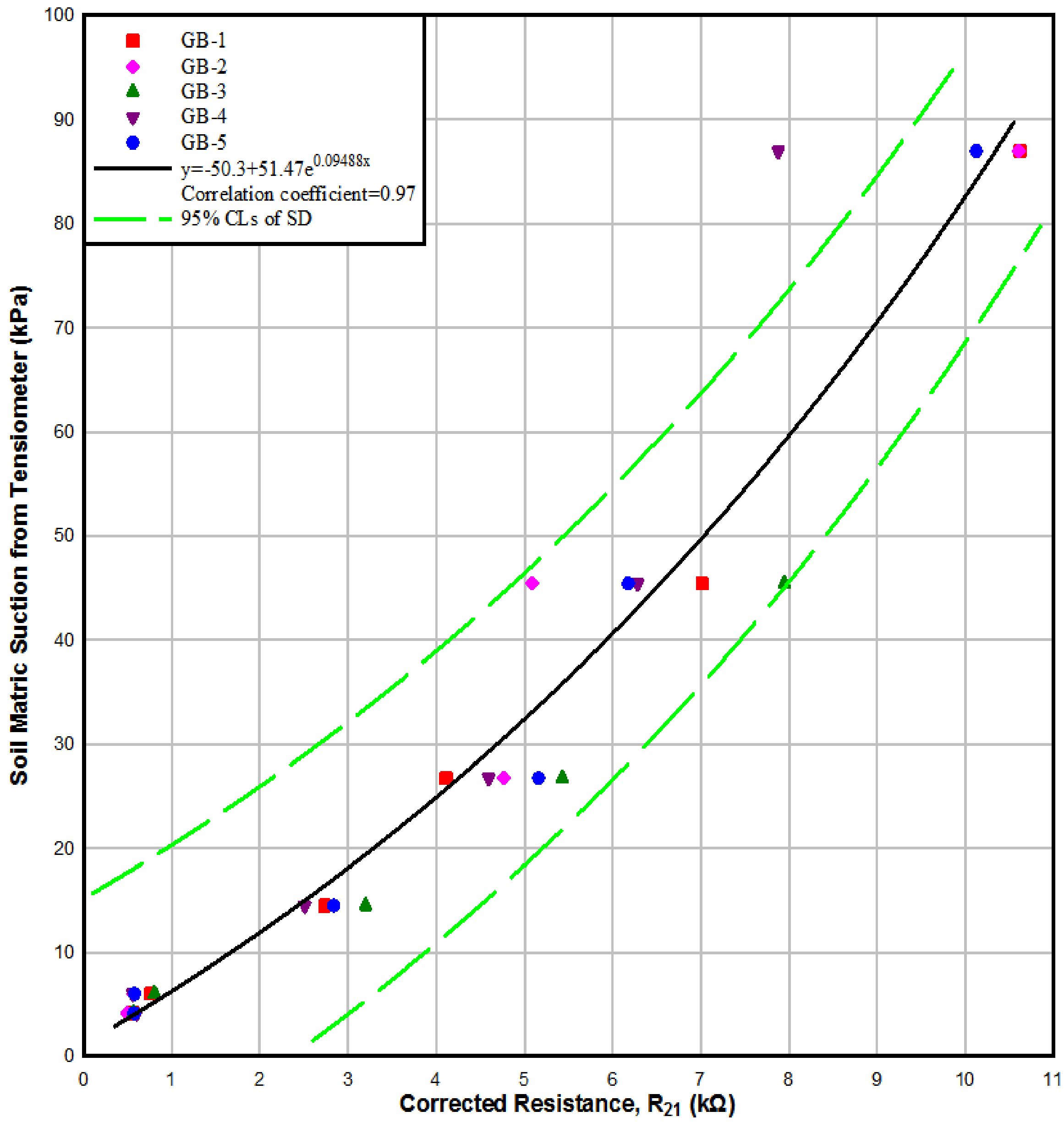

Note: "CL" stands for confidence level and "SD" stands for standard deviation.

Figure 42 - Relationship between Electrical Resistance and Soil Matric Suction for Watermark 200 GM Sensors in Sample A

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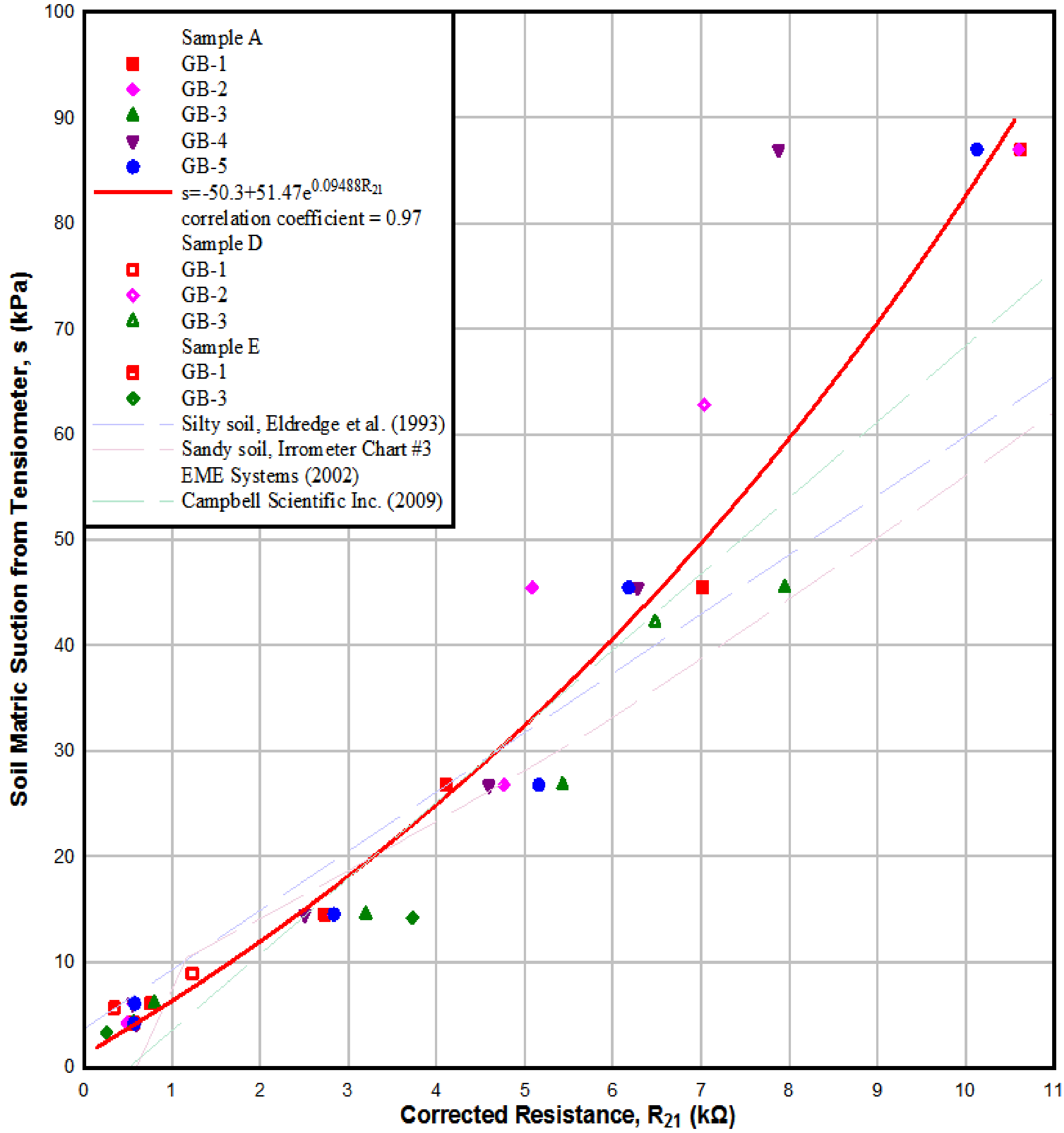

Figure 43 - Comparison of Relationships between Electrical Resistance and Soil Matric Suction for Watermark 200 GM Sensors in Samples A, D and E

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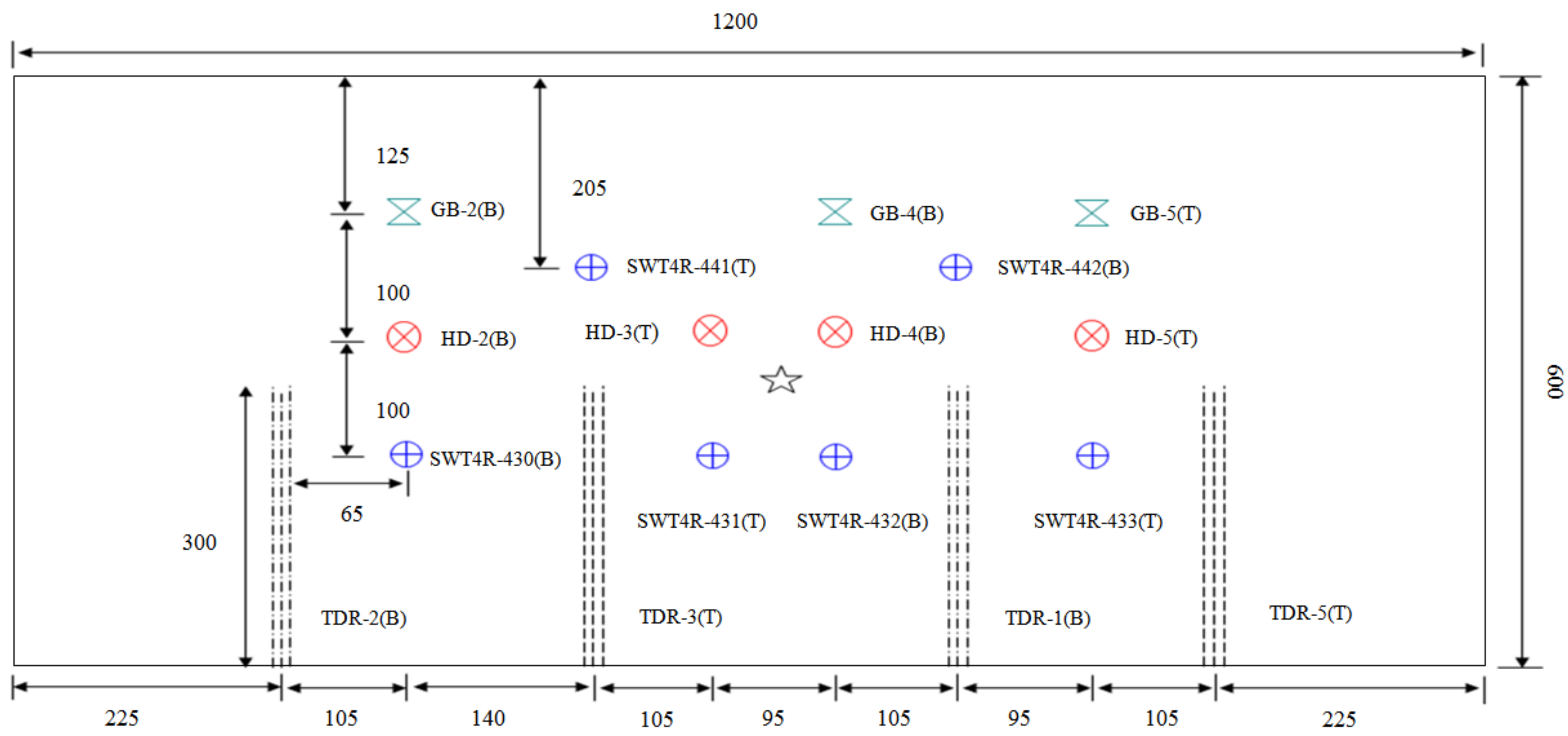

Legend:

⊕	SWT4R-432: SWT4R Tensiometer No. SWT4R-432	⊗	HD-2: 229 HD Sensor No. HD-2
⁞⁞⁞	TDR-2 : CS605 TDR Probe No. TDR-2	⌛	GB-5: Watermark 200 GM Sensor No. GB-5
☆	Thermo Probe		
(T)	at 230 mm below the soil surface	(B)	at 460 mm below the soil surface

Note: Dimensions in mm, not to scale.

Figure 44 - Layout of Sensor Installation (Phase II Tests)

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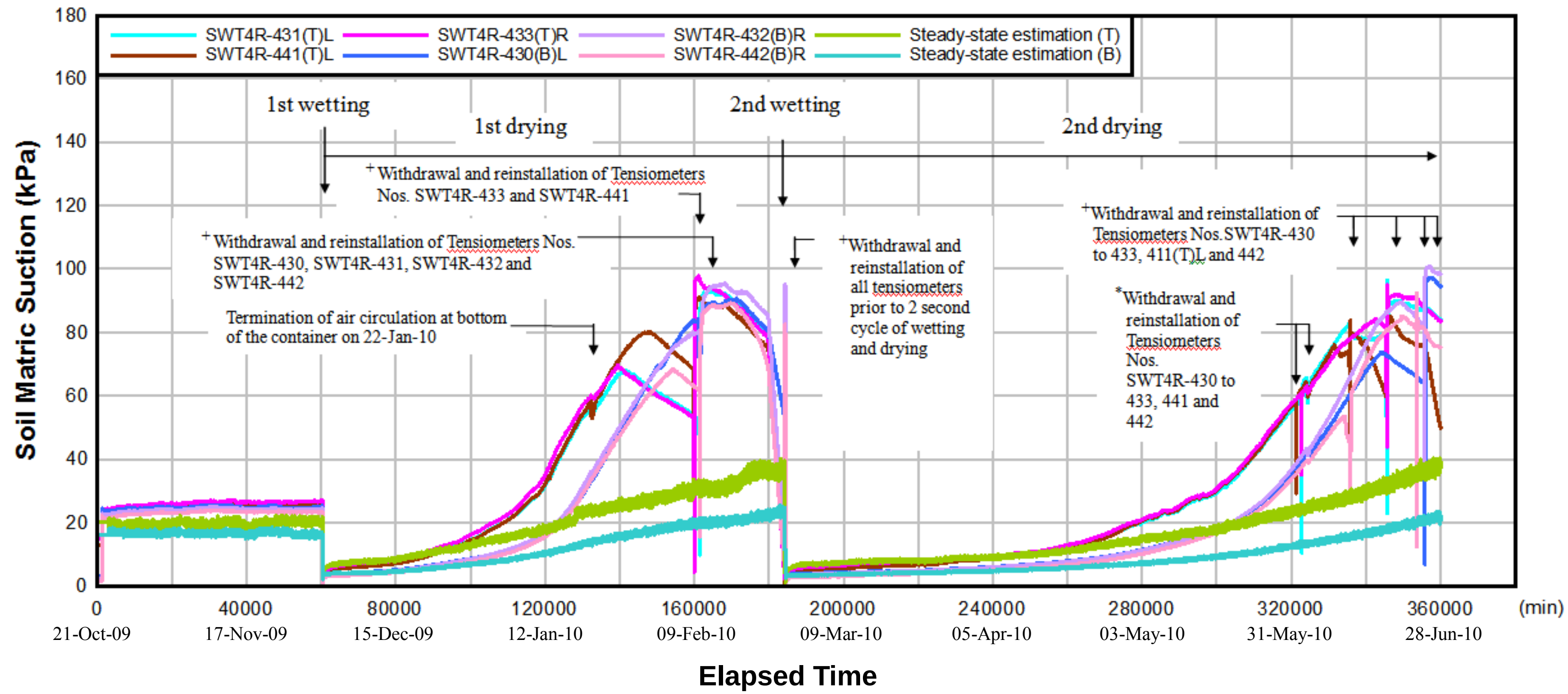

Notes:

(1) “T” (top monitoring level) denotes sensors installed at 230 mm below the soil surface and “B” (bottom monitoring level) at 460 mm below the soil surface.

(2) “L” denotes sensors installed in the left portion of the container and “R” in the right portion.

(3) The test soil is Soil Sample A compacted to 85% RC at about 15% MC.

(4) “Steady-state estimation (T)” denotes the soil matric suction estimation from the soil-water characteristic curve established under steady-state condition for Sample A, using the average soil moisture contents obtained from the CS605 TDR Probes installed at the top monitoring level.

(5) “Steady-state estimation (B)” demotes the soil matric suction estimation from the soil-water characteristic curve established under steady-state for Sample A, using the average soil moisture contents obtained from the CS605 TDR Probes installed at the bottom monitoring level.

(6) The soil-water characteristic curve for Sample A derived under steady-state condition (i.e. from the Phase I tests) is : s=6.419x104e-0.526w, where s= soil matric suction (kPa) and w= soil moisture content (%).

(7) “+” denotes refilling of the tensiometers after sudden drop of the tensiometer readings and “*” denotes refilling of the tensiometers before sudden drop of tensiometer readings was noted.

Figure 45 - Tensiometer Readings under Wetting and Drying Conditions

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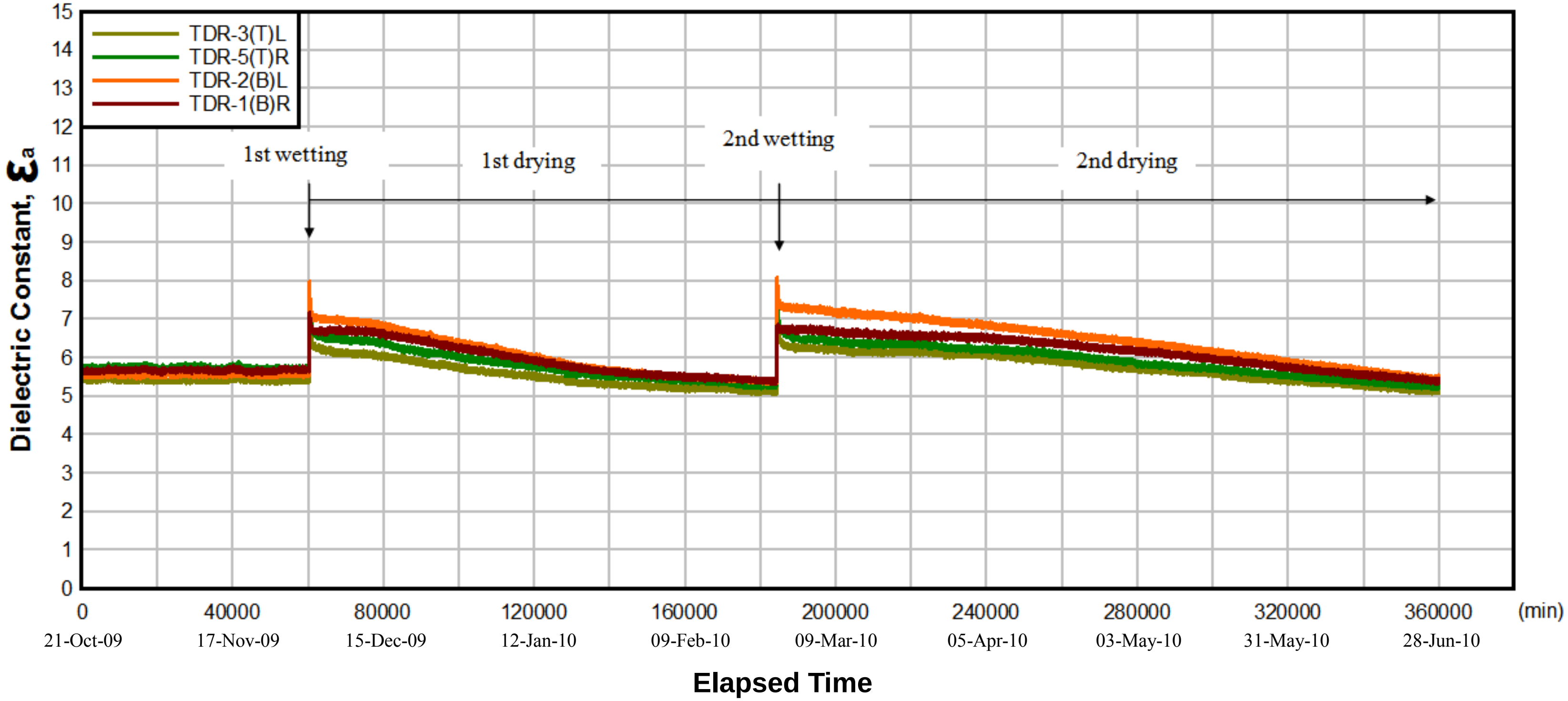

Notes:
(1) "T" (top monitoring level) denotes sensors installed at 230 mm below the soil surface and "B" (bottom monitoring level) at 460 mm below the soil surface.
(2) "L" denotes sensors installed in the left portion of the container and "R" in the right portion.
(3) The test soil is Soil Sample A compacted to 85% RC at about 15% MC.

Figure 46 - Readings from CS605 TDR Probes under Wetting and Drying Conditions

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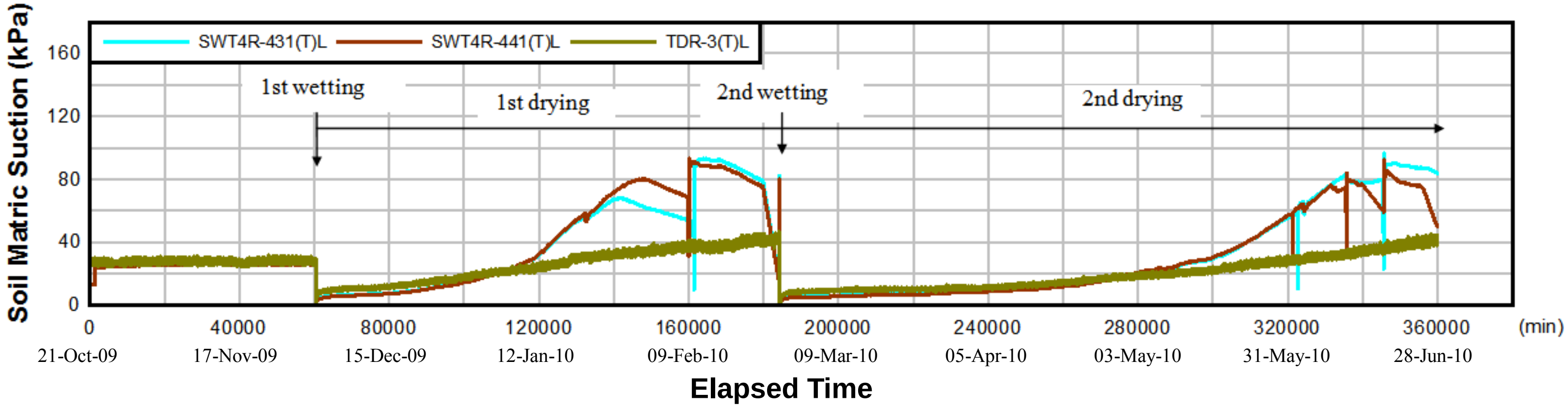
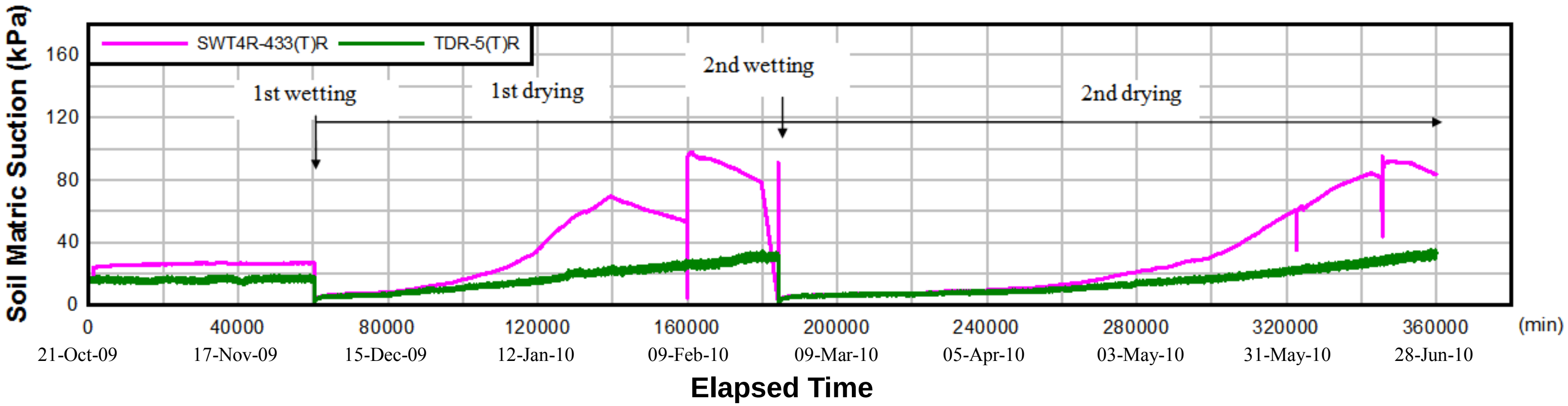


(a) Portion of Container



(b) Right Portion of Container

Notes:
(1) "T" (top monitoring level) denotes sensors installed at 230 mm below the soil surface.
(2) "L" denotes sensors installed in the left portion of the container and "R" in the right portion.
(3) The test soil is Soil Sample A compacted to 85% RC at about 15% MC.
(4) The soil matric suctions obtained from the TDR probes are based on the following relationships derived under steady-state condition (i.e. from the Phase I Tests): TDR-3: $s = 4.951x104e^{-1.385\varepsilon_a}$, TDR-5: $s = 4.868x104e^{-1.399\varepsilon_a}$, where s = soil matric suction (kPa) and ε_a = dielectric constant.

Figure 47 - Comparison of Soil Matric Suction from CS605 TDR Probes and Tensiometers at Top Monitoring Level

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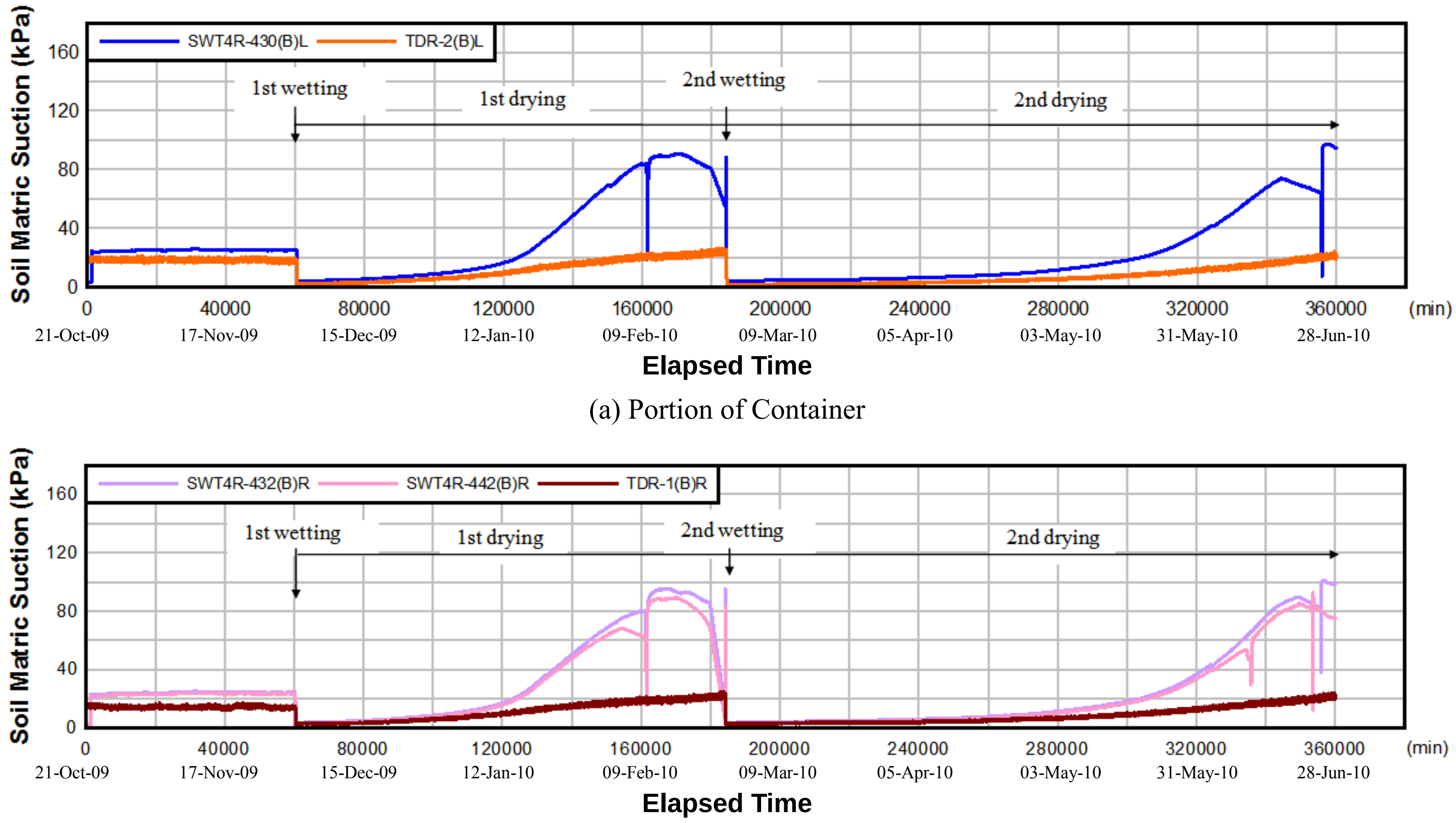

(a) Portion of Container

(b) Right Portion of Conta

Notes:
(1) "B" (bottom monitoring level) denoted sensors installed at 460 mm below the soil surface.
(2) "L" denotes sensors installed in the left portion of the container and "R" in the right portion.
(3) The test soil is Soil Sample A compacted to 85% RC at about 15% MC.
(4) The soil matric suctions obtained from the TDR probes are based on the following relationships derived under steady-state condition (i.e.from the Phase I Tests): TDR-1: $s = 7.904x104e^{-1.523\varepsilon_a}$, TDR-2: $s = 6.685x104e^{-1.479\varepsilon_a}$, where s = soil matric suction (kPa) and ε_a = dielectric constant.

Figure 48 - Comparison of Soil Matric Suction from CS605 TDR Probes and Tensiometers at Bottom Monitoring Level

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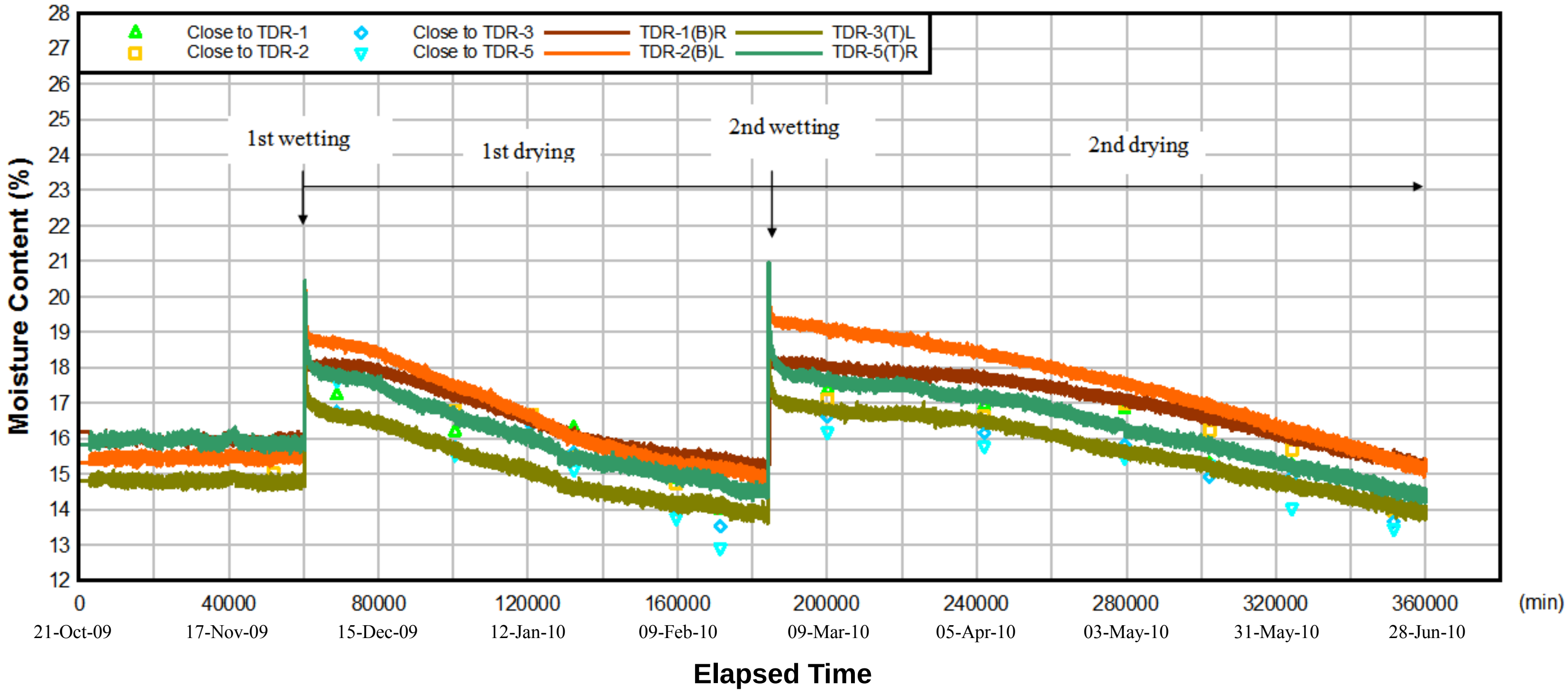

Notes:
(1) "T" (top monitoring level) denotes sensors installed at 230 mm below the soil surface and "B" (bottom monitoring level) at 460 mm below the soil surface.
(2) "L" denotes sensors installed in the left portion of the container and "R" in the right portion.
(3) The test soil is Soil Sample No. A compacted to 85% RC at about 15% MC.
(4) Discrete points of soil moisture contents were obtained from oven tests of soil samples from the container.

Figure 49 - Soil Moisture Content Obtained from CS605 TDR Probes and Oven Tests

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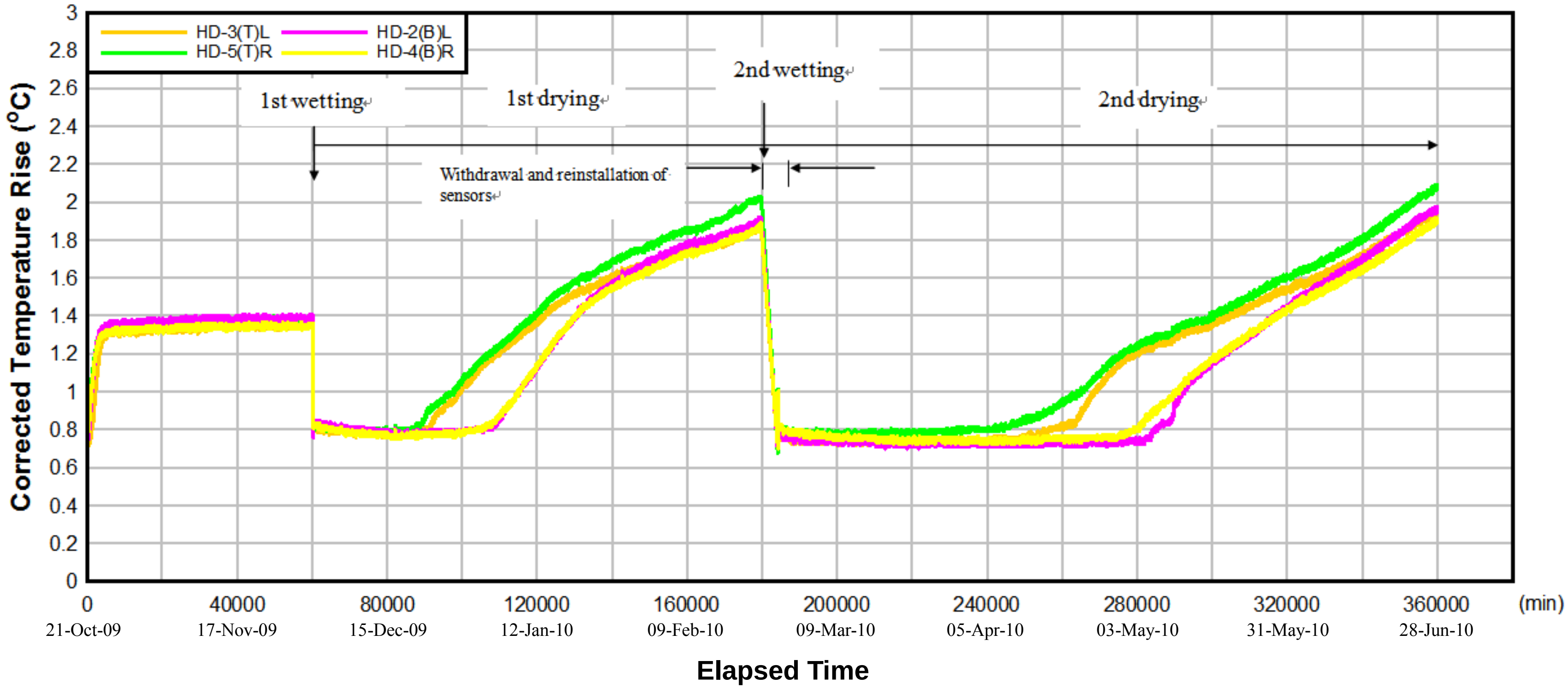

Notes:
(1) "T" (top monitoring level) denotes sensors installed at 230 mm below the soil surface and "B" (bottom monitoring level) at 460 mm below the soil surface.
(2) "L" denotes sensors installed in the left portion of the container and "R" in the right portion.
(3) The test soil is Soil Sample A compacted to 85% RC at about 15% MC.

Figure 50 - Readings from 229 HD Sensors under Wetting and Drying Conditions

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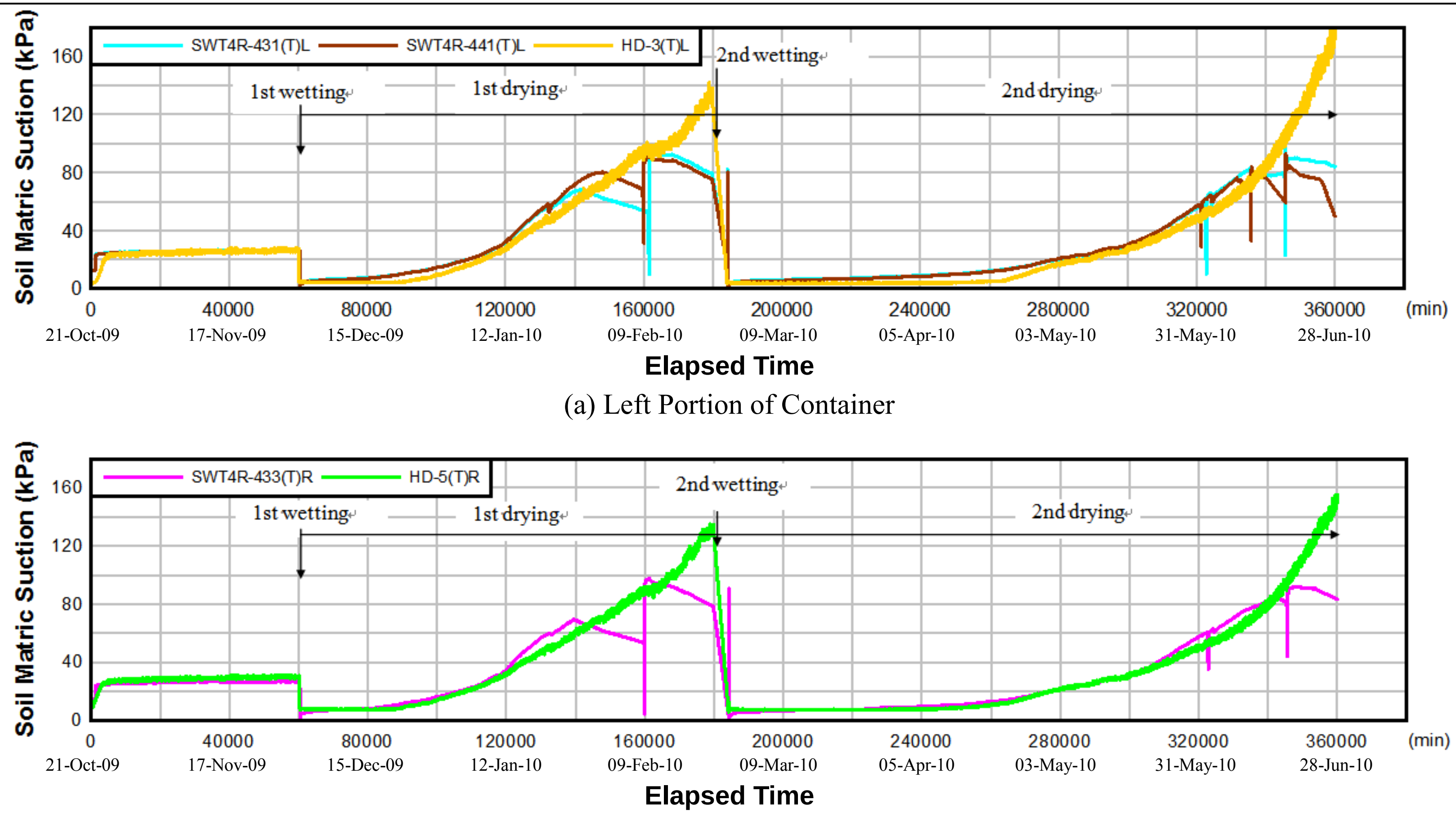

(a) Left Portion of Container

(b) Right Portion of Container

Notes:
(1) "T" (top monitoring level) denotes sensors installed at 230 mm below the soil surface.
(2) "L" denotes sensors installed in the left portion of the container and "R" in the right portion.
(3) The test soil used in test is Soil Sample A compacted to 85% RC at about 15% MC.
(4) The soil matric suctions obtained from the 229 HD Sensors are based on the following relationships derived under steady-state condition (i.e. from the Phase I Tests):
HD-3: $s = 0.371e^{3.162\Delta T}$, HD-5: $s = 1.175e^{2.338\Delta T}$, where s = soil matric suction (kPa) and ΔT = corrected temperature rise (°C).

Figure 51 - Comparison of Soil Matric Suction from 229 HD Sensors and Tensiometers at Top Monitoring Level

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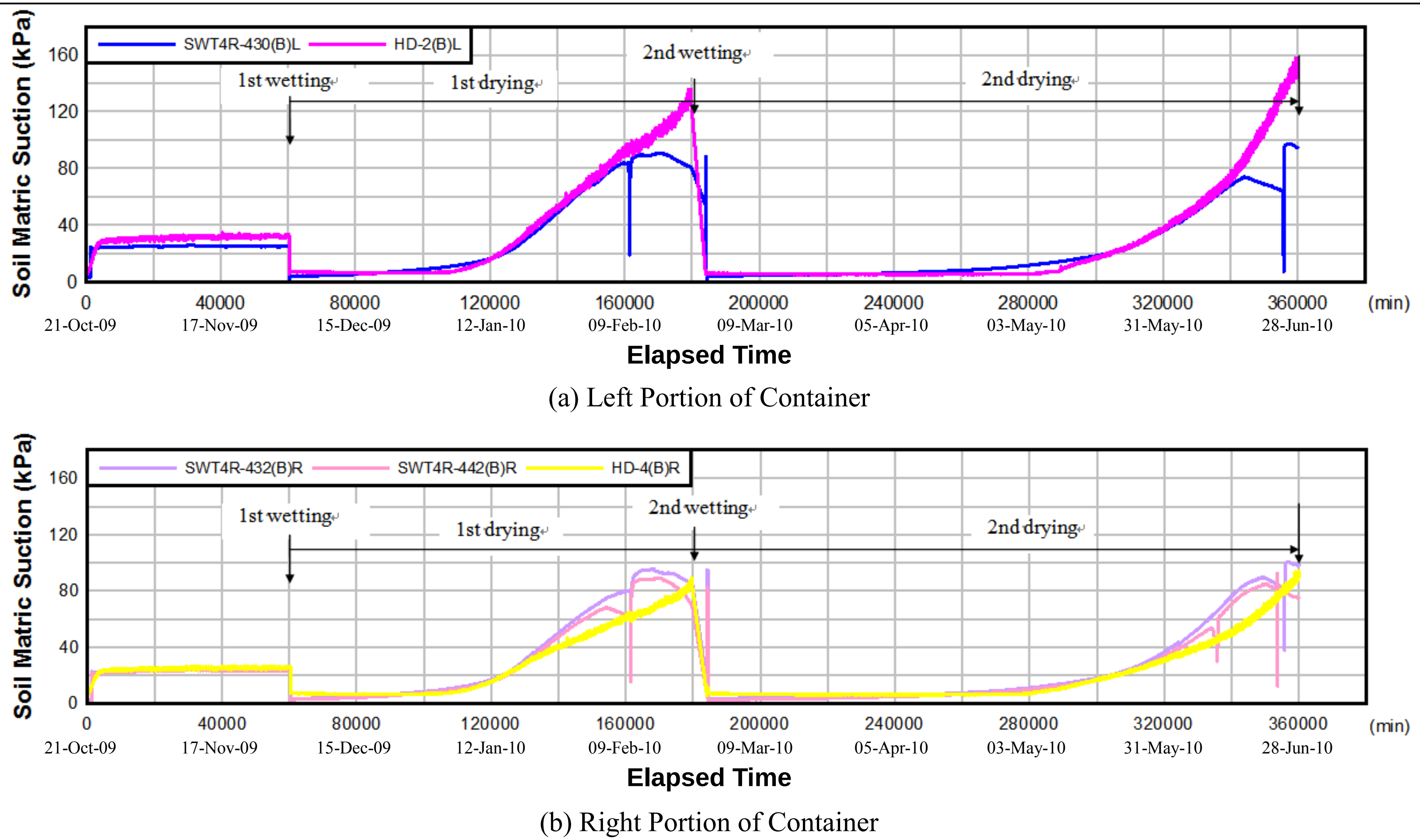

(a) Left Portion of Container

(b) Right Portion of Container

Notes:
(1) "B" (bottom monitoring lsevel) denotes sensors intalled at 460 mm below the soil surface.
(2) "L" denotes sensors installed in the left portion of the container and "R" in the right portion.
(3) The test soil is Soil Sample A compacted to 85% RC at about 15% MC.
(4) The soil matric suctions obtained from the 229 HD Sensors are based on the following relationships derived from the Phase I Tests (under steady-state condition): HD-2: $s = 0.723e^{2.726\Delta T}$, HD-4: $s = 1.155e^{2.299\Delta T}$, where s = soil matric suction (kPa) and ΔT = corrected temperature rise (°C).

Figure 52 - Comparison of Soil Matric Suction from 229 HD Sensors and Tensiometers at Bottom Monitoring Level

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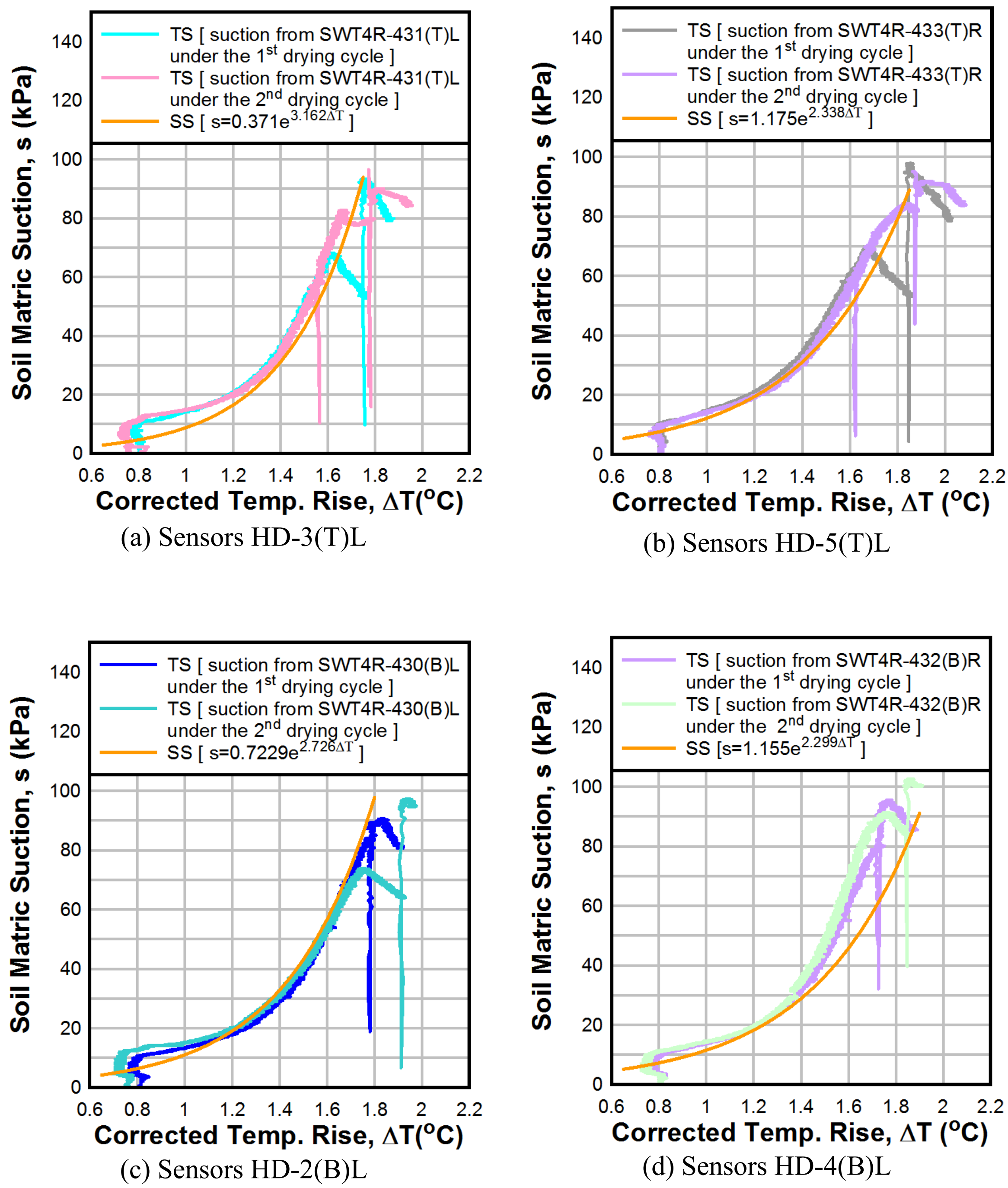

Notes:

(1) "TS" refers to the soil matric suction related to the temperature rise measurement under transient state condition.

(2) "SS" refers to the soil matric suctin related to the temperature rise measurement under steady state condition (i.e. the Phase I Tests).

(3) "T" (top monitoring level) denotes sensors installed at 230 mm below the soil surface and "B" (bottom monitoring level) at 460 mm below the soil surface.

(4) "L" denotes sensors installed in the left portion of the container and "R" in the right portion.

Figure 53 - Comparison of Relationships between Soil Matric Suction and Temperature Rise for 229 HD Sensors Based on Steady State and Transient State Measurements

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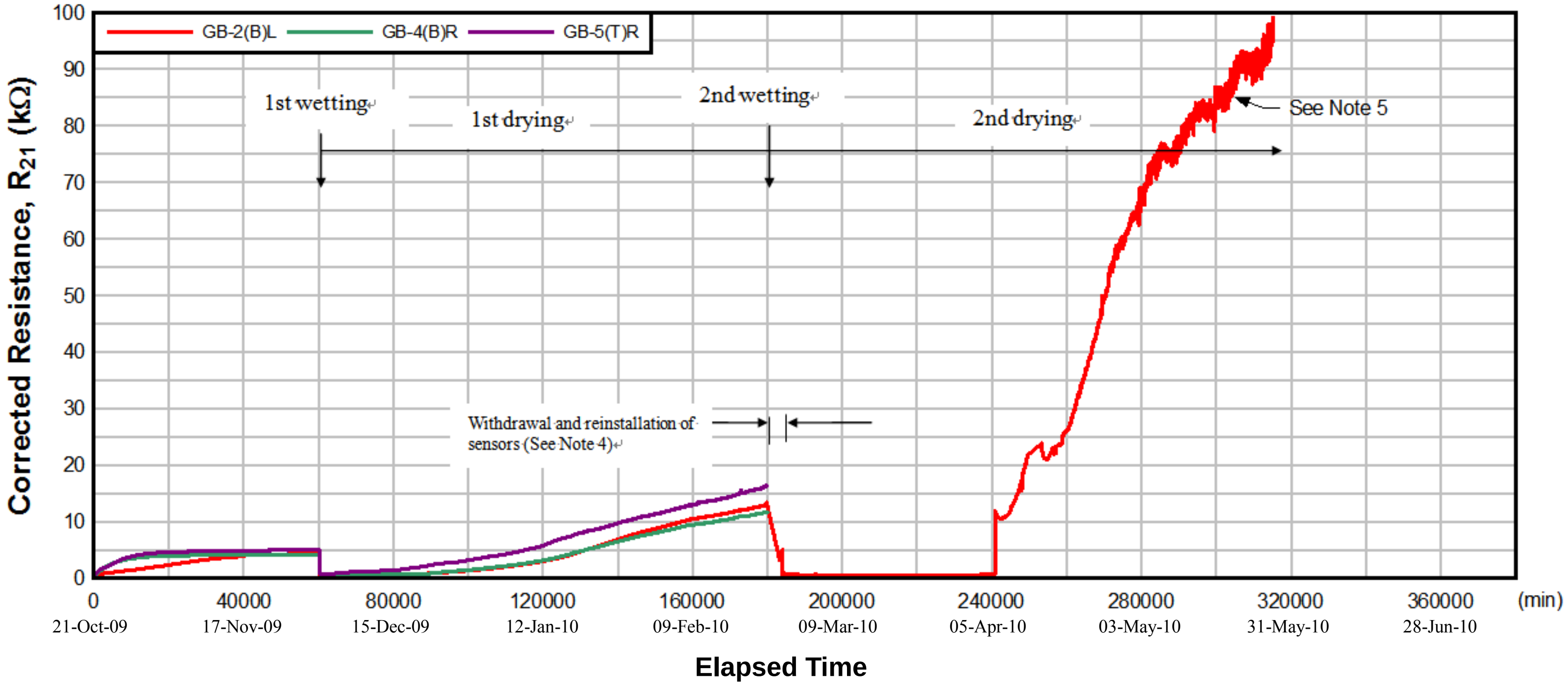

Notes:

(1) "T" (Stands for top monitoring level) denotes sensors installed at 230 mm below the soil surface and "B" (stands for bottom monitoring lsevel) at 460 mm below the soil surface.

(2) "L" denotes sensors installed in the left portion of the container and "R" in the right portion.

(3) The soil used in test is Soil Sample A compacted to 85% RC at about 15% MC.

(4) Sensor No. GB 4 was damaged during reinstallation and Sensor No. 5 malfunctioned when verification was conducted in water before the reinstallation.

(5) Sensor No. GB 2 malfunctioned with a rapid increase in the resistance reading to about 100 kΩ, based on which the estimated suction was over 2000 kPa.

Figure 54 - Readings from Watermark 200 GM Sensors under Wetting and Drying Conditions

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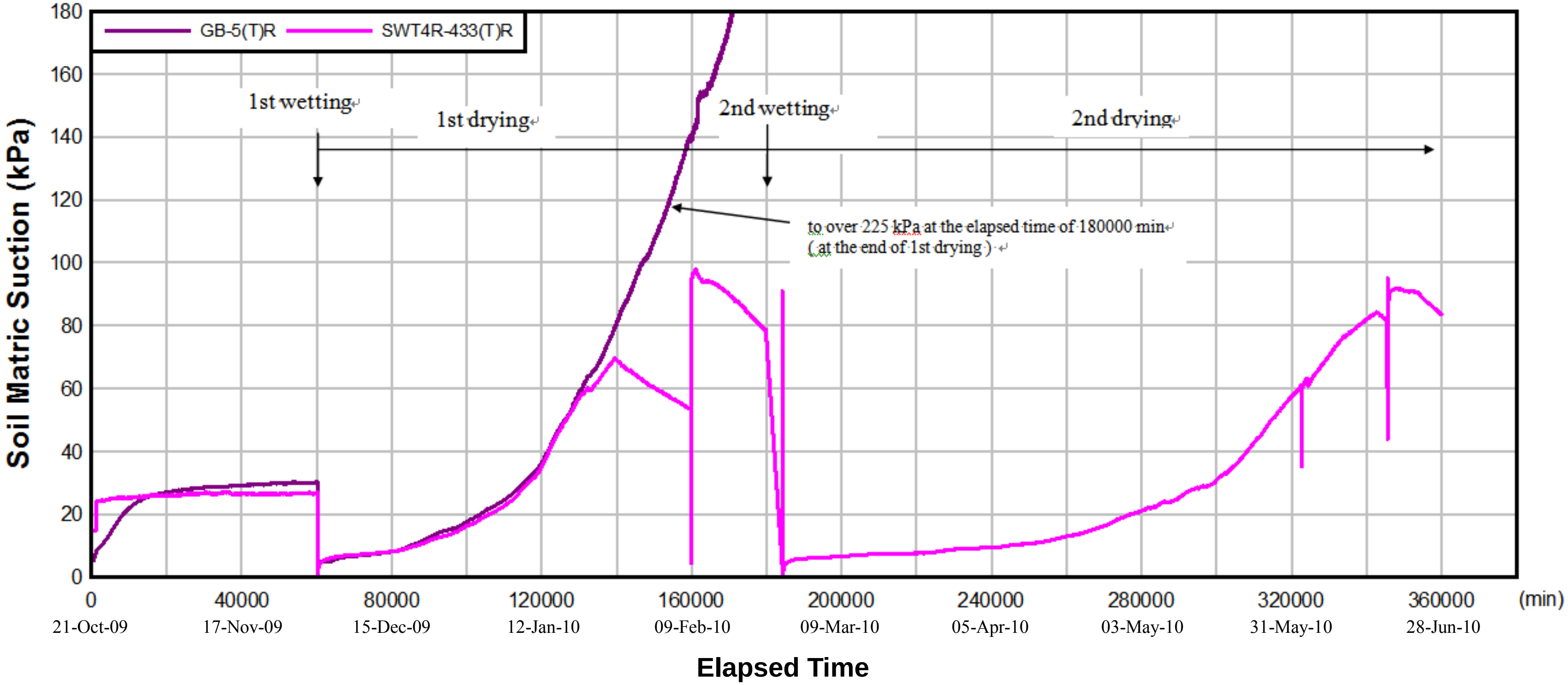

Notes:
(1) "T" (Stands for top monitoring level) denotes sensors installed at 230 mm below the soil surface.
(2) "L" denotes sensors installed in the left portion of the container and "R" in the right portion.
(3) The test soil is Soil Sample A compacted to 85% RC at about 15% MC.
(4) Because limited number of the GM Sensors were available for the test, only the right portion of the container at the top monitoring level was tested.
(5) The soil matric suctions obtained from the Watermark 200 GM Sensors are based on the following relationships derived from the Phase I Tests (under steady-state condition): GB 5: $s = -2.64+29.69e^{0.1339R21}$, where s = soil matric suction (kPa) and R_{21} = corrected resistance (kΩ).

Figure 55 - Comparison of Soil Matric Suction from Watermark 200 GM Sensors and Tensiometers at Top Monitoring Level

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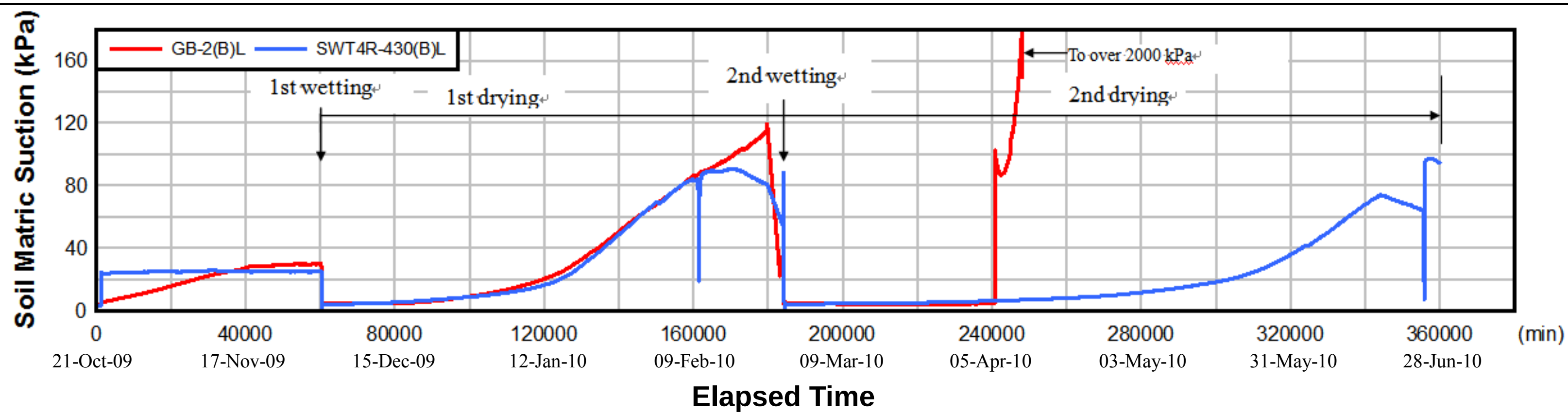
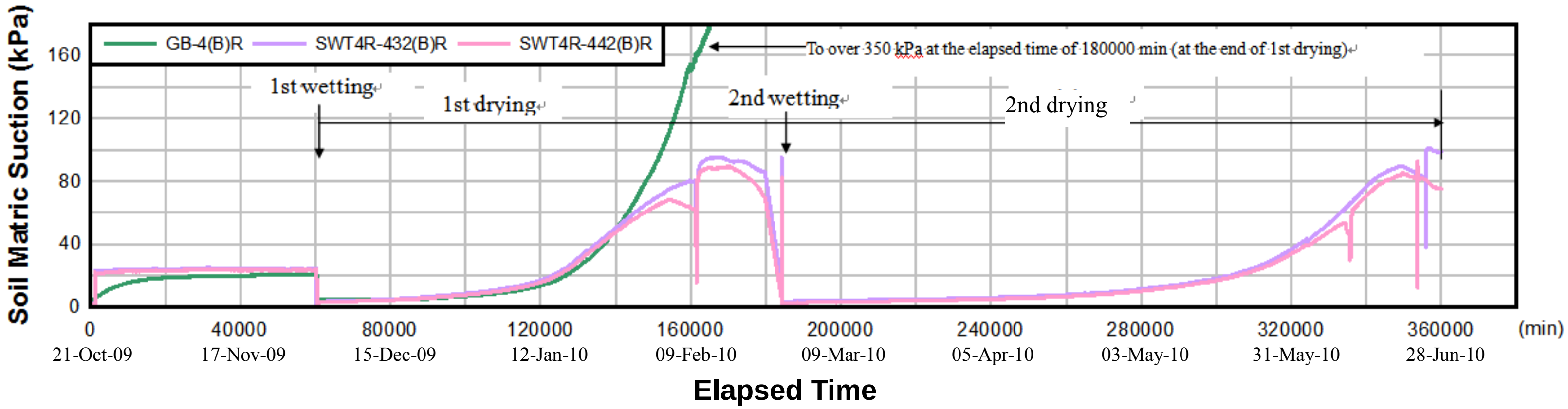


(a) Left Portion of Container



(b) Right Portion of Container

Notes:
(1) "B" (bottom monitoring level) denotes sensors installed at 460 mm below the soil surface.
(2) "L" denotes sensors installed in the left portion of the container and "R" in the right portion.
(3) The soil used in test is Soil Sample A compacted to 85% RC at about 15% MC.
(4) The soil matric suctions obtained from the Watermark 200 GM Sensors are based on the following relationships derived under steady-state condition (i.e. from the Phase I Tests):
GB 2: $s = -105.1+105.9e^{0.0564R_{21}}$, GB 4: $s = 0.7328+4.393e^{0.377R_{21}}$, where s = soil matric suction (kPa) and R_{21} = corrected resistance (kΩ).

Figure 56 - Comparison of Soil Matric Suction from Watermark 200 GM Sensors and Tensiometers at Bottom Monitoring Level

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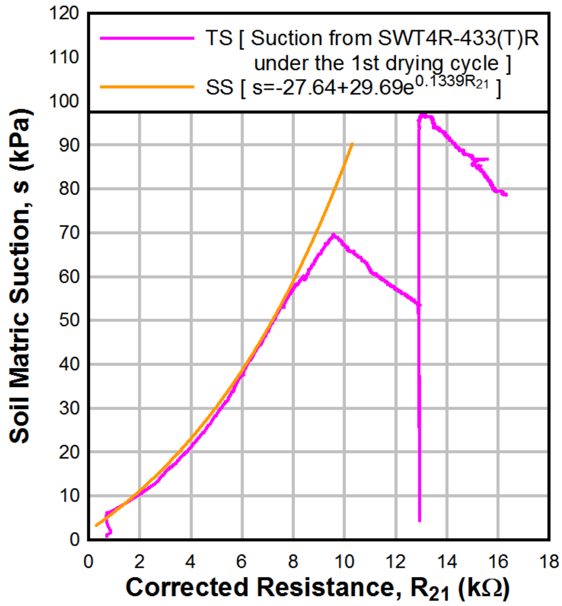
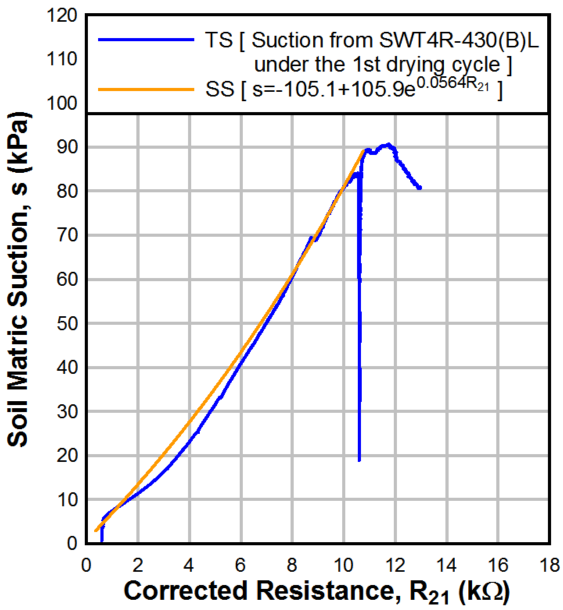
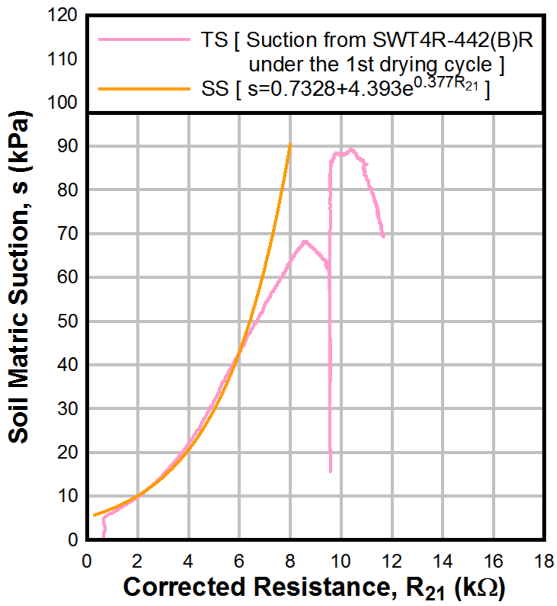


(a) Sensors GB-5(T)R



(b) Sensors GB-2(B)L



(c) Sensors GB-4(B)R

Notes:
(1) "TS" refers to the soil matric suction related to the sensor's change in resistance under transient state condition.
(2) "SS" refers to the soil matric suction related to the sensor's change in resistance under steady state condition. (i.e. Phase I Tests)
(3) "T" (top monitoring level) denotes sensors installed at 230 mm below the soil surface and "B" (bottom monitoring level) denotes sensors at 460 mm below the soil surface.
(4) "L" denotes sensors installed in the left portion of the container and "R" in the right portion.
(5) TS under the 2nd drying cycle was not provided as all the test sensors were found to have malfunctioined before and during the 2nd drying cycle.

Figure 57 - Comparison of Relationships between Soil Matric Suction and Electrical Resistance for Watermark 200 GM Sensors Based on Steady-state and Transient State Measurements

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LIST OF PLATES

Plate 1 - SWT4R Tensiometer

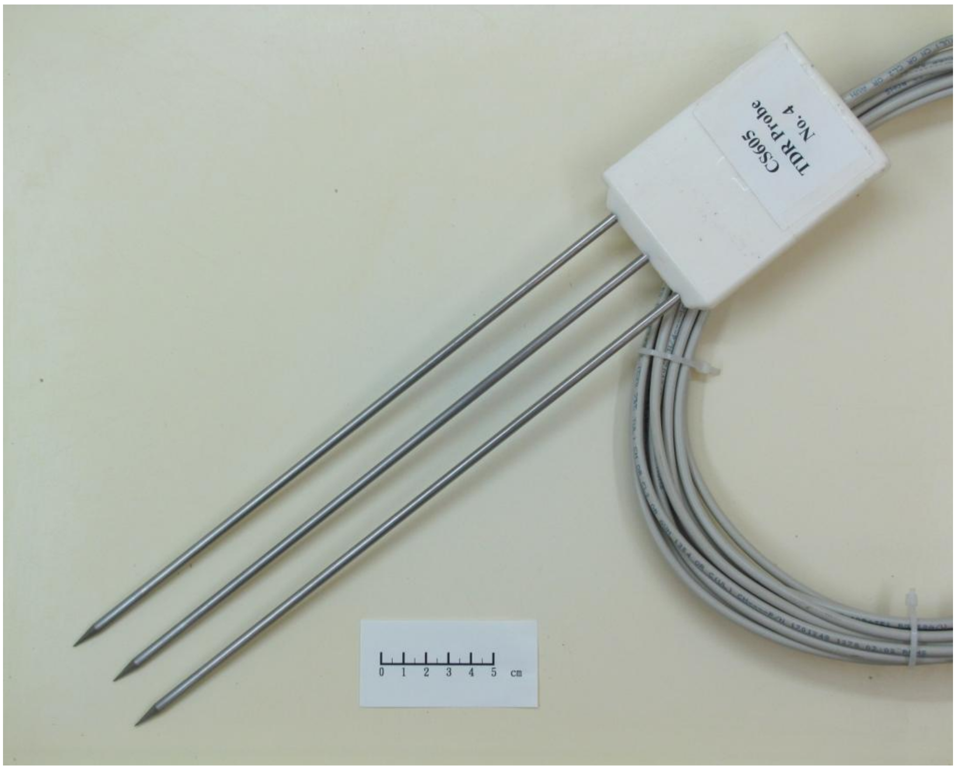

Plate 2 - CS605 TDR Probe

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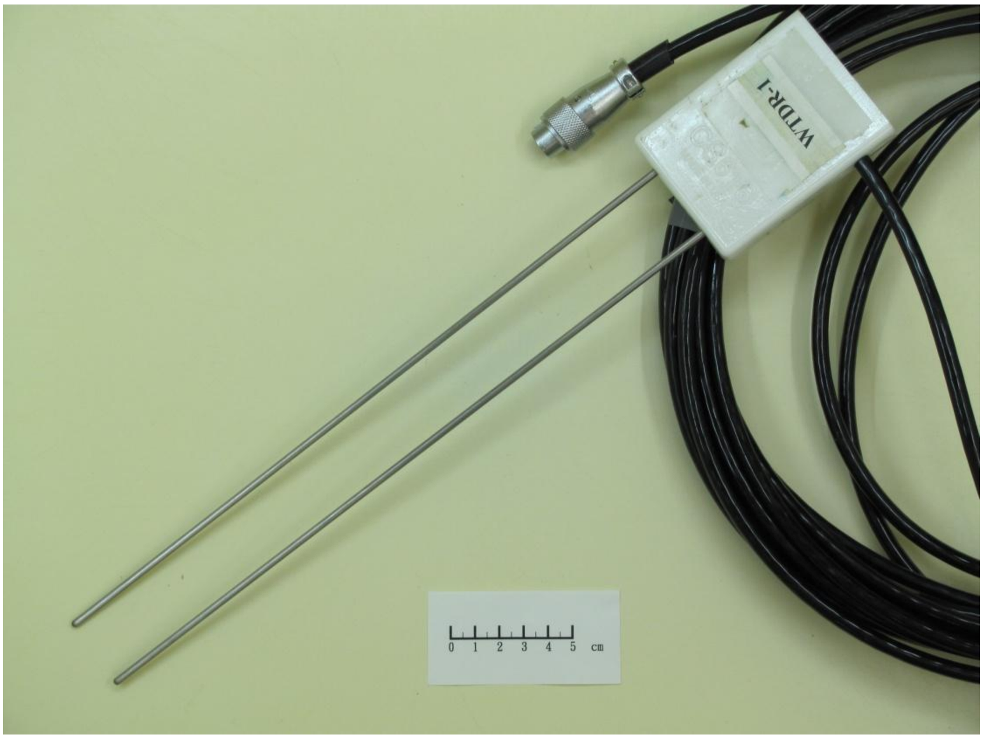

Plate 3 - CS616 WCR Probe

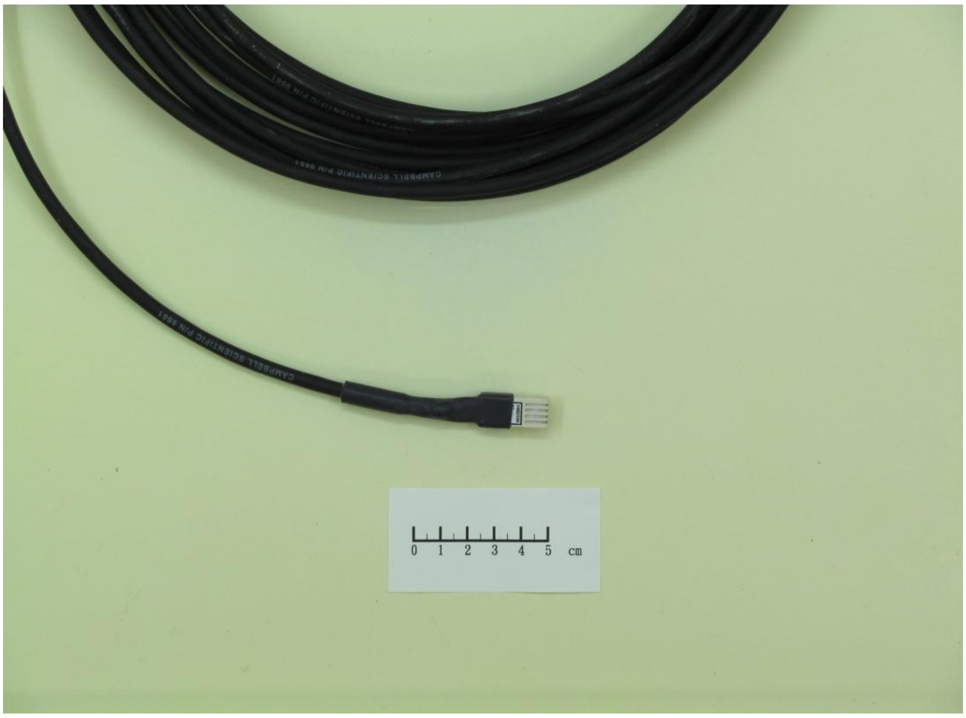

Plate 4 - CS210 Enclosure RH Sensor

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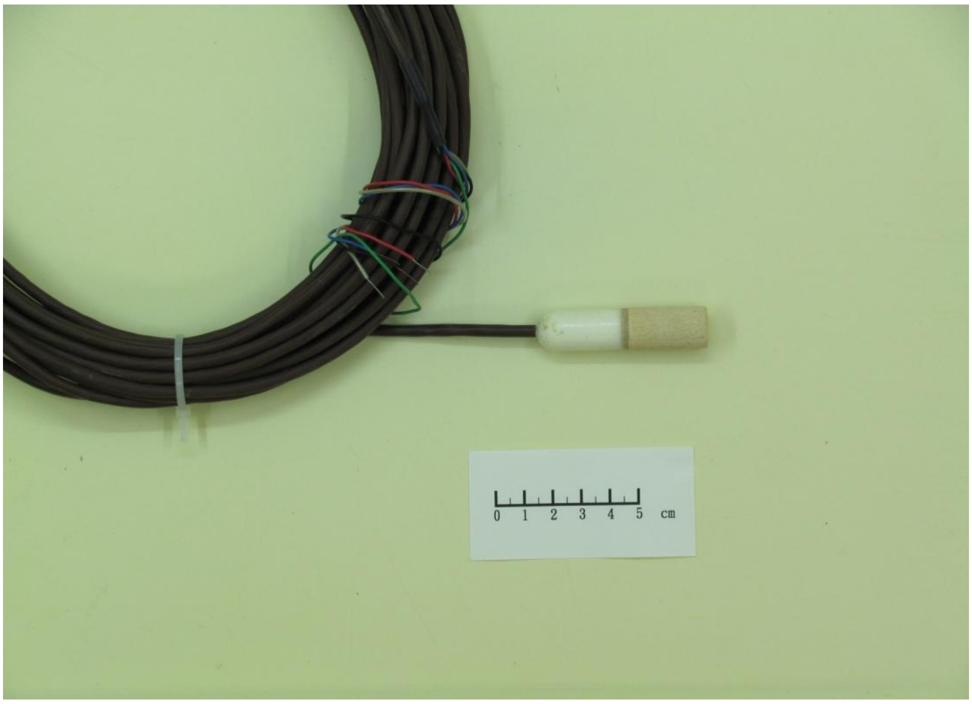

Plate 5 - 229 HD Sensor

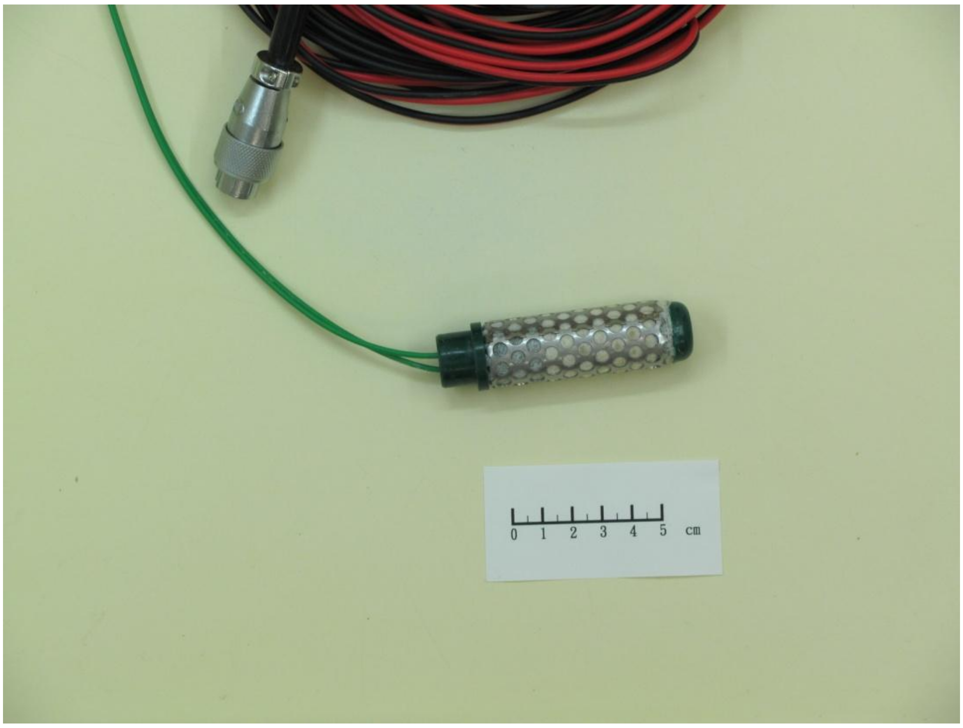

Plate 6 - Watermark 200 GM Sensor

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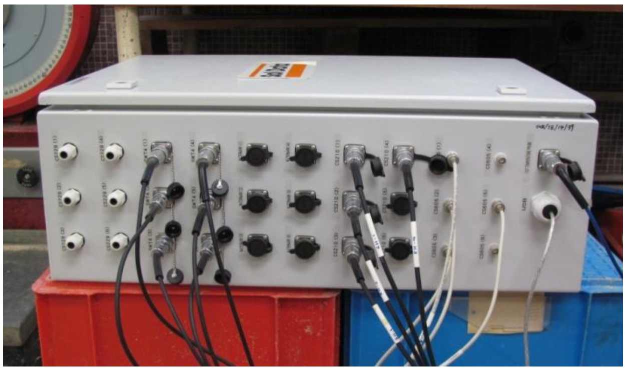
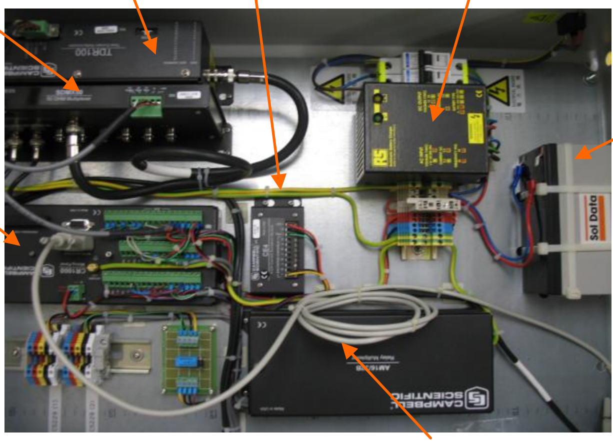
(a) Data Logger 1



(b) Data Logger 2



(c) Major Components of Data Logger

Plate 7 - Data Loggers

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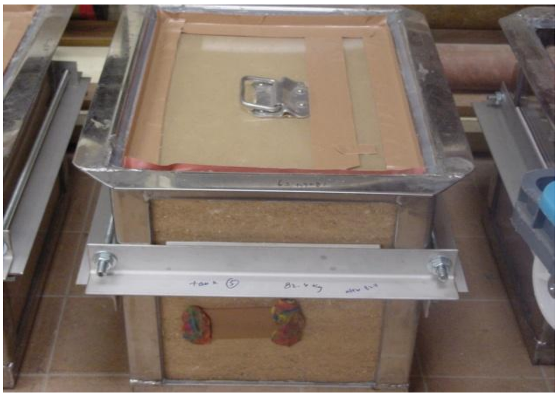
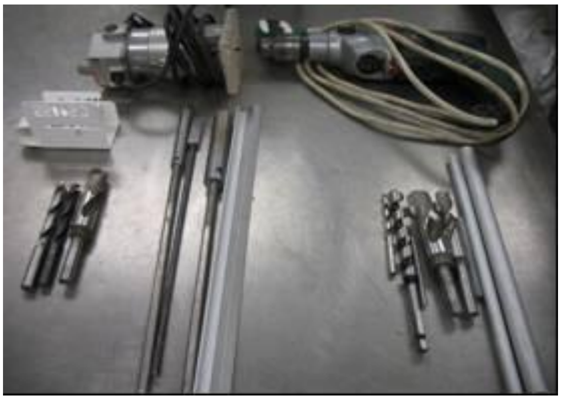
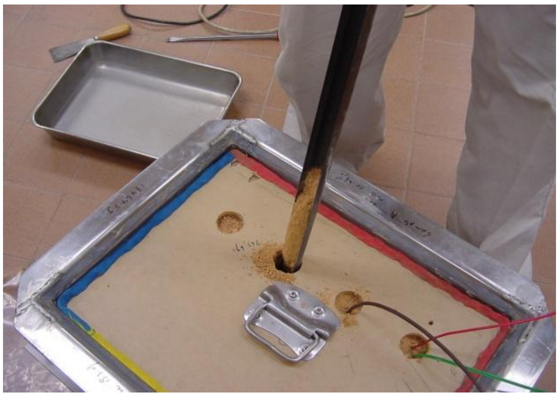


(a) Control Box (400L x 300W x 300H)

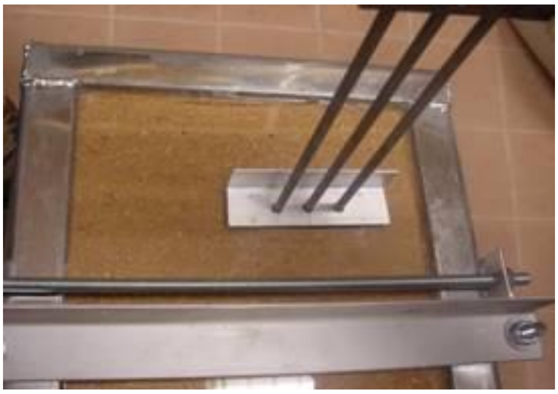


(b) Tools Used for Sensor Installation



(c) Predrilling to Test Depth by Augering

(d) Provision of Temporary Casing (where necessary)



(e) Installation of TDR/WCR Probes Using the Model Probe

(f) Test in Progress (box completely sealed)

Plate 8 - Control Box Used in the Study and Installation of Test Sensors

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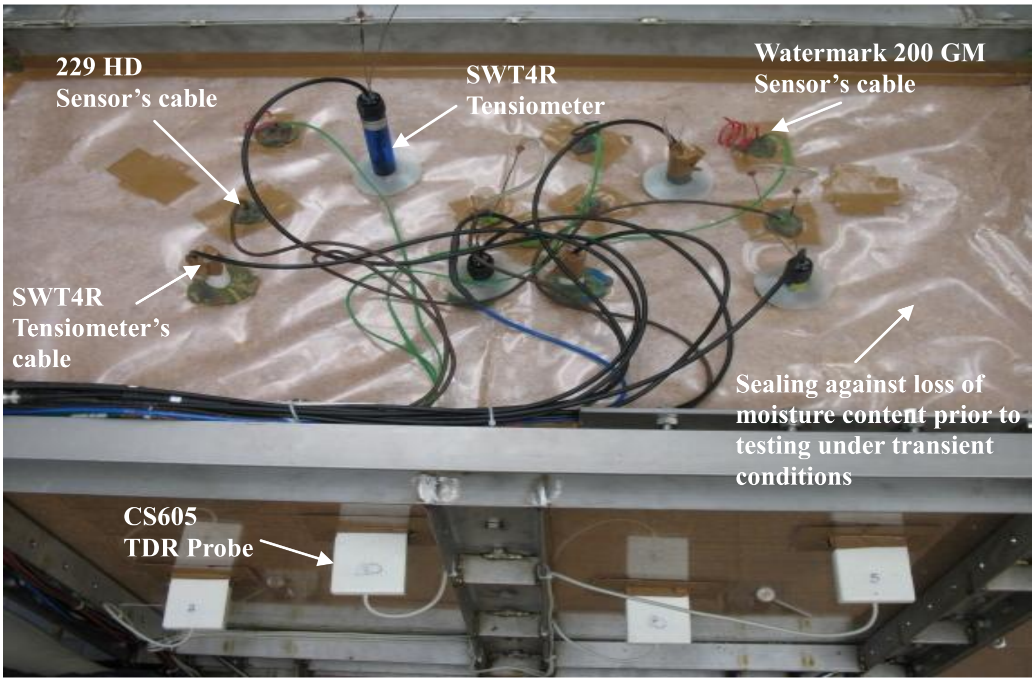
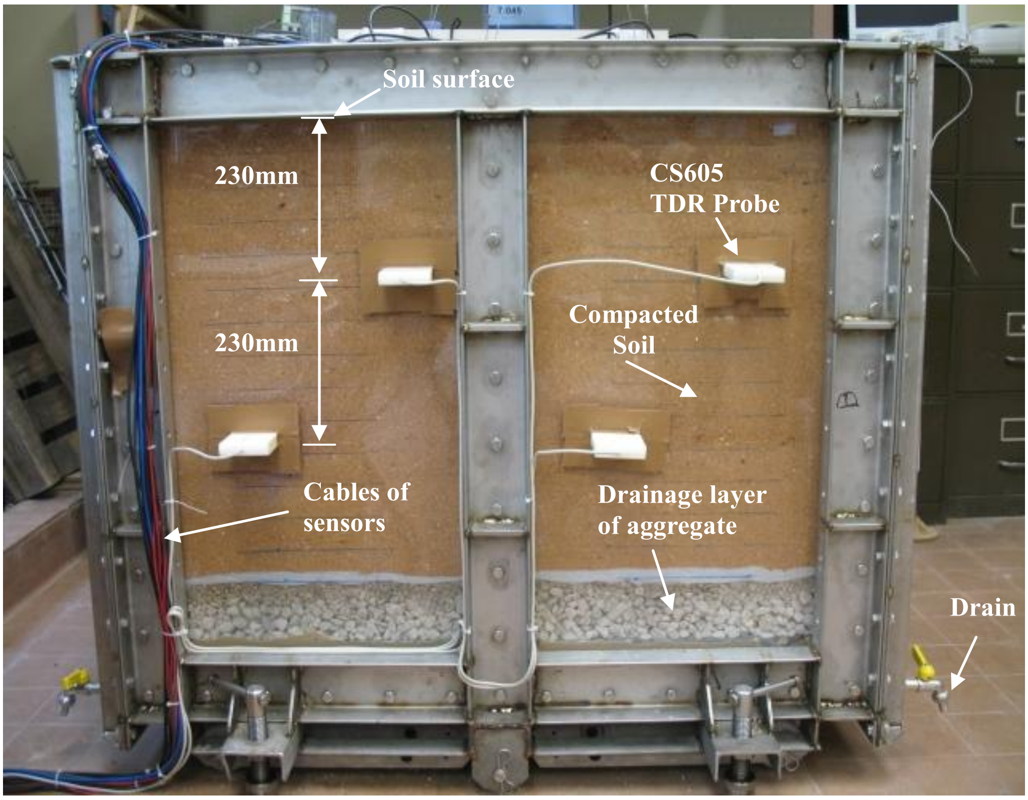


(a) Overview



(b) Front View

Plate 9 - Steel Container Used in the Study

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APPENDIX A

OPERATING PRINCIPLES OF THE TEST SENSORS

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A.1 SWT4R TENSIOMETER

SWT4R Tensiometer is a type of mini-tensiometer, comprising a high air entry ceramic filter (cup) connected to a pressure measuring device through a small plastic bore tube. The tensiometer is 300 mm long. As with other conventional tensiometers, it provides a direct measurement of negative pore water pressure in soil. Since a true semi-permeable membrane for soluble salts does not exist in the tensiometer (i.e. soluble salts are free to move through the ceramic filter cup), the effect of osmotic suction is not measured. The measured negative pore water pressure is numerically equal to the soil matric suction when the pore air pressure is atmospheric (i.e. zero gauge pressure). The measurement of soil matric suction requires hydraulic equilibrium between the soil water in the porous medium around the ceramic filter cup. The pore water outside the filter cup and the liquid in the interior of the tensiometer are bridged through water-filled fine pores of the cup. The pressure range is therefore limited by the air entry pressure value (150 kPa) of the ceramic filter cup as well as the cavitation (or boiling) pressure of water inside the tensiometer.

Unlike other large-scale tensiometers, the pressure sensor of the SWT4R Tensiometer is located immediately above the ceramic cup, thereby limiting the water column in the tensiometer within the cup only. As a result, the pressure correction due to the elevation head between the sensor and the mid-section of the ceramic filter cup will be limited to less than 0.5 kPa, which can be practically ignored. The tensiometer is also equipped with two small tubes that lead through the shaft to the ceramic filter cup for filling the cup with water externally. No correction is required for tensiometric measurement due to the temperature variation for this tensiometer, but attention is required for the insulation of the tensiometer portion that is above ground (i.e. in the event of the tensiometer not fully installed in the ground with the small tubes exposed to ambient environment) in order to avoid air bubbles growing inside the external tubes, as a result of any large temperature changes anticipated (Delt-T Devices Ltd, 2008). Capillary hysteresis will be also associated with tensiometric measurement, but it has been shown that the hysteretic behaviour could be significantly reduced with the full saturation of the tensiometer ceramic filter cup prior to measurement (Take & Bolton, 2003).

A.2 CS605 TDR PROBE

CS605 TDR probe consists of three pointed steel rods and an epoxy head connected with cables. The rods act as a wave guide in the test medium. The measurement is based on analysis of the behaviour of electromagnetic waves propagating through the test medium. In the measurement, a very fast rise time step voltage increase (electromagnetic pulse) is injected into the waveguide which carries the pulse to a probe placed in the medium. The propagation velocity of the pulse is monitored through the reflected waveforms, from which the apparent probe length in the medium can be determined. The dielectric constant (or apparent permittivity) of the medium as measured along the probe is determined using the following relationship: $\varepsilon_a = [La/L]^2$ (or $[ct/2L]^2$), where ε_a is the apparent permittivity of the medium, c is the light velocity, t is the traveling time measured along the probe and La is the apparent length of the probe.

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Because the dielectric constant of soil depends primarily on the amount of water present in the soil, the soil volumetric water content (θ) can be inferred from the measured dielectric constant. For the CS605 TDR Probes, the supplier has used the empirical relationship, $\theta = (-530 + 292\varepsilon_a - 5.5\varepsilon_a^2 + 0.043\ \varepsilon_a^3)/10^4$), which was proposed by Topp et al (1980), to relate the dielectric constant to the volumetric water content. In turn, the volumetric water content (or alternatively the gravimetric water content), or the measured dielectric constants, may be related directly to the soil matric suction, as the capillary phenomenon (i.e. matric suction) is a result of the pore water being held in the pores between soil particles.

While the dielectric constants of water is related to the temperature variation (Coym, 2004; Meissner & Wentz, 2004), no temperature correction was recommended in the user manual (Campbell Scientific Inc., 2009a) for the probe. However, it is noted that ASTM D6780 (2005) has laid down a TDR method for determining the water content and in-situ density of soils, and recommended the procedures for temperature correction.

A.3 CS616 WCR PROBE

The WCR Probe has two, 300 mm long, pointed steel rods connected to a probe head. The CS616 WCR Probes and the CS625 WCR Probe as adopted in OAP (2009) are basically the same. The only difference between these two model types is the use of a different data logger system. Whilst the CS616 WCR Probe is adaptable to the data logger system employed in this study, the CS625 WCR Probe is suitable for use with the small CR 200 series data loggers (Campbell Scientific, Inc., 2006a).

The CS616 WCR Probe works on a similar operating principle to that of CS605 TDR Probe, involving the propagation of an electromagnetic pulse along the wave guide. It does not require a separate pulse generating unit. The pulse is generated by a circuit within the probe head, whereby the arrival of the reflected pulse from the wave guide will trigger the next pulse. The probe does not output the dielectric constant of the test medium as in the normal TDR probes. Instead, it measures and outputs the wave guide signal reflection time in µsec (i.e. the period of the applied voltage), which in turn can be related to the water content of the test medium using an empirical relationship obtained through calibration. A temperature correction function is recommended by the supplier to correct the output periods for this probe. The supplier has also proposed an empirical relationship: $\theta = 0.0007\ \tau_{corr}^2 - 0.0063\ \tau_{corr} - 0.0663$, where θ is volumetric water content and τ_{corr} is corrected output period (µsec), for use of the probe to estimate the volumetric water content from the output period reading.

Kellener et al (2005) have studied the performance of this probe. The results showed that the performance of the probe may be affected by the dielectric dispersion and ionic conductivity of the soil. They suggested that the performance may be improved if the frequency of the operation can be increased to greater than 1 GHz, as the probe would become less sensitive to ionic conductivity at higher frequencies.

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A.4 CS210 ENCLOSURE RH SENSOR

The CS210 Enclosure RH Sensor is a bulk polymer relative humidity sensor composed of interdigitated metal fingers on substrate with a proprietary polymer coating placed over the surface. It changes resistance as the humidity changes. Typically, as the ambient humidity increases, the water absorbed by the polymer will increase. As a result, the resistance will decrease.

The use of this humidity sensor is not reported by the supplier (Campbell Scientific, Inc., 2007) for measuring the humidity of vapour space of the soil. Although the attempted measurement did not prove to be successful in this study (see Section 3), the total suction can in principle be evaluated based on the humidity in the soil, using Kelvin's law (Fredlund & Rahardjo, 1993).

A.5 229 HD SENSOR

The 229 HD Sensor comprises a 15 mm long cylindrically-shaped porous ceramic tip of 25 mm in diameter, in which a thermocouple is included together with a heating element. It uses the heat dissipation principle to indirectly measure the soil water suction. The measurement relies on the hydraulic continuity between the soil and sensor ceramic for water exchange. During the measurement, the water within the sensor will be heated up and the temperatures at the start and end of the heating process will be taken. As the temperature difference would depend on the water content as well as the thermal properties of the ceramic, it can be used in the calibration to relate to the soil matric suction.

Since the initial temperature of the sensor is sensitive to the rise in temperature and that the sensor property is temperature dependent, it is also necessary to normalize and correct the temperature difference. Flint et al (2002) proposed a set of normalization and correction procedures. Empirical relationships can then be established to correlate the temperature rise with the soil matrix suction. For example, Fisher (2002) has proposed a relationship expressed in terms of an exponential function: $s = e^{\alpha\Delta T + \beta}$, where s is soil matric suction, ΔT is the temperature rise, and α and β are constants.

The supplier of 229 HD Sensor (Campbell Scientific Inc., 2006b) has embedded the relevant coding in the data logger program (see Section 2.3). Feng & Fredlund (2003) have carried out tests on similar sensors, and demonstrated that the porous tips of this type of sensor were subject to hysteresis effect. The test results have shown that the hysteresis effect could attribute to an error of 30% to 70% for suction measurement higher than 100 kPa.

A.6 WATERMARK 200 GM SENSOR

The sensor consists of a 35 mm long perforated stainless steel cylinder of 32 mm in diameter supporting a permeable membrane. Inside the membrane is a tightly packed sand aggregate ("granular matrix" (GM)), concentric electrodes and a gypsum block close to the electrodes. The gypsum block provides buffering against soil acidity and salinity that may affect the readings, so that the electrical resistance between the electrodes would be dependent on moisture and temperature only.

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The sensor works on the electrical resistance principle. The water conditions in the unit change with variations in the soil's moisture content, with change reflected by the electrical resistance between the electrodes.

DC currents must not be allowed to flow through the wet part of the circuit as an irreversible reaction may occur, resulting in damage to either electrode. AC excitation must be used to avoid damages that may result from DC currents, which could give rise to irreversible reactions in the wet circuit.

The relationship between the electrical resistance reading and soil matrix suction is empirical. A number of empirical relationships have been published (e.g. Shock et al, 1998; Irmak & Haman, 2001; Eldredge et al, 1993). The relationships adopted by the supplier of the sensors include a linear function as well as a non linear function proposed by Thompson & Armstrong (1987). The supplier also suggested a temperature correction function to adjust the measured resistance to a reference temperature of 21°C (Campbell Scientific, Inc., 2009b). Detailed information on the hysteresis effects of this sensor could not be identified from the literature in this study, but it is understood that hysteresis can also be associated with this sensor type (Hu et al, 2010).

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Highway Slope Manual (2000), 114 p.

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Geoguide 7	Guide to Soil Nail Design and Construction (2008), 97 p.

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The Quaternary Geology of Hong Kong, by J.A. Fyfe, R. Shaw, S.D.G. Campbell, K.W. Lai & P.A. Kirk (2000), 210 p. plus 6 maps.

The Pre-Quaternary Geology of Hong Kong, by R.J. Sewell, S.D.G. Campbell, C.J.N. Fletcher, K.W. Lai & P.A. Kirk (2000), 181 p. plus 4 maps.

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