University of Southern Queensland

Faculty of Engineering and Surveying

Sensitivity of Capacitance Probes to Soil Cracks

A dissertation submitted by

Michael Scobie

In fulfilment of the requirements of

Courses ENG4111 and ENG4112 Research Project

Towards the degree of

Bachelor of Engineering (Environmental)

Submitted: January, 2006

Abstract

Capacitance probes are used in agriculture to allow the real time measurement of soil moisture to assist in irrigation scheduling. This type of frequency domain measurement system is fast replacing the older, neutron probe technology. Clay soils have a tendency to form cracks around the access tube as they dry. In dry conditions, these cracks may cause the sensors to give readings which could be lower than the actual moisture content. In wet conditions (immediately following a rainfall or irrigation event) the cracks could fill with water and cause the sensors to give a reading higher than the actual moisture content. Soil and water based experiments were undertaken in order to gain an understanding of the behaviour of a Sentek EnviroSCAN ® in terms of soil moisture, soil temperature, and salinity effect allows conclusions to be drawn on how these probes respond in cracking clay soils.

Similar work was conducted by Paltineanu and Starr (1997), and although some methodology and experimental procedures vary slightly, their work is used in many cases as a basis for results comparison.

Soil was packed around an EnviroSCAN ® access tube into a 293mm (ID) x300 mm deep sleeve. Sensor readings were collected from the centre of the soil mass. The cylindrical soil mass was then reduced in diameter by inserting smaller sleeves and shaving off the soil from the outside. Results indicated that 99% of the sensors response is obtained from within 72mm from the outside of the PVC access tube.

Experiments were conducted to investigate the degree to which temperature affects the capacitance probe response. The temperature experiments were undertaken by oven drying and heating the soil which gave little variation in response. This may be explained by the work of Paltineanu and Starr (1997) in that soil water is required in order to gain a response from soil temperature variation.

Water based experiments were also undertaken to determine the effects of varying electrical conductivity on the probes response. As discussed in Kelleners et al (2004) increased electrical conductivity resulted in the probe reporting moisture contents in excess of the actual volumetric moisture content (θ_v)

University of Southern Queensland

Faculty of Engineering and Surveying

ENG4111 & ENG4112 *Research Project*

Limitations of Use

Prof G Baker
Dean
Faculty of Engineering and Surveying

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Michael Scobie

Student Number: Q95239074

____
Signature

____
Date

Acknowledgments

Firstly I would like to thank my supervisor, Rabi Misra for all of his help, time and patience

I would like to thank the National Centre for Engineering in Agriculture and Sentek Australia for the provision of the equipment used in this series of experiments.

I would also like to thank Chris Galligan, Brian Aston, Glenn Bartkoski, Bernhard Black and Dan Eising the USQ engineering workshop and soils laboratory.

I especially would like to thank my wife for providing me with the opportunity to return to full time study and to complete this degree

Table of Contents

List of Figures

•

List of Tables

Chapter 1. Introduction

Irrigated agriculture covers 2.4 million hectares in Australia (ABS, 2005). Being the driest inhabitable continent in the world means that for irrigated agriculture to be a sustainable practice, efficient use of available water is essential.

Applying appropriate amounts of water at the right place in the field at the right time in the season for optimal plant growth is the philosophy behind for efficient water use. Determining the values of these parameters in real time is a challenging practice. Technologies exist to indirectly measure the soil moisture status in the field, which may assist a grower in making decisions about the timing and amount of irrigation necessary to fulfil a crop’s requirements.

Tools for this application include a variety of soil moisture probes. These probes have been widely used in agricultural applications because the data that they provide can be used to schedule irrigation which in turn assists is improving water use efficiency. The neutron and gamma probes which have been used for many years are being replaced with the safer TDR (time domain reflectometry) and capacitance probes. All soil moisture probes estimate soil moisture a discrete location in the field. This means that the readings that are taken are from a single point source are then inferred to be representative of the entire field.

Some clay soils are prone to shrinking and swelling as they change in moisture content. This shrinking and swelling can form surface and sub surface cracks in the soil. These cracks are of concern in point source moisture monitoring applications as they have the capacity to affect the probes readings if they are in contact with, or near the access tube (Kelleners et al, 2004).

Further developing the knowledge on the behaviour of capacitance probes assists the user to understand the effects that soil cracking has on the output form the probe and therefore improves basis for decision making .

1.1 Aims

The broad aim of the project is to investigate the behaviour of a capacitance probe when used in a single soil type while varying soil moisture and soil thickness surrounding the probe as well as other possible variables including soil temperature and salinity.

It is seen that the application of the results may provide insight to the infield behaviour of the probes in the presence of cracked soil. Similar work has been completed by Paltineanu and Starr (1997) and several comparisons are made between their work and the work presented here.

1.1.1 Project Aims

The project specification (Issue B) (Appendix A) delivered on the 16 May 2005 lists the specific project aims as

1. Research the background information on the behaviour and sensitivity of soil moisture measurement focusing on time domain and frequency domain (capacitance) probes.
2. Design a suitable apparatus to create compacted soil of known bulk density and water content which will allow successive reductions in the diameter of the apparatus in order to detect any variation in readings by the sensor
3. Develop suitable methods to collect, characterize and process soil materials for testing the sensitivity of capacitance probes
4. Investigate the effects of volumetric water content and bulk density of soil on the measured water content by a capacitance probe
5. Analyse results to evaluate the sensitivity of the capacitance probe to soil moisture within varying volumes of soil
6. Discuss the application of results to measurement of soil moisture in cracking clay soils

1.1.2 Aim of the Dissertation

The aim of the document is to present the information found during the work listed in the above section. Furthermore this dissertation contributes to satisfying the requirements of the course ENG4111and ENG4112 Engineering Research Project as part of the Bachelor of Engineering program at the University of Southern Queensland

1.2 Dissertation Overview

This document has been produced in chapters with three levels of subheadings to allow easy navigation through the work presented. Below is a brief outline of what is contained in each chapter.

Chapter 1 Introduction

This chapter provides an introduction to the reasons for undertaking this project and the aims of the project as specified in the Project Specification – Issue B (Appendix A).

Chapter 2 Background

Chapter 2 discusses in detail the techniques of soil moisture measurement especially focussing on the indirect methods using capacitance probes. It then explains how capacitance probes are commonly used in irrigation scheduling and then briefly describes cracking clay soils.

Chapter 3 Materials and Methods

In this chapter the material used including the Sentek EnviroSCAN ® and the testing apparatus is discussed. Also a description of the soil used and a full description of the methods used in both the soil and water based experiments conducted for this project. For simplicity the experiments conducted have been categorised into either soil based experiments or water based experiments.

Chapter 4 Results and Discussion

This chapter of the document presents the results obtained from the soil and water based experimental analysis. The results are presented as graphs and tables which are then discussed with respect to the impact on cracking clay soils. An analysis of the potential sources of experimental error has also been included in this chapter.

Chapter 5 Conclusions and Recommendations

Chapter 5 shows which of the tasks proposed in the Project Specification have been completed as well as some brief conclusions and suggestions for further work in this field.

Chapter 2. Background

Irrigated agriculture is thought to have started in what is now the Middle East between the Tigress and the Euphrates rivers (Upshur et al, 2002). Nowadays irrigation is an essential part of agriculture for crops requiring regular watering events. All crops have different water use requirements, and subsequently there are various methods of irrigation available to the grower. The question of when to irrigate and how much water to apply involves several unknowns including future weather variables and the current soil water status. While typically weather forecasting can be highly variable, there is some degree of certainty in the various forms of soil moisture measurement.

2.1 Soil moisture measurement

Soil is a complex heterogeneous mixture of solids, liquids and gases as well as a vast number of micro-organisms (Jury & Horton, 2004). The volumetric soil moisture content (θ_v) is the standard parameter for soil moisture measurement in agricultural applications and is defined as the volume of water associated with a given volume of soil (Brady & Weil, 1999).

The gravimetric method is a direct method of measuring soil water content and is simply the ratio of the weight of water to the weight of solids in a sample (Craig, 1997). While this parameter alone does not provide detail on the porosity of the soil it is used in the calculation of the more comprehensive volumetric soil moisture ($\square_v$) parameter. The gravimetric moisture content is calculated using Equation 1.

Equation 1

$$\theta_g = \frac{(M_w - M_S)}{M_S}$$

(McIntyre and Loveday, 1974)

Where	θ_g	Gravimetric moisture content	(g/cm^3)
	M_w	Wet mass of sample	(g)
	M_S	Mass of soil solids	(g)

The gravimetric soil moisture content can then be converted into a volumetric measurement using Equation 2

Equation 2

$$\theta_V = \theta_g \times \frac{\rho_B}{\rho_w}$$ (McIntyre and Loveday, 1974)

Where			
	θ_V	Volumetric moisture content	(cm^3/cm^3)
	θ_g	Gravimetric moisture content	(g/g)
	ρ_B	Bulk density	(g/cm^3)
	ρ_w	Density of water @ 20°C = 1.00	(g/cm^3)

This type of direct soil moisture measurement is not considered as the ideal method for determining soil moisture in agricultural application. The direct method is destructive and requires the removal of a sample from the field for laboratory analysis. Further direct methods do not allow for instantaneous or continuous soil moisture measurements.

It is for this reason that indirect methods were established. Indirect methods are comprised of nuclear techniques and electromagnetic techniques (Kelleners et al, 2004). The development of electromagnetic techniques have made nuclear techniques including the neutron scattering probe less appealing. Leib, Jabbro & Matthews (2003) state that the neutron probe is essentially a device which emits radiation, the device therefore has inherent safety issues. Regulations governing the use of radioactive materials have also made neutron scattering methods less desirable to the user (Baumhardt et al, 2000).

Lane and Mackenzie (2001) and Kelleners et al, (2004) suggest that the capacitance probe is faster, cheaper and safer and also has better resolution and is more easily automated than the neutron scattering probe. In addition, frequency domain techniques (capacitance probes) are operationally more simple than TDR (Dirksen, 1999)

2.2 Capacitance Probes

Capacitance Probes are an electromagnetic method for measuring soil moisture content. They allow for real time monitoring and as such are widely used as an irrigation management tool (Fares and Alva, 2000).

There are several commercially available capacitance probes which vary by design but the principals behind the devices are the same. The probes electrodes are places in the soil in such a manner that the soil surrounding them acts as the dielectric of a capacitor in a resonant circuit. The inductance of the circuit is fixed and the resonant frequency varies dependant on the dielectric properties of the soil, water, air mix (Dane and Topp, 2002).

Capacitance probes are able to respond to small changes in volumetric soil moisture because a relatively small amount of water (with its high dielectric constant) can significantly increase the average dielectric constant of the soil, water air mix (Morgan et al, 1999)

The probe design can be adapted to suit various electrode configurations which are then buried or pushed into the soil. The electrode configurations may take the form of two or more parallel rods or 1 of more pairs of brass rings which are separated by a non conductive plastic ring (Dane and Topp, 2002).

The capacitance probe used in the series of experiments presented in this document was the EnviroSCAN ® supplied by Sentek (Adelaide, Australia). Figure 2-1 is a sketch of the brass ring electrode configuration used in the EnviroSCAN ® capacitance probe.

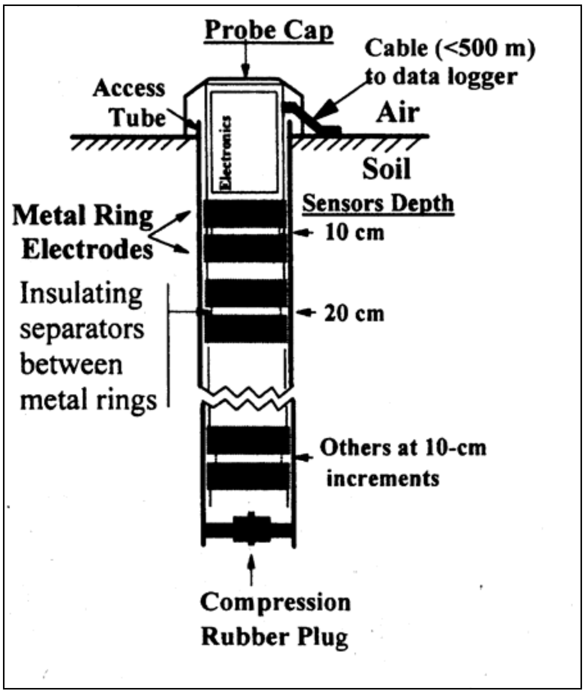


Figure 2-1 **EnviroSCAN ® capacitance probe** **(Dane and Topp, 2002)**

Dane and Topp (2002), list the positive features of capacitance probes as robust and stable instrumentation, fast response times, accuracy with good soil-probe contact, ease of use, safety, availability in several sensor configurations, and ability to be linked to an automatic data logger. However, for a capacitance probe to function correctly it is absolutely essential that there is good contact between the access tube and the surrounding soil materials (Kelleners et al, 2004). de Rosny et al (2001) also found the sensitivity of the capacitance probe to soil moisture was significantly reduced when good contact between the access tube and surrounding soil is not maintained.

Like neutron scattering methods and TDR, the accuracy of soil moisture estimates from a capacitance probe is largely dependant on the equation used to convert the raw signal into a moisture content in cm^3 cm^{-3}. While Sentek provides a default calibration equation derived from sands, loams and clay loams, it is common practice to generate a calibration equation for the particular soil type that is being used and Jabbro et al (2005), have stated that not only soil specific but site specific calibration is essential for precise soil moisture content.

The calibration equation used to convert the output from the probe into a moisture content must be of the form given in Equation 3.

Equation 3

$$y = Ax^B + C$$

Where y = Scaled Frequency
x = Volumetric soil water content in mm
A, B, C = Calibration coefficients determined experimentally

The default values supplied by Sentek for the coefficients are:

A = 0.19570
B = 0.40400
C = 0.02852

The scaled frequency is discussed in further detail in Chapter 3.1.3

Despite Jabbro et al (2005) claim, Sentek (2001) have suggested that for the typical irrigator that uses a capacitance probe, purely for irrigation scheduling purposes, soil and site specific calibration is not important. Sentek (2001) have also stated that most of the economic gains recorded with their capacitance probe in commercial agriculture have been made using the concept of “relative change” in soil water.

2.3 Irrigation Scheduling

Increased knowledge of the relationships between soil, water and plants, produces better technologies and management strategies which allow a more efficient use of resources.

Irrigation scheduling is a management strategy based on understating the amount of water in the soil that is available to plants at any given time. From this knowledge a grower can determine when are the optimum times and rates required to fulfil the plants needs.

If irrigation scheduling is undertaken correctly, it should both increase yield, because available water should never be the limiting factor, and increase water use efficiency, because the amount of water applied should match the requirements of the plant and limit losses to deep drainage (Meyer, 1985).

The strategy is based on understating the amount of water required by the plant and the amount of water stored in the soil at any given time. From this knowledge a grower can determine when are the optimum times and amounts to irrigate to fulfil the plants needs. Meyer (1985) has suggested two methods of calculating the soil moisture balance.

1) Through measurement, either directly by soil sampling, which is destructive and not often practical during the growing season, or by the use of soil moisture measuring probes which has been discussed earlier.
2) A method based on meteorological variables that can be used to calculate the evaporative capacity of the weather conditions and the transpiration rates of the plant.

Using a capacitance probe to provide soil moisture information for irrigation scheduling allows instant and continuous information that can be remotely accessed if necessary by a GSM modem.

The risk involved in using only a capacitance probe is apparent in the presence of cracked soils especially when the cracks are surrounding the access tube. There is the potential for erroneous raw counts to be recorded by the capacitance probe sensors as they detect the air gap. These results may cause the irrigator to make decisions based on misinformation on the soils water status and potentially over irrigate.

2.4 Cracking Clay Soils

Clay soils can form either in place or after translocation of decomposed minerals and the recombination of weathered materials (Singer and Munns, 1996).

A cracking clay as the term suggests is a soil (>35% clay (McKenzie et al, 1999)) that has a tendency to significant swelling and shrinking as it becomes wet or dry (Marshall and Holmes, 1988). Clays that crack on a small scale (distance between cracks <100mm) can be treated the same as any other soil. However soils that form cracks of greater than 100mm wide require particular management strategies in order to work with them effectively (Dane and Topp, 2002).

Cracking clays are generally the soils of either alluvial plains (south eastern and eastern Australia) or the slightly undulating uplands of the arid southwest (Hubble, 1984). Australia has large areas of cracking clay soils which form a major part of the county's soil resources (Hubble, 1984) comprising much of the Darling Downs and it is the seasonal wetting and drying of the soil whichcauses surface and sub surface cracking (McKenzie et al, 1999).

The study of water flow in cracking clays is an area of complex soil physics. (Smiles, 1984) and the use of capacitance probes for soil moisture detection inherits many of these difficulties. However the water holding capacity of these soils (McDonald et al, 1984) and the flat or gently sloping terrain on which they are found make for an attractive site for cropping enterprises.

Chapter 3. Materials and Methods

3.1 Sentek EnviroSCAN capacitance probe

3.1.1 Design

As mentioned in Chapter 2.2, the capacitance probe used in this series of experiments was the Sentek EnviroSCAN ®.

The probe used consists of a circuit board and six sets of brass rings which form the electrodes (Figure 3-1) discussed in Chapter 2.2. Each pair of brass rings acts as one sensor which is approximately 100mm in length including circuitry, with the sensors being spaced 100mm apart (centre to centre). This allows the user to install the probe into the access tube and continuously and instantaneously monitor or access the moisture content at specific depths below the soil surface. Additional sensors can be added on to a probe until all possible positions on probe are filled. The usual configuration is to measure at every 100mm or 200mm below surface to the rooting depth of the plant.

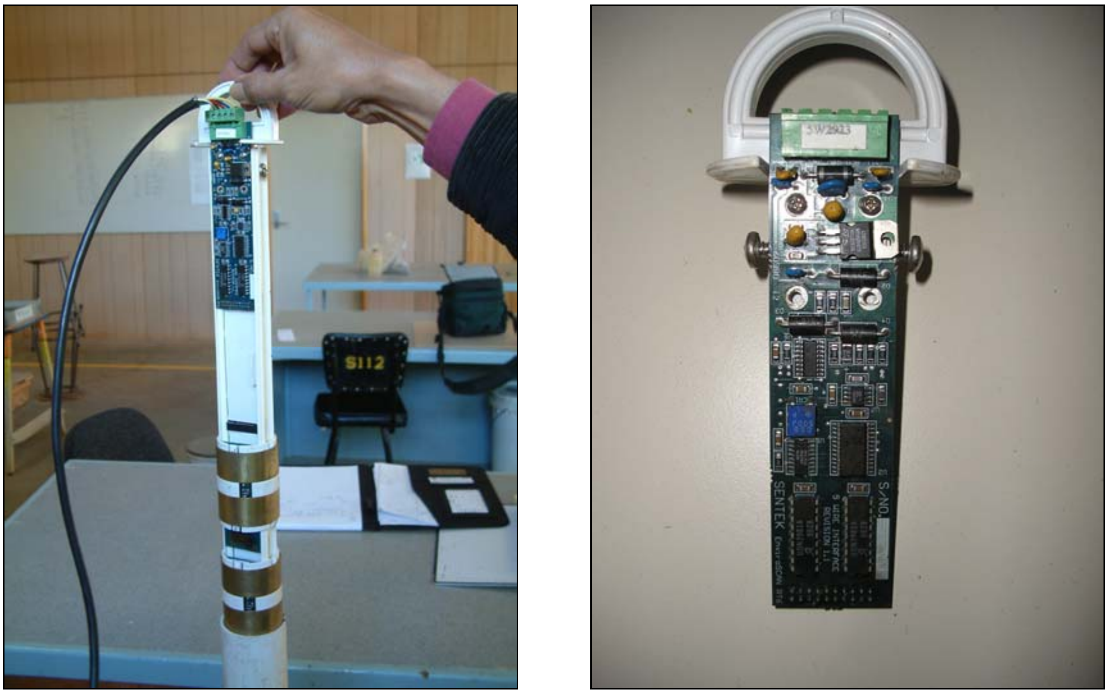


Figure 3-1 Sentek EnviroSCAN ® showing two sensors and the circuit board

Typically a PVC tube housing, known as the access tube which is 56.7 mm outside diameter is buried into the ground and the capacitance probe with several sensors at known depths, is positioned in the access tube which is then connected to the logger box. This is in contrast to the Sentek Diviner capacitance probe in which the access tube is left in the ground and the user inserts the probe when a soil moisture reading is required.

3.1.2 Air and Water Reference Counts

The sensors report what is known as a raw count thorough the circuit board the logger. The raw count is converted to a scaled frequency based on Equation 4. The calculation can be made automatically by the Sentek Software for conversion into a soil moisture content in mm, but the scaled frequency for the series of experiments presented here was calculated using a Microsoft Excel spreadsheet for the series of experiments presented here.

Air and water counts are taken before the capacitance probe is used to detect soil moisture. The air count is the sensors response (raw count) when the probe is surrounded by air and in essence provides a 0% moisture content. To do this the probe is held at arms length and at room temperature inside the PVC access tube so as to limit any interference from the user. As air has a low dielectric constant (typically 1.0 (Clipper controls, 2005)) the attenuated frequency when air surrounds the sensors is quite high, therefore the air reference counts are approximately 35000Hz (depending on individual sensor)

Similarly the water count is the sensors response when water is surrounding the access tube. This was done by sliding the probe through a modified esky that has been filled with water (Figure 3-2) at room temperature this essentially provides a 100% moisture content. The modified esky has a short piece of access tube installed in the centre. This allows the sensors to be surrounded by at least 100mm of water in all directions. The distance from the front edge to the centre of the esky was noted to ensure that each sensor was in the middle of the esky at the time when the water count was logged using the Sentek software. Water having a much higher dielectric constant (approximately 80.0 (Clipper controls, 2005))) has a large effect on the signal, therefore the water reference counts are in the order of 25000 Hz – 26000 Hz

Air and water counts are performed for each of the sensors separately to accommodate any variation between the sensors.

Figure 3-2 **Modified esky for taking water counts from the EnviroSCAN ®**

3.1.3 Scaled Frequency

The purpose for determining an air and water count for each of the sensors before beginning testing is so that the scaled frequency can be calculated. The scaled frequency is a measure that is used to determine the proportion of the signal that can be attributed to the soil medium that surrounds the access tube and uses the air and water counts discussed above as the 0% and 100% values. The equation used for calculating scaled frequency is given as Equation 4.

Equation 4

$$Scaled\ Frequency = \frac{Air\ Count - Soil\ Count}{Air\ Count - Water\ Count}$$

The scaled frequency is then used as a variable in a calibration equation to yield a soil moisture content. While Sentek provides a default calibration equation (Equation 3) derived from sands. Loams and clay loams, it is common practice to generate a calibration equation for the particular soil type that is being used.

For this series of experiments comparison is being made between the actual soil moisture content and the sensors response. Therefore, while sufficient data has been collected to develop a soil specific calibration equation, this has not been done because any effects that the soil moisture has on the probes behaviour will be detected in the variation in scaled frequency.

3.2 Testing Apparatus

3.2.1 Concept

As mentioned in Chapter 2 the behaviour of capacitance probes with any variation in the actual soil moisture was the primary interest in this series of experiments. In order to analyse the capacitance probe response to these variations in terms of scaled frequency, an appropriate testing apparatus needed to be designed and constructed. Ideally the design needed to allow soil of a known moisture content to be packed to known bulk density. The capacitance probe would then be used to take raw counts which would then be converted into scaled frequencies. Then a known amount of soil could be removed from the outside of the packed mass without disturbing the remaining soil. Scaled frequencies would then be calculated based on raw counts that had been taken from this slightly smaller mass of soil. This process would continue until there was a very small (or no) amount of soil surrounding the access tube. This same apparatus should also be water tight so that experiments using water of varying electrical conductivity could be undertaken.

As the signal from the EnviroSCAN ® operates between the two brass rings in an annular shape (Sentek, 2001), it was decided that the shape of the packed soil mass should be circular so that the distance from the sensor to the outermost boundary of the packed mass would be the same on all sides. Paltineanu and Starr (1997) have conducted a radial and axial sensitivity study and state that 99% of the EnviroSCAN ® capacitance probes response is obtained from 100mm both radially and axially from the centre of the brass rings. This information was considered when designing the testing apparatus.

3.2.2 Construction

It was decided that a set of sleeves of various diameters would be an appropriate basis for the testing apparatus. The largest sleeve would be packed with soil and then the thickness of soil surrounding the access tube would be reduced by pushing a smaller sleeve inside the existing soil packed sleeve. The soil shaved from the outside of the mass would be collected and used in a composite sample for assessing the actual moisture content and bulk density. A packing tool was also needed to ensure that the soil was packed evenly into the largest sleeve.

Without knowledge of how the dry, moist and wet soil would behave with respect to cohesion, it was decided that the sleeves would be left in place while the capacitance probe was used to take the raw count readings. This meant that the material that the sleeves were made of was significant. Obviously a device like a capacitance probe which uses electrical signals would be affected by any metallic components in the testing apparatus.

The idea of a series of sleeves was based on an assumption that prefabricated tube in a variety of sizes would be readily available. At the beginning of construction of the testing apparatus this was not the case. Stormwater and pressure pipe available to the university purchasing officer were only available in 90 mm, 100 mm, 200 mm etc. The distance between each of these pipe sizes would not have allowed the precision that was required in testing the capacitance probes behaviour, especially at close proximities to the access tube (small soil thicknesses).

It was then decided to construct each sleeve in 2 halves using 3mm acrylic or polycarbonate sheeting. Polycarbonate was purchased and cut to size but maintaining a consistent temperature in the polycarbonate for long enough to allow moulding to the required shape was a very difficult task. Three methods were tried and retried. The first method involved slumping the rectangular sheet (300 mm x (300 mm x π)/4) to form half of a circular sleeve, into a concave mould. This was done by drying and heating the polycarbonate in accordance with the manufacturer’s specifications then placing it over the concave mould and allowing it to slump under its own weight in the oven. The second method was to use the same sized piece of polycarbonate and again used the slumping technique only this time over a lathed timber cylinder of 300 mm height and 300 mm diameter. The third and final method was to use both the concave mould and the lathed timber cylinder together with the polycarbonate sheet between the pair. All three methods encountered the same problem, a differential in the temperature on either side of the formed sheet while it cooled. This meant that the sleeve half would loose its shape when it was removed from the mould. As mentioned earlier it was considered important that the sleeves were round so that the distance from the access tube to the boundary of the soil would be the same in all directions.

After two weeks of trials and much effort from the USQ Engineering workshop one full sleeve of 297 mm diameter was constructed.

This timing coincided with the release of a new catalogue from a material supplier which were able to provide acrylic tubing in approximately 5 – 10 mm diameter increments from 38mm to 300mm.

5 sections of 3 mm acrylic tubing was purchased and cut down to 300 mm lengths. The internal diameters of the sections were: 86 mm, 100 mm, 120mm, 147 mm and 200 mm (Figure 3-3). A bevel was machined into one end of all of the acrylic sleeves to create a cutting edge so when they are pushed into an existing soil mass the outer soil is shaved down leaving the inner soil undisturbed. These five sleeves and the 297mm polycarbonate were then used in the final design of the testing apparatus.

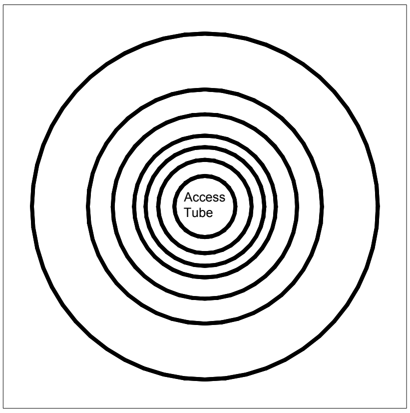
3.2.3 Final design

The final design used a 1 metre length of access tube mounted in a stand such that would allow a capacitance probe with multiple sensors to slide through the packed soil mass (Figure 3-4). This design allows each sensor to be positioned in the centre of the soil mass while the raw count is recorded. Using multiple sensors on the EnviroSCAN ® compensates for any inherent problems that a single sensor may have.

Table 1 shows the diameters of the set of six sleeves (1 polycarbonate and 5 acrylic) and the corresponding radial distance from the outside of the access tube to the inside edge of the sleeve.

Table 1 Description of polycarbonate and acrylic sleeves used in final design of the testing apparatus

Sleeve	Inside Diameter (mm)	Distance from access tube (mm)
1	78	11
2	100	22
3	120	32
4	157	50
5	200	72
6	297	120



The largest sleeve (297 mm inside diameter) was made in two sections so a brace was required to hold the two sections together and to provide strength to the sleeve when packing soil into it. The second largest sleeve 200 mm was also cut along its length to allow it to be easily removed when the next smallest sleeve was inserted into the soil mass. The thought behind the design was to use heavy plastic tape to hold the two halves together while inserting the sleeve into the soil mass and then the tape would be cut to allow for the next smallest sleeve to be inserted into the soil mass. Unfortunately the internal stresses caused the prefabricated sleeve to lose its shape when it was cut and a pair of donut shaped timber disks were needed to maintain the circular section of the 200mm sleeve.

Experimentation indicated that for moist to wet samples the sleeve was able to be removed and the soil mass would retain its cylindrical shape. This also allowed the next smallest sleeve to be pushed through the free standing sample to shave of the out portion of soil. This meant that it was not necessary to cut the remaining sleeves (1, 2, 3 and 4) along their length.

Figure 3-3 Sleeves surrounding access tube showing the largest 2 sleeves cut along their length

Figure 3-4 shows the final design of the constructed testing apparatus. The access tube is mounted into the platform stand which holds the soil that has been packed into the largest sleeve using the compacting tool

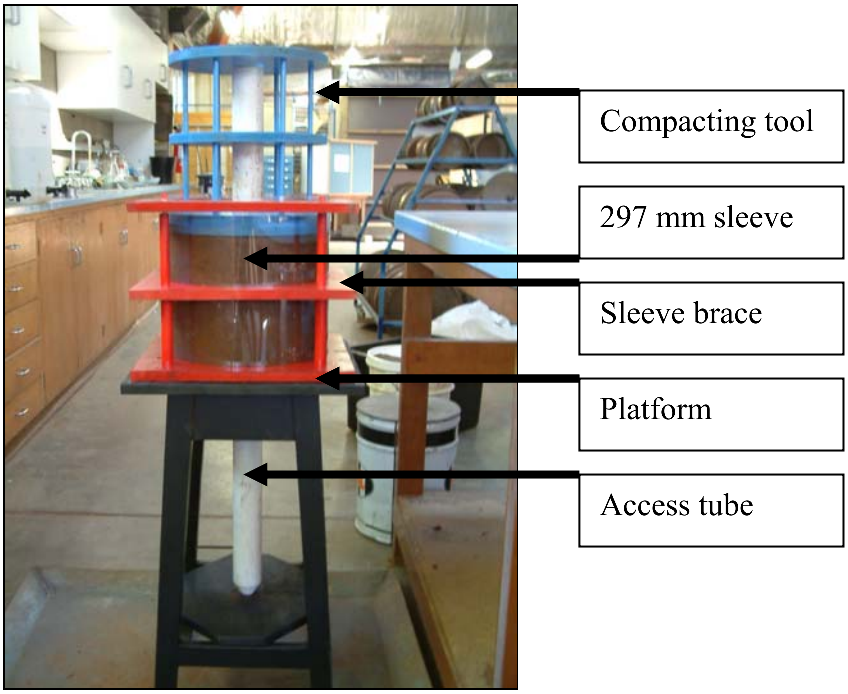


Figure 3-4 **Testing apparatus showing largest sleeve and brace and the compacting tool**

3.3 Soil

In this series of experiments the behaviour of the capacitance probe is being examined. It is this behaviour that will be compared with some of the known properties of cracking clays (primarily shrinking and swelling). Therefore, it was not seen to be essential to necessarily use a cracking clay in the experimentation.

The ease of access to a red Ferrosol and the comparative ease to work with this type of soil was the reason that this soil was chosen for use in the soil based experiments.

3.3.1 Description of Soil

Red Ferrosols are typically permeable clayey soils with greater than 5% free iron oxide (McKenzie et al, 1999). They are well drained and are used for a wide variety of crops including sugar cane in south central Queensland, grain crops and vegetables in south Queensland (Mackenzie et al, 1999).

The in field physical properties of the red Ferrosol used in the soil experiments have been summarised in Table 2

Table 2 Physical properties of the Ferrosol in field

Colour	5YR 3/3 Dark Red Brown
Field Texture	Clay Loam
Coarse Fragments	None visible
Structure	Pedal Sub angular Blocky
Consistence	Very Firm
Field pH	5.5

3.3.2 Collection of Soil

The red Ferrosol used was sourced from the University of Southern Queensland Agricultural Plot located on Baker St, Toowoomba, Queensland.

A sample of soil in an undisturbed state would have been ideal and would have provided a representative indication of the in-field structure and bulk density of the Ferrosol. However the volume required for each soil experiment (300 mm deep x 297 mm diameter core) would have been difficult to collect as well as difficult to vary the moisture content in such a way that it was consistent through the entire sample.

The soil was sampled by removing the vegetation (grasses) from the top 30 mm – 40 mm with a shovel then further scraping with the shovel to no greater than 100 mm to collect sufficient soil to process and conduct experiments. One collection of soil (approx 30 kg) was less than was required for all of the experiments that were conducted and so a second collection was undertaken some weeks later. The second collection was taken from the same location, in the same manner to avoid any experimental errors that may occur from any slight variation in the soil.

3.3.3 Processing Soil

The soil that was collected required sieving to obtain a particle size that would allow wetting such that the moisture was relatively consistent throughout the sample. While Sentek advise that sieving to 5 mm was sufficient for laboratory based determination of the calibration equation, it was decided to use a smaller sieve size of 2 mm. the smaller particles allowed for a more even distribution of water through the sample and fewer unwanted air spaces when packing the soil into the 297 mm sleeve. The soil was sieved using a set of standard brass soil sieves. Care was taken when using the sieves as Tan (1996) states that some abrasion of the sieves can occur and may have impact on the results of tests. Some mechanical breaking up of the larger aggregates was performed using a mortar and pestle and later using an asphalt compacting tool. The asphalt compacting tool was used to save time by allowing larger volumes of soil to be compacted in each session. The processing of the soil was performed initially and for each new experiment that required soil.

The processed soil was then oven dried at 50°C for at least 24 hours and then stored in plastic bags to limit the change in moisture content of the soil due to absorption from the atmosphere. Initially it was thought that using oven dried soil would be necessary so that the actual soil moisture content could be varied accurately. After initial testing, the process for selecting which soil moistures should be tested was changed. This is discussed in Chapter 3.5.1.

3.4 Water

Water was used in the soil based experiments as well as in water based experiment which did not use soil at all and instead tested the capacitance probes behaviour when just water was used in contact with the access tube.

Using distilled water to take the water reference counts and to add to the air dried soil as well as for use in the water based experiments would have been ideal, however the volumes required and the expense to distil the water meant that Toowoomba tap water was used instead.

3.5 Soil Based Experiments

The methodologies used in this experiment are a combination of those documented in Methods of Soil Analysis Part 4 – Physical methods and Paltineanu and Starr (1997) and some techniques that were developed specifically for this project.

3.5.1 Varying Moisture Content

Initially calculations were made for combining soil and water in exact amounts to obtain a volume of water and a volume of soil required to pack the largest sleeve to a known water content and bulk density.

For example, to create the exact amount of soil and water required for 20% volumetric soil moisture to be packed into the 293 mm sleeve (19459.48 cm^3) at a bulk density of 1.15 g cm^{-1} would require: 22378.402 kg of air dried soil (with a gravimetric water content =2.9%) to be mixed with 3846 ml of water (Appendix B).

These calculations and precise measurements were not required because the format in which the results are reported (Chapter 4) did not require precise intervals for the actual soil moisture i.e. it was not important to test at 5%, 20% and 40%. Values such as 3.6%, 21.38% and 43.03% were acceptable for regression analysis. The actual moisture content was not determined at the time of mixing the soil and water but instead the volumetric soil moisture was determined at the end of each test through the process outlined in Chapter 2.1. Another reason for not accurately measuring the soil and water required was the loss of some soil in the mixing process which will be discussed later. If the exact quantity of soil was to be mixed then any losses would need to be considered when packing the soil into the 293 mm sleeve.

The soil/water mix for the first test was mixed in a large container using a trowel. The moistened soil was then transferred to a sealed bucket and stored for at least 24 hours to allow sufficient time for the water to permeate into the soil pores. Due to the large volume of soil used in comparison to most laboratory based physical soil investigations, the mixing by hand with a trowel required significant effort to ensure a good mixing had occurred. The USQ soils laboratory has a large (approximately 0.5 m^3) industrial cement mixer used mainly for concrete blending trials. With the exception of the first test, all soil and water mixing was done with the industrial cement mixer. Approximately 25 kg of air dried soil was added to the mixer and then a measured quantity of water, was added by trickling over an open hand so as to reduce the incidence of one single portion being much wetter than the rest of the sample. The trickling method was developed due to some poor mixing in earlier experiments which yielded poor results.

When all of the water was added at once, one large mud ball formed with the rest of the soil remaining dry. More time in the industrial mixer did, in time, break up the mud ball and disperse the water through the soil sample. However, the cohesive nature of the red Ferrosol and the continual rotation of the mixer caused the sample to form many smooth spheres varying in size from approximately 5mm to 8mm in diameter. These spheres, when packed into the 293mm sleeve left air spaces throughout the sample. The cylindrical soil mass did not behave well when a smaller sleeve was used to shave the sample down to a smaller volume.

As a result the mixer was used for the shortest possible time to still allow adding all the water required and sufficient mixing.

All mixes were still stored in an air tight bucket for at least 24 hours to allow time for the water to completely infiltrate the soil pores.

3.5.2 Packing Acrylic Sleeves

Once the soil had been prepared and stored for at least 24 hours it was able to be packed into the largest sleeve (293mm). This was done by adding approximately 4 x 500ml scoops of soil to the sleeve positioned on the stand with the access tube in place. These four scoops were then spread evenly around the sleeve created a depth of soil approximately 2cm.

Figure 3-5 Tool used for compacting soil into the largest diameter sleeve

The compacting tool shown in Figure 3-5 was then placed on top of the soil and struck five times with a rubber mallet to compact the soil. The surface of the compacted soil was then roughened on using the scoop and another 2cm of soil was added to the sleeve and compacted. The roughening of the surface was done to reduce the possibility of any stratification in terms of density in the sample. The filling and compacting of the 2cm layers was continued until the sleeve was full to the top and the sample was 300mm deep.

While using the compacting tool shown in Figure 3-5 there was some difficulty in packing the soil to high bulk densities. This was not seen as a great concern as long as the bulk density was uniform throughout the sample. However, while care was taken to ensure that there were no large air spaces in the compacted soil, the wet sample presented in Figure 4-3 tended to form clumps which were not able to be completely removed by compaction.

3.5.3 Collecting Air and Water Reference Counts

Air and water reference counts were collected for each sensor on the EnviroSCAN ® as described in Chapter 3.1.2 in order to define the upper and lower boundaries for the raw counts and allow the calculation of scaled frequency. Air and water reference counts were taken before each experiment was conducted. To ensure that the EnviroSCAN ® was delivering consistent responses through the duration of the experiment, air and water reference counts were collected at the beginning of the experiment and at the completion of the experiment for comparison. Figure 3-6 shows the air and water reference counts before testing began on the y-axis and the air and water reference counts collected at the end of testing on the x-axis. The R^2 values for the regression line indicates that there is very strong relationship between the air and water reference counts before and after testing. This suggests that there is very little change in the sensors response throughout the testing period.

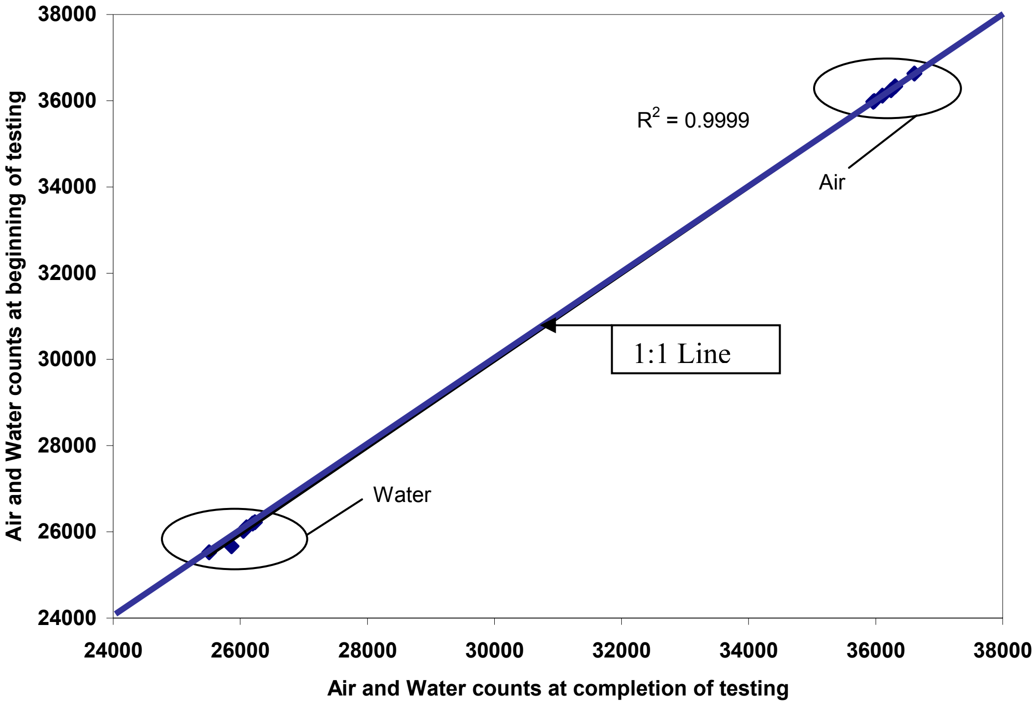


Figure 3-6 Comparing the air and water counts before and after testing

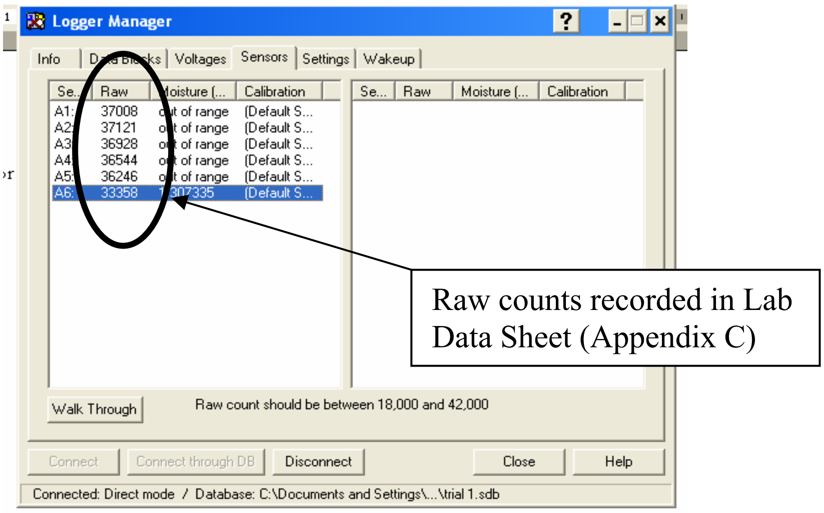
3.5.4 Collecting Raw Counts

Raw counts were then collected from the packed soil mass so that a scaled frequency could be calculated using Equation 4

The capacitance probe was inserted into the access tube until the sensor closest to the bottom of the probe (sensor 6) was aligned with the centre of the packed soil mass. This gave 150mm of soil above and below the centre of the sensor in accordance with Bolvin et al (2004). The Sentek software “Logger Manager” (Figure 3-7) was used to observe the instantaneous raw counts detected by the sensor. The sensor was left in place to allow the reading to stabilise as per Morgan et al (1999) and then the raw counts were entered into a Microsoft Excel spreadsheet. An example of the spreadsheet used to capture the data has been included as Appendix C.

The probe was then inserted a further 100mm into the access tube until the centre of the next sensor (sensor 5) was aligned with the centre of the soil mass. This was repeated for sensors 4, 3 and 2 and raw counts were collected from all but the top sensor. The length of the access tube above the soil mass inhibited the probe being inserted any deeper. Readings were taken from 5 out of the 6 sensors on the EnviroSCAN ® so that the effects of any inherent errors in a single sensor would be reduced.

As a quality control, the raw count readings were repeated 3 times for each soil thickness and the values were recorded from all sensors regardless of their position relative to the soil mass. For example when sensor number 3 was in the centre of the soil mass, raw counts for sensors 2, 3, 4, 5 and 6 were all recorded. This allowed data checking to be done before calculating the scaled frequency.



Se...	Raw	Moisture (...	Calibration
A1:	37008	out of range	(Default S...
A2:	37121	out of range	(Default S...
A3:	36928	out of range	(Default S...
A4:	36544	out of range	(Default S...
A5:	36246	out of range	(Default S...
A6:	33358	1 307335	(Default S...

Se...	Raw	Moisture (...	Calibration

Raw count should be between 18,000 and 42,000

Connected: Direct mode / Database: C:\Documents and Settings\...\trial 1.sdb

Raw counts recorded in Lab Data Sheet (Appendix C)

Figure 3-7 **A screen capture from Sentek's 'Logger Manager' Software**

The process of recording raw counts and then moving on to the next sensor and taking more raw counts was repeated three times for each thickness of soil. This meant that there was in total 5 sensors x 3 repeats = 15 raw counts for each soil thickness

3.5.5 Calculating Scaled Frequency

The scaled frequency was calculated using the equation shown in Chapter 3.1.3. Air and water reference counts that are unique to each sensor were used to calculate the scaled frequency for each raw count from each repetition for each soil thickness. An example of a scaled frequency calculation has been shown below.

<u>Sensor 5 (counts taken on 8 August 2005)</u>

Air count	36335	
Water count	26124	
Soil count	28095	(120mm soil thickness, $\theta = 34.53$)

$$Scaled\ Frequency = \frac{36335 - 28905}{36335 - 26124} = 0.72765$$

The scaled frequency is unit-less as the units of the raw and reference counts are in Hertz on both the top and bottom of the equation and are therefore cancel out. This example shows that the higher the dielectric constant (water ≈ 80, air ≈ 1 (Clipper controls, 2005)), the greater the attenuation of signal, which leads to a lower raw count. Which when applied to the scaled frequency formula above it can be seen that the wetter the soil, the higher the scaled frequency.

From this equation it may be incorrectly assumed that the scaled frequency will tend towards unity as the water content increases, but this would only be the case if there were no soil surrounding the probe, only water. This is because the response from the sensor is based on the combined dielectric properties of the soil, water and air in the sample (Paltineanu and Starr, 1997). Experiments were also conducted (Chapter 3.6) which involved just water without soil surrounding the access tube as well as water with varying electrical conductivities.

3.5.6 Reducing Soil Thickness

As previously mentioned the two largest sleeves (293 mm and 200 mm diameter) were cut along their length (Figure 3-3). This allowed them to be easily removed as the next smallest size sleeve was used to shave off the outer section of the soil mass. The larger sleeves were held in place as the next smallest sleeve was pushed down into the soil mass. The split sections allowed the expansion of the soil mass due to displacement when the new sleeve was being inserted. A series of raw counts were collected as outlined in 3.5.4 for each sleeve.

The remaining, smaller sleeves (147mm, 120 mm, 100 mm and 86 mm) were able to be gently removed by lifting them off the top of the moist soil mass to leave a free standing sample surrounding the access tube. This free standing sample was then shaved back to a smaller diameter using the next smallest size sleeve. Obviously the ability to form the free standing column of soil was dependant on the cohesive properties of the soil, which increased (to a point) with increased moisture content.

When testing the dry soils which would not bind together and form a cohesive soil mass, a different method for reducing the thickness of soil surrounding the access tube needed to be developed.

The testing apparatus was made with no metallic components to reduce potential interference in the capacitance probe readings. However, all materials have a dielectric constant which is the material property that is responsible for the attenuation in the signal from the capacitance probe. Clipper controls (2005) has indicated both polycarbonate which is the material that the largest sleeve is made from, and acrylic (all other sleeves) has a dielectric constant of approximately 3. The dielectric constant of soil is approximately 3 to 4 (Clipper controls, 2005). This information lead to experiments being undertaken to determine if leaving the sleeves in place while taking readings with the capacitance probe would have an effect on the raw counts collected.

Raw counts were taken using the EnviroSCAN ® while the largest sleeve was in place holding the sample together. Then raw counts were taken with the sleeve removed and the sample held together by the cohesive properties of the soil. This was then repeated for the remaining sleeves. The raw counts taken when the sleeves were in place (over the range of soil thicknesses) were then plotted against the raw counts collected when there were no sleeves present for a wet soil (Figure 3-8) and for a moist soil (Figure 3-9). The linear best fit for the wet soil had an R^2 value of 0.9328 which indicates a strong linear relationship between the raw counts with and without the sleeves in place. The relationship between the raw counts for a moist soil is even stronger with an R^2 of 0.9953.

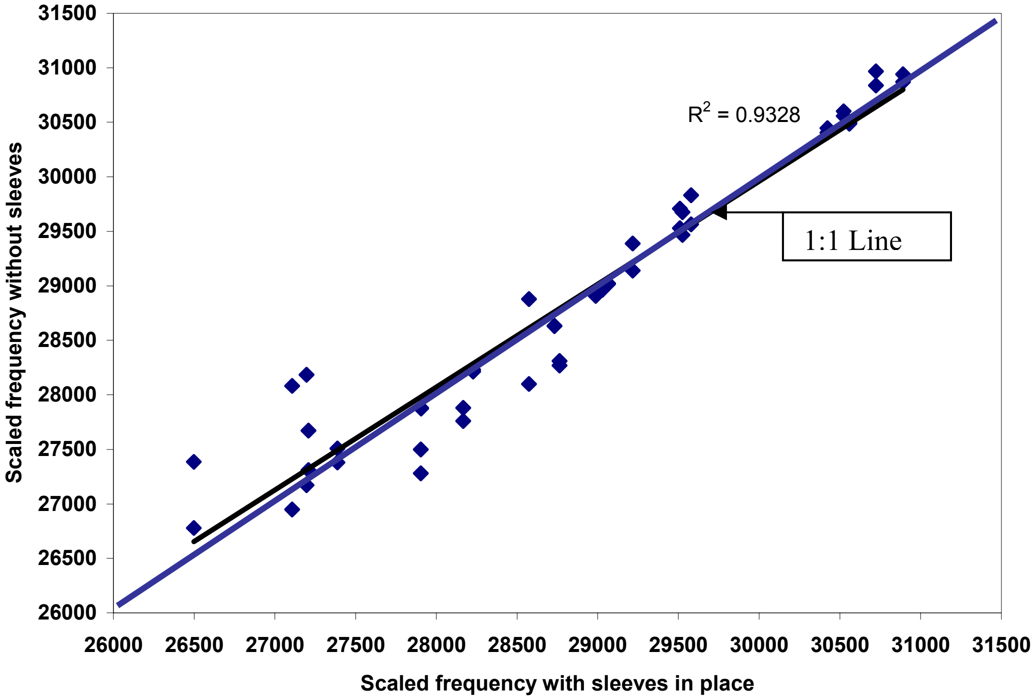


Figure 3-8 **Comparing the scaled frequency with and without Perspex sleeves in place using wet soil**

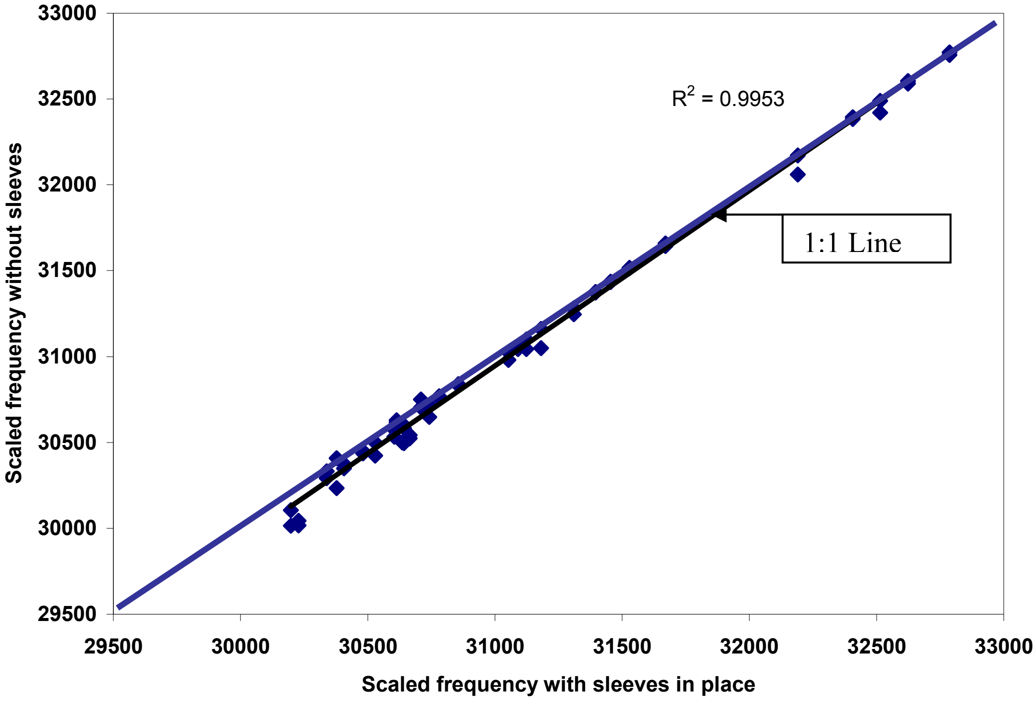


Figure 3-9 **Comparing the scaled frequency with and without Perspex sleeves in place using moist soil**

Further to this analysis, a paired T-test was undertaken to determine if there was a significant difference between the two different treatments.

A t-test is used to determine if two population means are equal and allows the user to determine if there are any significant differences present in the data sets. Because there were two treatments that were measured in the same manner, a paired t-test was an appropriate statistic to use.

The test was undertaken using the built-in data analysis functions in Microsoft Excel (Appendix D). These functions generate a test statistic (t Stat) based on the degrees of freedom of the data set and P value. If the p-value associated with t is low (< 0.05), there is evidence to reject the null hypothesis. This means that there is evidence that there is a difference in means across the paired observations.

The P values calculated for the wet and moist samples were 0.92 and 0.71 respectively. As these values are both greater than 0.05, it can be accepted that there is no significant difference between the raw counts taken when the sleeves are in place and when the sleeves are not used.

3.5.7 Determining Bulk Density

As mentioned previously the bulk density was not predetermined but calculated after the soil sample had been analysed.

Bulk density is defined as the ratio of the mass of a given sample to its volume (Blake, 1965; McIntyre and Loveday, 1974). The mass of the sample is determined by oven drying at 105°C for at least 24 hours this effectively removes all water from the sample. The volume of the samples used in these experiments is simply the sum of the volumes inside each sleeve minus the volume occupied by the access tube and the sleeves themselves. The equation for calculating the bulk density is shown in Equation 5.

Equation 5

$$\rho_B = \frac{M_S}{V_B}$$

(McIntyre and Loveday, 1974)

Where ρ_B Bulk density (g/cm^3)
M_S Mass of soil solids (g)
V_B Bulk Volume (cm^3)

Bulk Density is often required to determine the degree of the compactness (Roberts, 1996) or as indicator of the aeration status but the primary use for it in this series of experiments is to convert the soil moisture from a gravimetric to a volumetric measurement (McIntyre and Loveday, 1974).

3.5.8 Determining Soil Moisture

The soil moisture was calculated as an average of the soil moistures determined from each successive shaving of the cylindrical soil mass. The soil that was shaved from the outside of the soil mass was collected and weighed. It was then placed in an oven in accordance with Dane and Topp (2002) for at least 24 hours to completely remove any soil moisture. The gravimetric soil moisture content could then be calculated using Equation 1.

The volumetric soil moisture content was then determined using the bulk density as determined above and the gravimetric moisture content using Equation 2.

3.5.9 Temperature of soil

Baumhardt (2000) suggests that the temperature of the surrounding soil has the potential to affect the attenuation of the frequency emitted by the access probe. This statement is also supported by Paltineanu and Starr (1997) in their findings. This effect is of concern in situations when the exposed soil heated and cooled during normal cycles (Dane and Topp, 2002). An experiment was derived to examine the scaled frequency variation when using a soil that was significantly hotter than the ambient working temperature in the laboratory.

Approximately 25 kg of air dried soil from the material used in the soil based experiments, and discussed in Chapter 3.3.1, was oven dried at 105°C for a period of no less than 24 hours. The soil was immediately removed from the oven and packed into the largest sleeve where raw counts were taken using the capacitance probe in the same manner as the previous soil experiments.

The temperature of the soil that was being tested decreased in as it approached the ambient laboratory temperature as the experiment proceeded. The temperature of the soil was recorded using a mercury thermometer at each reduction in soil thickness. Table 3 shows the temperatures recorded while the raw counts were being collected. The ambient temperature was only measured before the experiment began, but it is assumed that the ambient temperature remained reasonably constant.

Table 3 Soil temperature change while conducting experiment using hot soil

Time	Sleeve	Soil Temperature	Ambient Temperature
11:57	293 mm	72.6 °C	Approx 19.5°C
12:34	200 mm	68 °C	Approx 19.5°C
13:05	157 mm	64 °C	Approx 19.5°C
13:41	120 mm	59 °C	Approx 19.5°C
14:12	100 mm	51 °C	Approx 19.5°C
14:49	78 mm	45 °C	Approx 19.5°C

3.6 Water Based Experiments

Following investigations into the behaviour of capacitance probes response to varying soil moisture and soil temperature with varying soil thickness surrounding the access tube, tests were undertaken to investigate the capacitance probes response to varying thickness of water and air gaps between the access tube and water.

3.6.1 Modifying Testing Apparatus

The four smallest sleeves that had not been cut along their length were positioned around the access and sealed with silicon on the flat platform of the testing apparatus. The access tube was also sealed to the testing apparatus to create a water tight unit.

3.6.2 Creating Saline Solutions

A saline solution was made using sodium chloride in order to increase the electrical conductivity (EC) of the water. Approximately 10 litres of solution was mixed by hand in a bucket. The solution was then tested using a calibrated TPS MC84 Salinity/conductivity meter which determined the conductivity of the solution to be 12.27 dS/m.

A second saline solution was created by adding fresh water to the 12.27 dS/m solution to reduce the salinity. The electrical conductivity was again measured using the TPS MC84 which reported an EC of 8.28 dS/m.

A final saline solution was created by adding more fresh water to the 8.28 dS/m. solution to further reduce the salinity to 5.91 dS/m.

This gave in total 4 solutions for use in the water based experiments:

- 0.36 dS/m (tap water)
- 5.91 dS/m
- 8.28 dS/m
- 12.27 dS/m

3.6.3 Collecting Air and Water Reference Counts

Air and water reference counts were taken for each sensor prior to beginning the experimental work. The water reference counts were taken as per the methods described in 3.5.3 using the modified esky filled with fresh water (EC 0.37dS/m). However there was a slight variation to the method used to collect air reference counts.

For this set of experiments, the air reference counts were taken from the access tube mounted in the testing apparatus and not from the spare access tube held at arms length (as in all previous experiments). The reason for this was so that the sealed acrylic sleeves were incorporated into the air reference counts. Unlike the soil experiments where only one sleeve was used at a time, the sleeves were sealed to the platform and were present through all stages of the water experiments and as such needed to be considered when collecting air reference counts.

3.6.4 Collecting Raw Counts

The cavity between the access tube and the first sleeve (11 mm thickness) was filled with Toowoomba tap water (Appendix E). The capacitance probe was then used in the same manner as in the soil based experiments. By moving the capacitance probe so that each sensor was positioned in the centre of the water mass, a raw count was able to be recorded from each sensor. Then the next sleeve (100mm) was filled with water providing a 22mm jacket of water surrounding the access tube while raw counts were again recorded for each sensor. This was repeated using the 120 mm sleeve (32 mm water thickness) and the 157 mm sleeve (50 mm water thickness). As mentioned in Chapter 3.6.1 the two largest sleeves were not used as they were cut in half along their length.

Once sleeves 1, 2, 3 and 4 were filled with water and raw counts had been taken and recorded, the sleeves were sequentially drained from the inner most sleeve outward. Sleeve 1 (78 mm) was drained leaving an 11 mm air gap between the access tube and the remaining water-filled sleeves. Raw counts were collected and then the 100mm sleeve was also drained leaving a 22 mm air gap between the access tube and the water filled sleeves. This process was continued until all the sleeves were drained. The sequence of filling and draining had been represented graphically in Appendix F.

The process was repeated using the 5.91 dS/m, 8.28 dS/m and 12.27 dS/m solutions of saline water. Scaled frequencies were then calculated using the methods described in 3.1.3.

Chapter 4. Results and Discussion

4.1 Volumetric Moisture Content

While seven experiments were performed using different soil moisture contents and bulk densities, only three have been reported here, a dry soil (θ = 0.036 cm^3 cm^{-3}), a moist soil (θ = 0.217 cm^3 cm^{-3}) and a wet soil (θ = 0.430 cm^3 cm^{-3}). Only a limited amount of data could be collected from the remaining experiments. The reasons behind this were, at low moisture contents and/or low bulk densities the cohesive properties of the soil sample made reducing soil thickness difficult. Especially when using the smaller diameter sleeves, the soil mass would crumble as the sleeve was being inserted. This problem was somewhat overcome by wrapping the soil mass with clear cling film before inserting the sleeves. This allowed some expansion of the mass while the sleeve was being inserted, but was not effective in all cases. However, the use of a dry, moist and wet soil sample was seen as adequate to develop an understanding of the behaviour of a capacitance probe with respect to varying soil thickness surrounding the access tube.

After the raw counts from each sensor, and each repetition were collected, the scaled frequencies calculated. The mean of the scaled frequencies for each soil thickness was then determined. The mean scaled frequency was then plotted on the y-axis against the thickness of soil surrounding the access tube in millimetres on the x-axis.

Figure 4-1 is the graph of an air dry soil sample. Using the methods discussed in Chapter 3.5.8, the volumetric soil moisture content was determined to be 0.036 cm^3 cm^{-3}. The six data points on the graph correspond with the six sleeves used during the testing. The standard error of the mean associated with these data points was very small ranging between 0.00494 to 0.00567 or approximately 1%. These values for the standard error of the mean would not have been visible on the scale used, as such the error bars used on Figure 4-1, Figure 4-2 and Figure 4-3 have been used in this instance to describe one standard deviation from the mean.

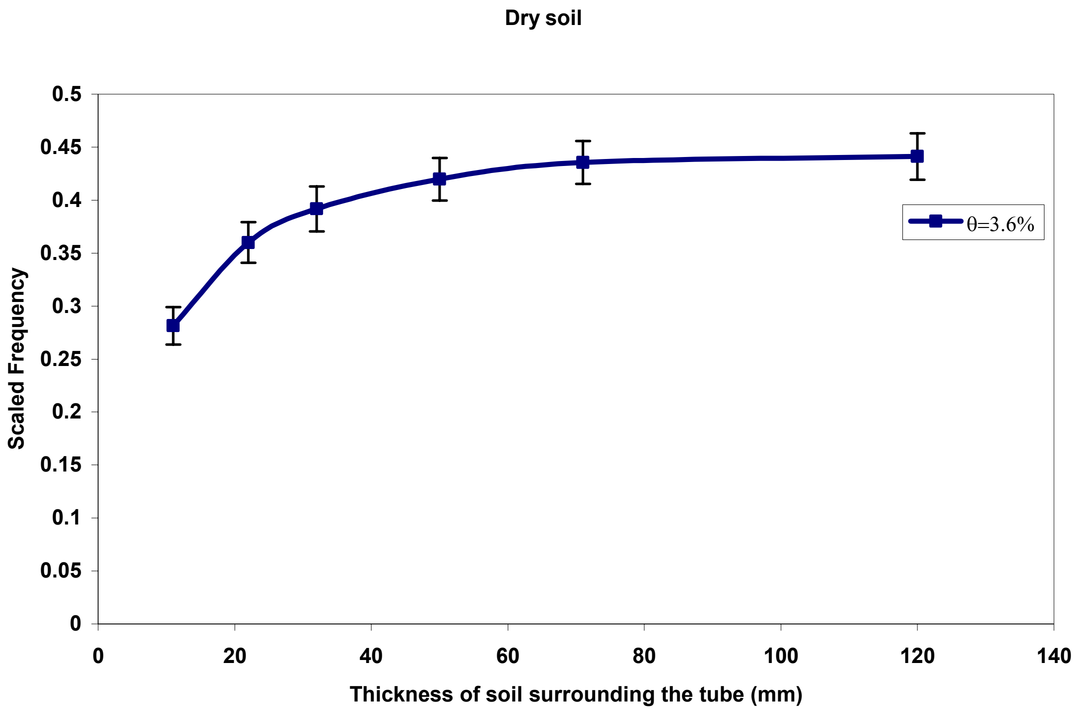


Figure 4-1 Variation in scaled frequency with increasing thickness of soil surrounding the access tube for a dry soil

From the above figure it can be seen that the average scaled frequency tends to decrease with reducing thickness of soil surrounding the access tube. Whereas at greater thicknesses of soil surrounding the access tube the change in scaled frequency is relatively small.

The results that were obtained when comparing the average scaled frequency to the thickness of soil surrounding the access tube (mm) for a moist soil (θ_v = 0.217cm^3 cm^{-3}) showed a similar trend to the dry soil (Figure 4-2).

Again the scaled frequency showed little change at large soil thicknesses but tended to decrease quickly with reducing soil thickness. The obvious difference between the dry and moist soil curves is the difference in maximum values, which as expected, increased with greater volumetric moisture content in the soil. Again, the error bars in Figure 4-2 describe one standard deviation away from the mean.

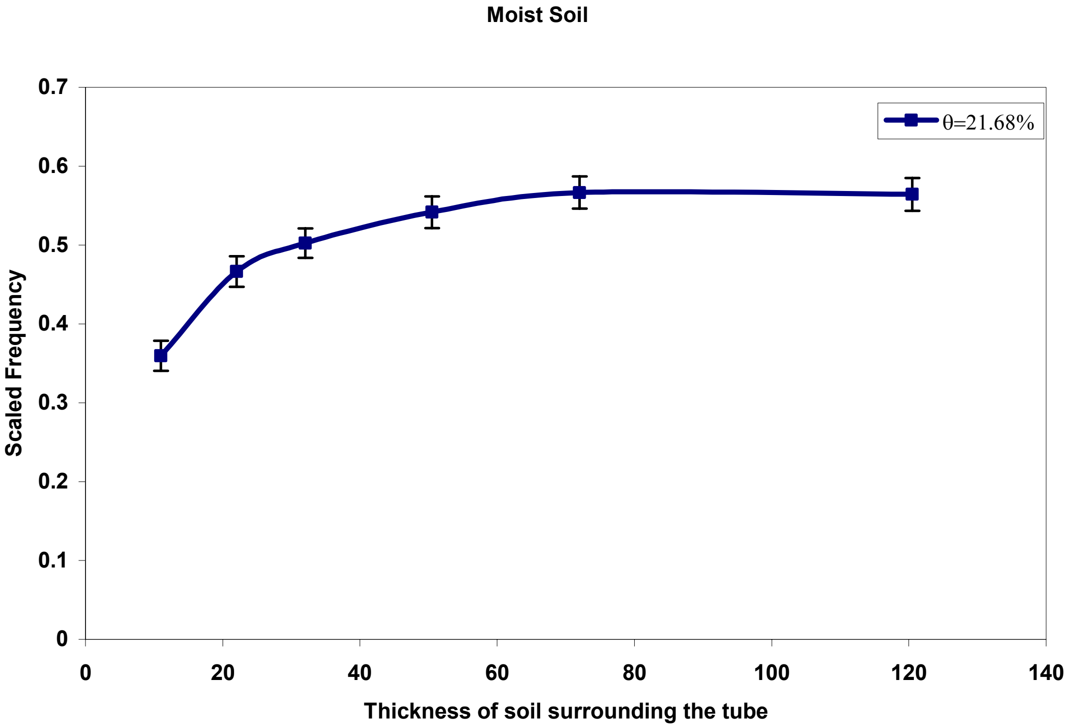


Figure 4-2 **Variation in scaled frequency with increasing thickness of soil surrounding the access tube for a moist soil**

The curve for the wet soil ($\theta_v = 0.430 cm^3\ cm^{-3}$) shows lower scaled frequency at smaller soil thicknesses surrounding the access tube. The decrease in scaled frequency appears to be much more pronounced in the wet soil than it did in the dry and moist soils. Is should be noted that only five out of a possible six sleeves were used to create varied soil thickness surrounding the access tube. The reason behind this has been described above as the soil mass slumped when attempting to insert the smallest sleeve.

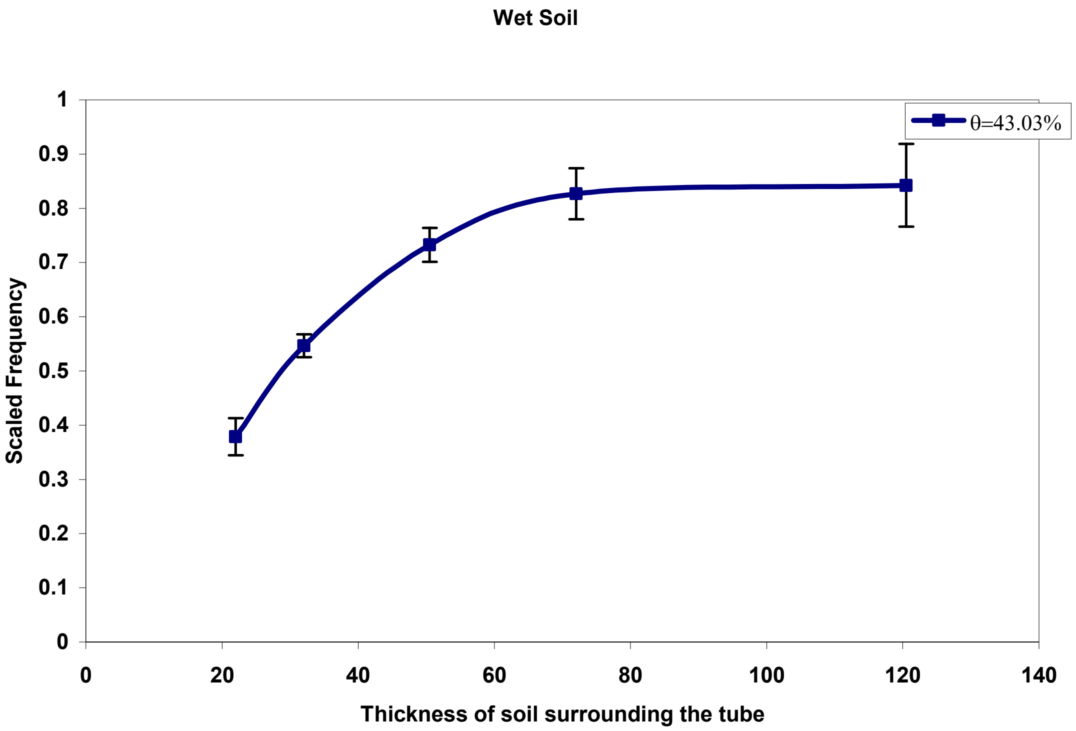


Figure 4-3 **Variation in scaled frequency with increasing thickness of soil surrounding the access tube for a wet soil**

Figure 4-4 shows the three curves plotted together, however the magnitude of the curvature is masked by the variation in the maximum scaled frequency.

It is expected that the wet curve is in error due to the air spaces left in the sample after packing.

The degree of attenuation of the raw count received by the sensor is a function of the amount of water present in the soil. At higher water contents, the attenuation is greater and the raw count received is lower than the raw counts received for a dry soil. This lower raw count is then translated into a higher scaled frequency. This means that for a given thickness of soil, the scaled frequency of a wet sample (greater attenuation) would always be higher than the scaled frequency of a dry sample (less attenuation). This is not the case shown for the wet curve in Figure 4-5 and will be further discussed in Chapter 4.3.

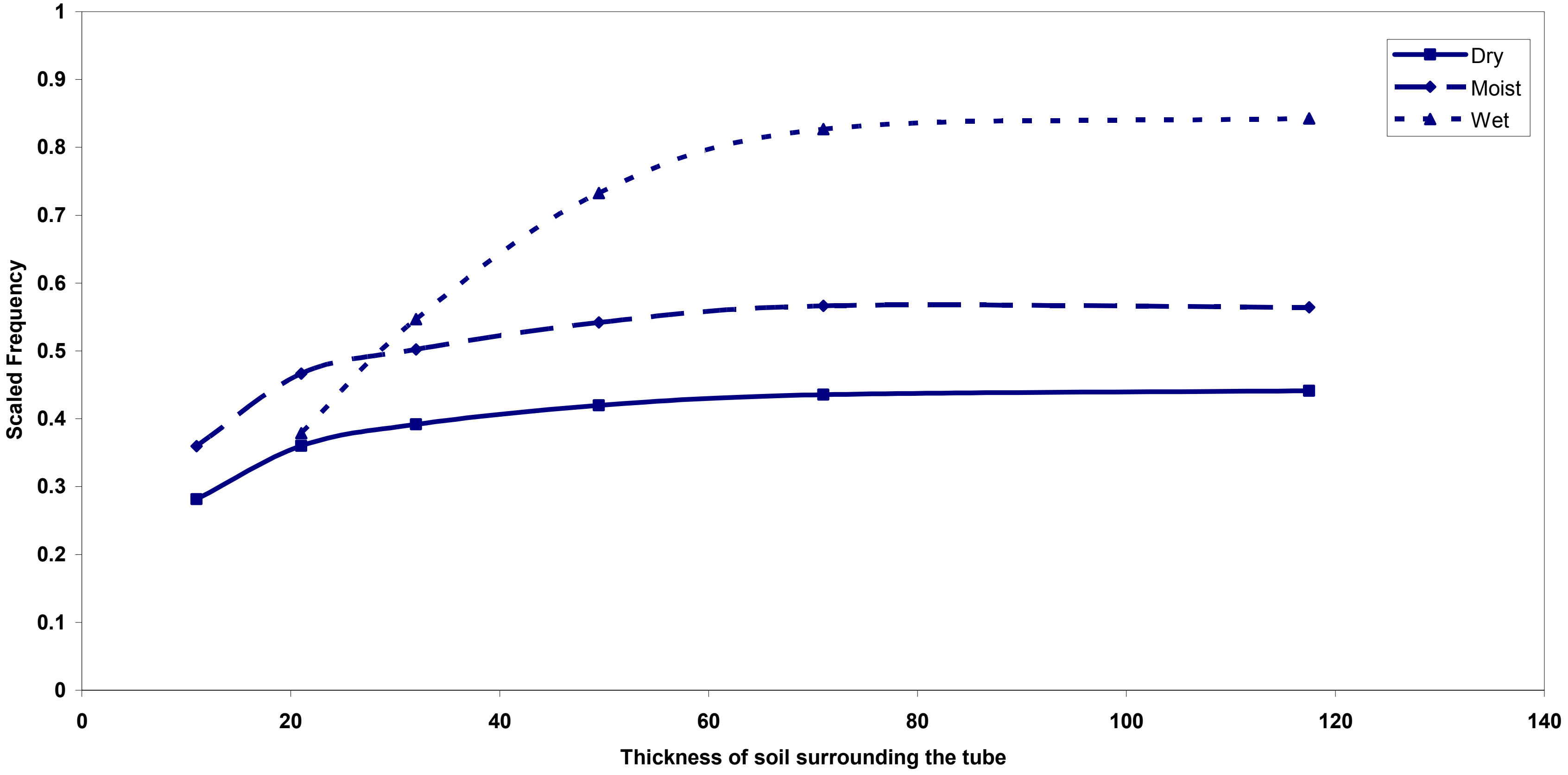


Figure 4-4 **Variation in scaled frequency with increasing thickness of soil surrounding the access tube for a dry moist and wet soil**

In order to compare all three curves on a single graph it was necessary to present the scaled frequency as a percentage of the maximum scaled frequency for each moisture content (Paltineanu and Starr, 1997). Table 4 provides an example of the calculations used to plot Figure 4-5.

Table 4 Example of calculation of SF/SF_{max} for Figure 4-5

Scaled Frequency (SF)	0.359571	0.466343	0.502394	0.541681	0.566485	0.564193
Maximum scaled frequency (SF_{max})	0.564193	0.564193	0.564193	0.564193	0.564193	0.564193
SF/SF_{max}	0.637906	0.815951	0.88804	0.951491	0.987364	1

This is also the form that Paltineanu and Starr (1997) have used to present their ‘Radial Distance to Air’ data (Figure 4-6.)

Figure 4-5 shows that the curves for the dry and moist soils are closely related in terms of curvature. While it is difficult to determine exactly where the wet curve begins to deviate from the moist and dry curves, it can be seen that the deviation occurs between sleeves 3 and 4 (50 - 72 mm soil surrounding the access tube).

The reasons for this deviation are to potentially be found in one of the forms of error discussed in Chapter 4.5.

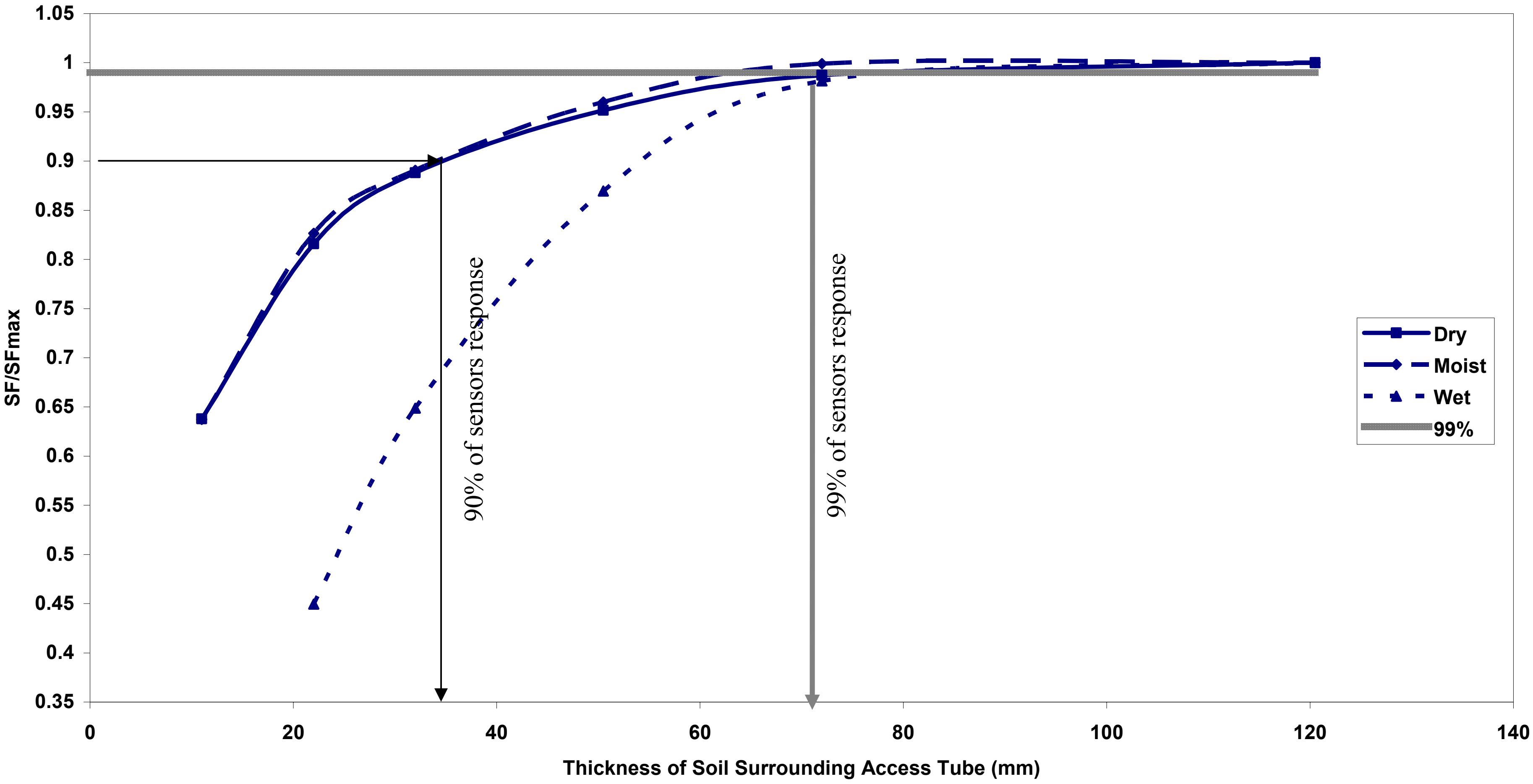


Figure 4-5 **Scaled frequency curves as a percentage of the maximum scaled frequency for dry, moist and wet soil**

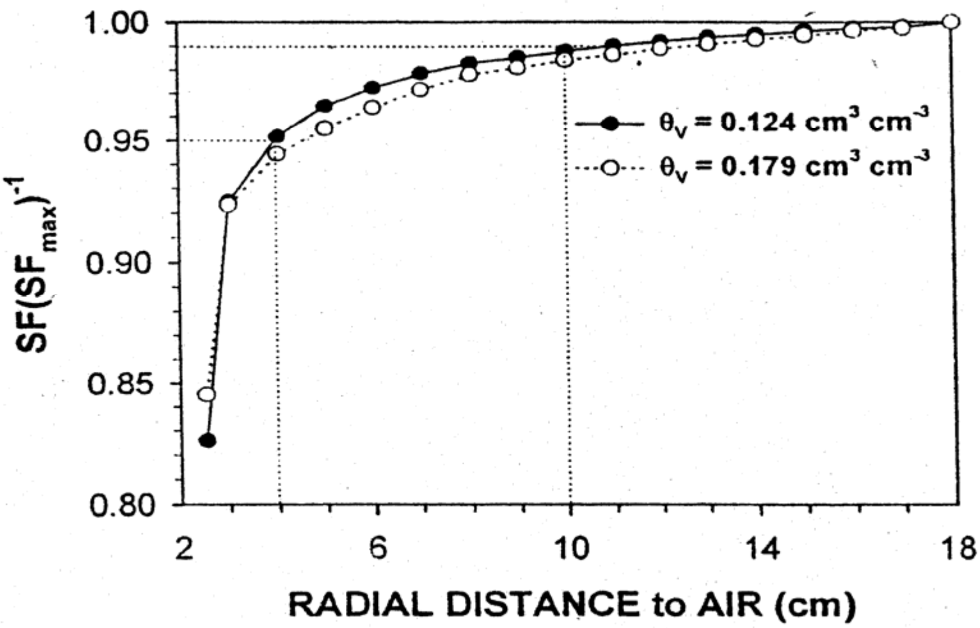


Figure 4-6 **Paltineanu and Starr 'Radial distance to air against SF/SFmax**

Paltineanu and Starr (1997) have reported that their trials were conducted using five different volumetric moisture contents ranging from 7% to 37% unfortunately they have only presented two out of the five curves in Figure 4-6.

While the volumetric moisture content of the dry, moist and wet samples shown in Figure 4-5 were relatively evenly spaced (0.036 $cm^3\ cm^{-3}$, 0.217 $cm^3\ cm^{-3}$ and 0.430 $cm^3\ cm^{-3}$ respectively) the two curves presented by Paltineanu and Starr were quite close together (0.124 $cm^3\ cm^{-3}$ and 0.179 $cm^3\ cm^{-3}$). Reporting on the dry and wet extremes of study conducted by Paltineanu and Starr (1997) may have shown that the wet curve shown in Figure 4-5 is in error due to the air spaces left after packing. A set of experiments was then derived to test sensors response to the wettest possible condition: the sleeves filled with water and no soil. These experiments are discussed in Chapter 4.3.

Kelleners et al (2004) have also conducted sensitivity studies which have revealed that 90% of the sensors response is obtained from a zone which extends about 30 mm above and below the brass electrodes and 30 mm radially. The radial distance is confirmed by Paltineanu and Starr (1997) in Figure 4-6 but the distance found to provide 90% of the response shown in Figure 4-5 is 34mm.

Figure 4-5 shows a horizontal line representing 99% of the maximum scaled frequency for the dry, moist and wet soil. This 99% line intersects all three curves at 72mm of soil thickness surrounding the access tube regardless of the moisture content. Paltineanu and Starr (1997) have reported that 99% of the sensors response was obtained from within 100mm radial distance to air. It appears that there is a discrepancy between these results and those reported by Paltineanu and Starr (1997)

Paltineanu and Starr (1997) have reported that the remaining 5% of the response extended to a soil thickness of 180 mm from the outside of the access tube. This may suggest that the 100mm radial distance measurement may have been taken from the centre of the access tube and not the outside edge as reported. The reasoning behind this assumption is that Paltineanu and Starr (1997) state that their calibration box is 355 mm x 355 mm square by 400mm deep. The access tube (56.7mm OD) is then inserted into the centre of the box allowing (355 mm – 56.7 mm)/2 = 149.15 mm minimum thickness of soil from the outside of the access tube. This value would not allow Paltineanu and Starr to report to 180 mm radial distance from the outside of the access tube.

However, if the measurements were taken from the centre of the access tube (and not the outside edge) then the minimum radial distance would be 355 mm/2 = 177.5mm ≈ 180mm. If this was the case then 99% of the sensors response (in Paltineanu and Starr's work) would be obtained from 100mm – (56.7mm/2) = 71.65 ≈ 72mm which is the same soil thickness that was determined in Figure 4-5.

4.2 Temperature of Soil

The laboratory work was undertaken at room temperature between May and September 2005 in the University of Southern Queensland's Soil Laboratory. A sample of hot and dry soil was prepared by oven drying soil for at least 24 hours at 105 ^{o}C. The 'hot and dry' soil was packed into the largest sleeve and tested in the same manner as the previous soil tests (as discussed in Chapter 3.5.9. As soon as the soil was removed from the oven it started cooling to ambient temperature. Once testing had been completed, the oven dried soil was then stored in an open container.

The soil was reused the following day in the 'dry' soil experiments. Having just been removed from the oven, the hot dry soil was assumed to have a soil moisture of zero cm^3 cm^{-3}, and as such, volumetric moisture (θ_v) determination was not undertaken.

Tan (1996) states that oven dried soil becomes hygroscopic when not stored in an airtight container, and will draw moisture from the atmosphere. This is likely to have occurred in the 24 hours between testing the 'hot and dry' soil and testing the 'dry' soil. Evidence of this in that volumetric moisture content calculations were performed on the 'dry' soil after testing and yielded a θ_v of 0.036 $cm^3\ cm^{-3}$.

Figure 4-7 shows the variation between the scaled frequency curves of the 'hot and dry' soil and the 'dry' soil. There is an obvious variation in the maximum scaled frequency (measured at 120 mm soil thickness) between the two curves. It is difficult to ascertain if this variation is a result of temperature difference in the soils. The variation in volumetric moisture content between the treatments may be the cause for the differing maximum scaled frequency which may be creating a masking effect on any response to the temperature variation.

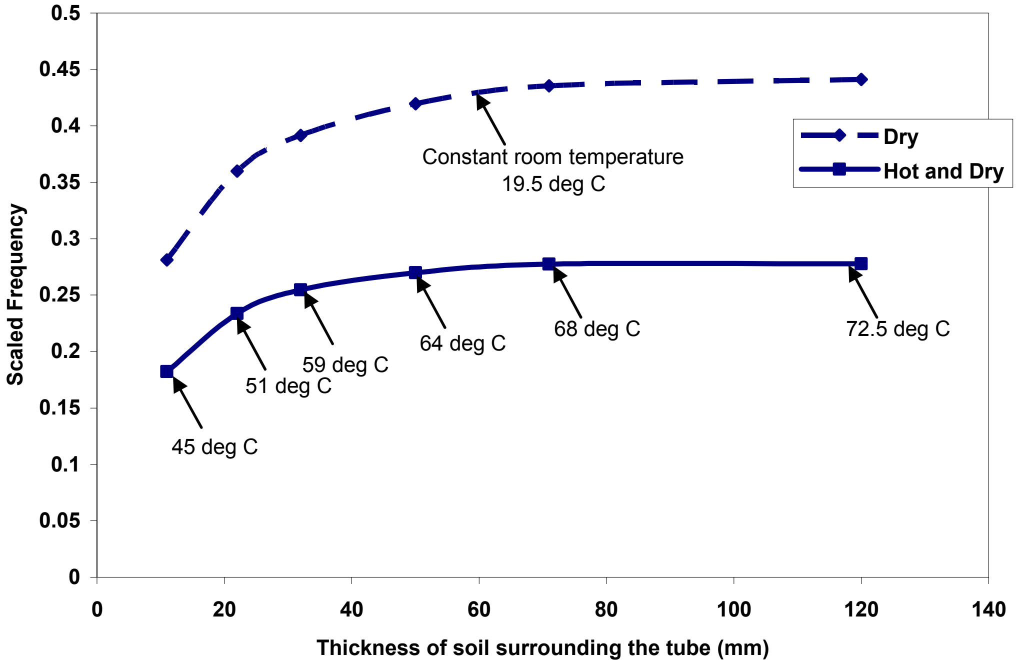


Figure 4-7 **Variation in curve shape with hot soil**

Paltineanu and Starr (1997) state that the dielectric constant of water is inversely related to temperature using Equation 6

Equation 6

$$K_w = 78.54\left[1 - 4.579\times10^{-3}\left(t^o - 25\right) + 1.19\times10^{-5}\left(t^o - 25\right)^2 - 2.8\times10^{-8}\left(t^o - 25\right)^3\right]$$

The inverse relationship between water temperature and dielectric constant means that there will be a direct relationship between water temperature and scaled frequency (scaled frequency has an inverse relationship with dielectric constant). However they then proceed to report that there is a weak negative relationship between air temperature and relative frequency (frequency at temperature / frequency at 20 °C).

Based on the assumption that there is an absence of water from the dry samples and that the soil temperature behaves the same as air temperature in terms of dielectric constant, Paltineanu and Starr (1997) support the findings shown in Figure 4-7. This is apparent because the 'hot and dry' soil curve has a maximum scaled frequency lower than that for the 'dry' soil suggesting that the temperature is inversely proportional to scaled frequency and thus directly proportional to the dielectric constant of the surrounding material.

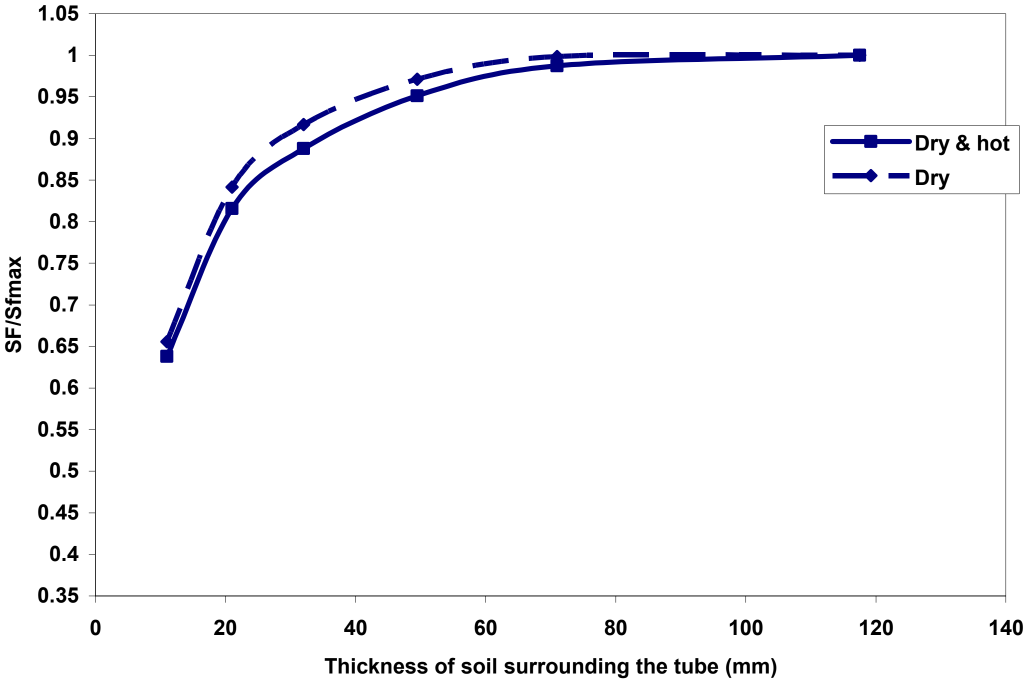


Figure 4-8 **Scaled frequency curves as a percentage of the maximum scaled frequency for dry and hot soil and dry soil**

When the ‘hot and dry’ and ‘dry’ curves are presented as SF/SF_{max} (Figure 4-8) there appears to be only a slight variation between the two curves. This suggests that there is little effect of hot soil on the capacitance probe readings. Baumhardt et al (2000), states that the EnviroSCAN ® is sensitive to soil temperature and that variations of temperature need to be considered when interpreting the derived moisture content.

It would appear that this would only be the case if there is some water present in the soil to allow the dielectric constant of the soil water medium to vary inversely with temperature.

4.3 Detection of water

Baumhardt et al (2000), reports that using saline water (EC of 11.3 dS/m) in soil based experiments yields a soil moisture content of up to 20% greater than the volumetrically determined moisture content. Although this is considered highly saline (especially for use on clay soils (de Hayr and Gordon, 2005)) it provides an indication of the possible effects that saline soils or saline irrigation water could have on the output from a capacitance probe.

Figure 4-9 shows the increase in scaled frequency with the increasing electrical conductivity. It is assumed that with more data points this would become a smooth curve tending to an upper limit.

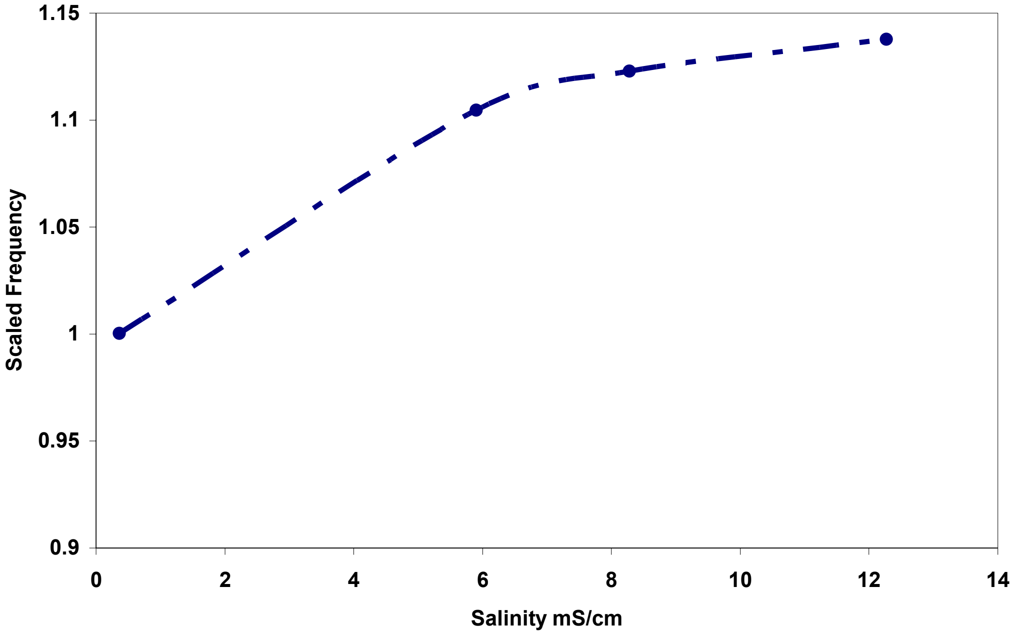


Figure 4-9 Variation in scaled frequency with increasing salinity

Figure 4-10 shows the variation in scaled frequency for the four different saline solutions tested. The maximum scaled frequency shown on this graph for the fresh water is 1.0. This is to be expected due to the form of Equation 4 used to calculate scaled frequency. When the material being tested (usually soil) is the same as the material used in the water reference count, then the scaled frequency equation takes the form of Equation 7.

Equation 7

$$Scaled\ Frequency = \frac{Air\ Count - Water\ Count}{Air\ Count - Water\ Count} = 1$$

As Paltineanu and Starr (1997) and Kelleners et al (2004) have indicated, the presence of salts in the soil water will directly influence the dielectric behaviour of a soil. This is reflected in the maximum scaled frequencies shown in Figure 4-10. An increase in EC increases the dielectric constant of the water which results in a reduced raw count being received by the sensor, this in turn results in an increased scaled frequency.

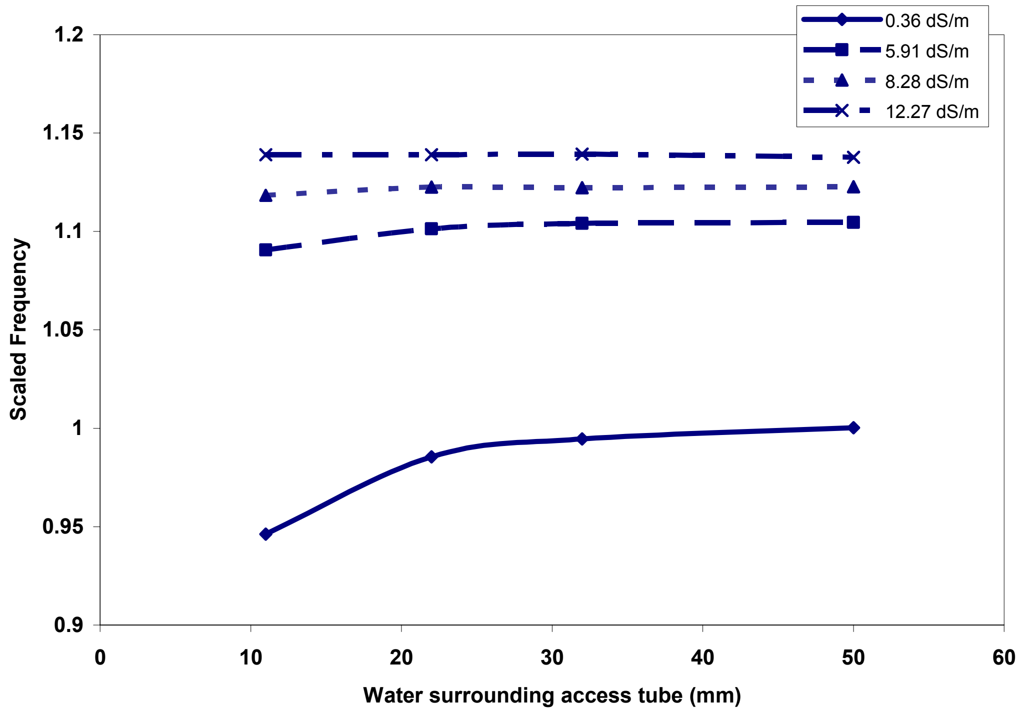


Figure 4-10 Behaviour of EnviroSCAN ® response in scaled frequency with varying amount of water surrounding the access tube

The scaled frequency data displayed in Figure 4-10 has been converted into a percentage of the maximum scaled frequency in a similar process as shown in Chapter 4.1 for each of the four saline solutions. The resulting graph is given as Figure 4-11.

While it has been shown in Chapter 4.1 that 99% of the sensors response in soil was obtained within 72 mm of the access tube for soil this appears to differ when there is no soil only water being used.

Figure 4-11 shows that for fresh water 99% of the response from the capacitance probe is taken from the first 24 mm around the access tube. This becomes even closer to the access tube for higher salinities (13 mm for 5.91dS/m, others not determined).

The salinity of the solution also appears to have an effect on the scaled frequency readings at low water thickness surrounding the access tube. The scaled frequency becomes less affected by the thickness of water surrounding the access tube as the EC increases. This is shown by the straightening out of the lines as the EC increases. This is due to the dissolved salts increasing the attenuation of the signal received by the sensors.

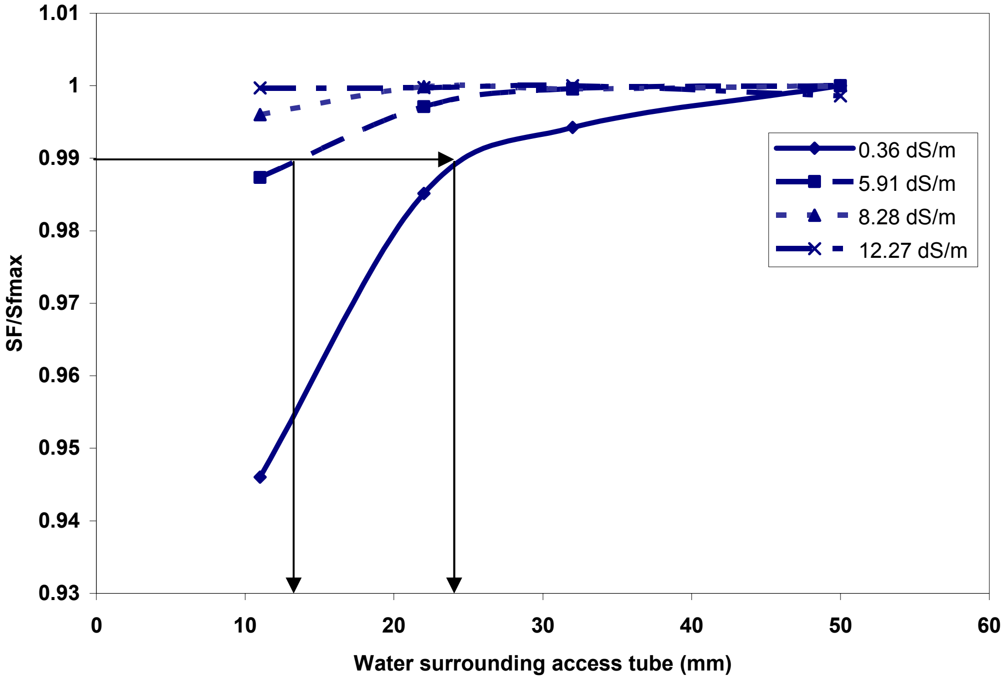


Figure 4-11 Scaled frequency curves as a percentage of the maximum scaled frequency for various Electrical Conductivities

Following the experiments of filling the sleeves to increase the thickness of water surround the access tube, another set of experiments was conducted which involved the sequential draining of the sleeves to create air gaps of varying width adjacent to the access tube.

Figure 4-12 shows that draining the inner most sleeve had by far the largest effect on the scaled frequency readings. This creates an air gap of 11 mm surrounding the access tube which reduces the scaled frequency to approximately 10% of the maximum.

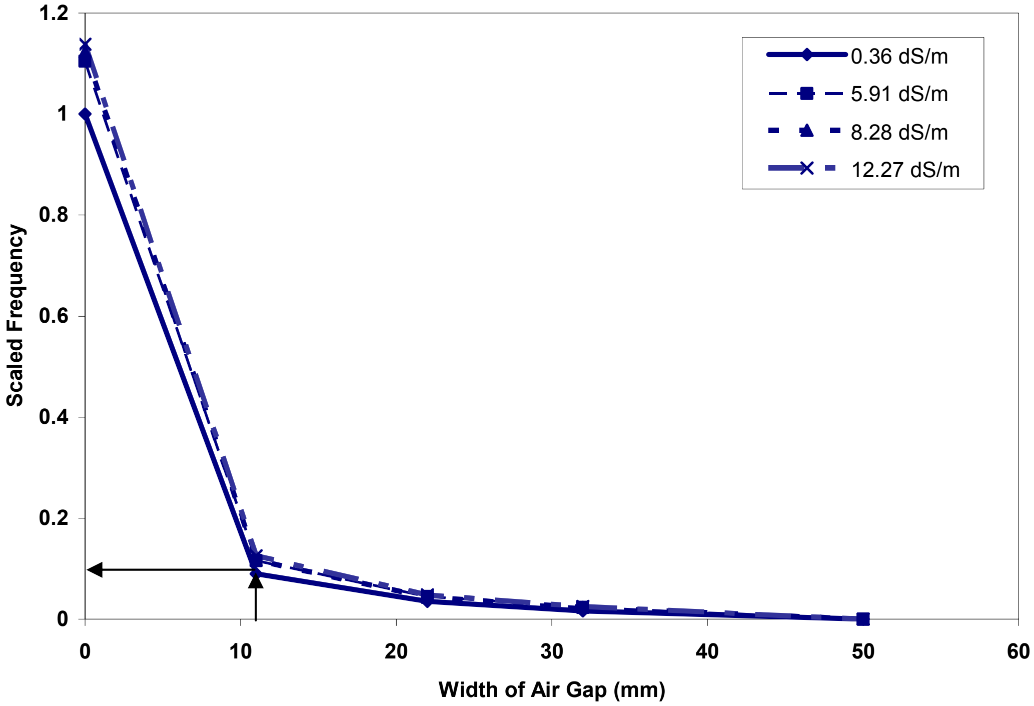


Figure 4-12 Rapid decrease in scaled frequency with increasing air void surrounding the access tube

Further draining of the sleeves as illustrated in Appendix F showed an exponential decay in the sensors response to the water almost irrespective of the electrical conductivity. This indicates that even small air gaps in contact with the access tube have the potential to cause large scale variations in the probes ability to detect soil moisture

These findings have been supported by finite element modelling undertaken by de Rosny et al (2001). Their research revealed that the sensitivity of a capacitance probe to soil moisture is significantly limited when there is not good contact between the access tube and the soil.

4.4 Applications to Cracking Clays

As discussed in Chapter 2.4, the shrinking and swelling nature of cracking clays means that these soils require special management. Installing capacitance probes to measure field soil moisture is of great benefit to the decision making process involved in irrigation scheduling. But for efficient water use it is essential that an accurate estimate is recorded. If cracks occur around or near the access tube, the probes ability to accurately detect the soil moisture is inhibited (Kelleners et al, 2004). Both the proximity of the crack to the access tube and the crack width will have varying degrees of effect on the soil moisture estimated by the capacitance probe.

4.4.1 Crack Proximity to Access Tube

Experiments undertaken using dry, moist and wet soil have shown that the 99% of capacitance probe response to soil moisture is obtained within 72 mm from the outside of the access tube. However, the response is not linear function of distance as 90% of the response is obtained within 30 mm (Kelleners et al, 2004; Paltineanu and Starr, 1997) to 34 mm of the access tube.

This suggests that a crack within 72 mm of the access tube has the potential to effect the capacitance probes response and a crack within 30 mm may have a significant effect.

4.4.2 Temperature of Soil Surrounding Access Tube

Testing a hot, oven dry soil against an ambient, air dried soil was not able to comprehensively detect the variation in the probes response to changing temperatures. The reason for this is most likely that the additional variable (soil moisture) may have masked the effects of the soil temperature variation. Paltineanu and Starr (1997) have stated that the raw counts collected by the sensor are directly proportional to water temperature with a slope of $4.4 \times 10^{-4}\ ^{o}C^{-1}$ and as the dielectric constant dominates the combined dielectric constant of the soil, water air mix, it is seen that a change in (moist or wet) soil temperature will impact on the sensors performance.

The practicality of this, is that the fluctuations in air temperature which affect the top 300 mm of soil (Baumhardt, 200), are likely to cause the sensor to over predict the volumetric soil moisture content. Sensors below this are less likely to be affected by temperature variations and therefore less likely to over predict the moisture content with changes in air temperature.

Following this analysis, water based experiments were undertaken to detect any variation in the sensors response with:

1. varying electrical conductivity of the solution; and
2. the presence of air gaps adjacent to the access tube.

4.4.3 Electrical Conductivity of Soil and Irrigation Water

The testing undertaken demonstrated that increased electrical conductivity was matched by an increase in scaled frequency. The responses recorded are reinforced by Baumhardt et al (2000) findings, that an increase in electrical conductivity may cause the sensor response to over predict the volumetric soil moisture.

The obvious implications to cracking clays are that in saline soils or when saline irrigation water is applied the capacitance probe may over predict the actual volumetric soil moisture content.

4.4.4 Width of Crack Surrounding Access Tube

By sequentially draining the water filled sleeves, an air gap surrounding the access tube was induced. This air gap was used to simulate a crack formation in direct contact with the access tube. The results indicated that a crack width of greater than 11 mm (smallest sleeve size used) would result in a 90% reduction in the probes response.

Therefore if a crack of >11 mm is in contact with the access tube then the capacitance probe is likely to under predict the actual volumetric soil moisture content by at least 90%

4.5 Sources of Error

The sources of error involved in this project can be classified into four categories. These are listed below:

- Instrumental Errors
- Operative Errors
- Personal Errors
- Analytical errors (Tan, 1996)

Each of these errors will be introduced generically in the following sections with potential project specific sources discussed in further detail. The nature of errors is such that if they can be identified, often they can be avoided or compensated for. It is the unforseen or unnoticed errors that have the greatest potential to deliver spurious results.

4.5.1 Instrumental Errors

These errors are obviously related to the instrumentation or equipment used. If the error is a constant error (occurs 100% of the time) then it can be compensated for in other areas of the project work. For example if an un-calibrated balance is used, then adjustments can be made in the calculations using the weights obtained from that balance (Tan, 1996).

Potential areas instrumental errors found in this project are in the capacitance probe, the balance used for weighing the samples and in the electrical conductivity meter.

The EnviroSCAN ® was supplied by Sentek and no modifications have been made to the probe, sensors or software. Air and water reference counts were taken as described in 3.1.2 at the beginning of each experimental session for use in the scaled frequency calculation. Further to this an analysis of the air and water reference counts at the beginning and end of an experiment was undertaken to determine if there was any drift in the sensors during the experiment (Chapter 3.1.3.).

The balance used was able to report to ± 0.1g and auto calibrated each time it was switched on. This balance was used for the all the weighing undertaken for the calculations of the volumetric water content of the soils tested.

The TPS MC80 was calibrated using a 3 point calibration according to the user manual immediately before it was used to determine the electrical conductivity of the solutions used in water based experiments.

It is expected that there was little instrumental error that could be attributed to instrumental error.

4.5.2 Operative Errors

Operative errors are those caused by the operator performing the analysis. These are often a result of inexperience or careless work. Operative errors may include poor sample selection, improper use of equipment, spills, etc (Tan, 1996).

Baumhardt et al, (2000) suggests that imprecise sensor positioning when taking water reference counts had the effect of incorporating some air effects on the water reference reading which would cause bias in all scale frequency calculations.

The collection of soil shaved from the cylindrical soil mass was collected as carefully and as thoroughly as possible using a large tray under the testing apparatus to catch any fallen soil. However, it was not always possible to collect all of the soil removed for each successive sleeve. This is not considered to have impacted on the calculations for gravimetric water content and bulk density because the values calculated for these parameters was base on an average for all of the sleeves used during each experiment.

The sleeves were not rinsed with fresh water and dried prior to filling with a solution of saline water. It is expected that the few droplets that remained on the sleeves after each one had been drained was of little consequence when considering the volume of solution added to each sleeve.

The transfer of data from the Sentek ‘Logger Manager’ software to the Microsoft Excel spreadsheet was done using manual data entry. Using this method there is always the potential for mis-keying data. Raw count data was collected for all sensors regardless of their position relative to the centre of the soil mass. This provided approximate value (from the sensors either side) for comparison during data checking.

The data collected was checked in excel to ensure that the raw counts recorded for the soil based experiments were between the air and water reference counts.

The air spaces that were present in samples after compaction has had an effect on the raw counts and therefore the scale frequency especially in the wet sample that has been described in Figure 4-3. This error may also be included in the analytical error category because the method of using the compacting tool shown in Figure 3-5 and a rubber mallet was not sufficient to compact the soil such that large air spaces were removed.

Tan (1996) has suggested that the operative errors can be of significant value and it is expected that there is high potential for this type of errors to have an effect on this project.

4.5.3 Personal Errors

Personal errors are those related to judgments made by the person performing the investigation. A personal error can be made intentionally or unintentionally and these errors have the potential to affect the outcomes of an experiment quite significantly (Tan, 1996).

As discussed in Chapter 3.3.2 the soil used (red Ferrosol) was sampled from the same location at the USQ Ag Plot to reduce the risk of variations in results due to differing soil composition.

The selective inclusion and exclusion of experimental data based on wether sample crumbled prior to completion of the experiment may be considered an intentional personal error. However, it is seen that the effects of including data collected when the soil mass was no longer representing a constant thickness of surrounding the access tube, is considered a greater error.

During the soil based experiments, the length of access tube mounted in the testing apparatus was not used to take air reference count; instead a spare section of access tube was used. The potential for this to cause erroneous results is low as both tubes were the factory supplied special sized PVC access tube and it is not expected that there would be inconsistencies in the tubes large enough to cause a large scale change in the air reference count.

There is the possibility that personal errors may have had an effect on the project outcomes.

4.5.4 Analytical Errors

Analytical errors are related to flaws in the procedures and methods and not necessarily the person performing the tasks. These errors have the potential to mask any trends that may be occurring in the data set (Tan, 1996).

All of the laboratory work was conducted by one person therefore it is expected that there is little variation in the methods and techniques used that have not been accounted for. However, as previously mentioned some of the methods used were developed specifically for this project and may in fact be inadequate or inappropriate or inconsistent with the intended aims of the experiments.

As mentioned under operative errors the choice of compaction method was inadequate. The target measurement when using a capacitance probe is volumetric soil moisture content which accounts for bulk density (Equation 2). Therefore the amount of compaction was not critical as long as it was consistent throughout the sample volume. However, the air spaces left caused problems in the accurate determination of the scaled frequency. This could have been over come by using an hydraulic press similar to that used by Paltineanu and Starr (1997).

All calculations have been undertaken and reported as a thickness of soil or water from the access tube. It would be very rare to find an application whereby the capacitance probe is being used without an access tube, therefore the 0.2mm clearance between the brass rings and the inside wall of the access tube and the 2.7mm wall thickness of the access tube have been considered a constant and have not been included in the distance calculations.

Also, during the water based experiments as well as during the dry soil experiments when the acrylic sleeves were left in place during the testing, no consideration was given to the effect that the sleeves would have on the raw counts from the sensors. The sleeves effectively added 3mm to the thickness of the medium being tested. This was not of great consequence in the soil experiments as detailed in Chapter 3.5.6 because the soil solids and polycarbonate/ acrylic have similar dielectric constants (Clipper controls, 2005), but in the water based experiments the difference between the dielectric constants of the water and the acrylic may have caused an effect.

It is considered that analytical errors would have had some effect on the experimental outcomes.

Chapter 5. Conclusions and Recommendations

5.1 Completed Objectives

The aims of this project as given in the Project Specification (Issue B) dated 16 May 2005 (Appendix A) have been tabulated below along side the status of work for each of the tasks.

Table 5 Project tasks and status of each task

Task	Status
Research the background information on the behaviour and sensitivity of soil moisture measurement focusing on time domain and frequency domain (capacitance) probes.	Completed
Design a suitable apparatus to create compacted soil of known bulk density and water content which will allow successive reductions in the diameter of the apparatus in order to detect any variation in readings by the sensor	Completed
Develop suitable methods to collect, characterize and process soil materials for testing the sensitivity of capacitance probes	Completed
Investigate the effects of volumetric water content and bulk density of soil on the measured water content by a capacitance probe	Completed
Analyse results to evaluate the sensitivity of the capacitance probe to soil moisture within varying volumes of soil	Completed
Discuss the application of results to measurement of soil moisture in cracking clay soils	Completed
As time permits	
Expand the investigation to detect the effect of cracks of various geometry and orientation on readings from the capacitance probe	Incomplete
Examine the possible application of models in dielectric behaviour of materials to the project data	Incomplete

5.2 Conclusions

The EnviroSCAN ® made by Sentek is a capacitance probe used for detecting soil moisture. Capacitance probe technology is a non destructive indirect method for detecting soil moisture in real time. The capacitance technique is effective due to the large variation in the dielectric constants of air and soil (1 and 3-4 respectively) and water (80) (Morgan et al, 1999 and Clipper controls, 2005). A small change in the water content of an air, water, soil mix will significantly impact on the combined dielectric of the matrix.

The radial sensitivity tests were conducted to determine if varying moisture content had an effect on the radius of influence of the sensor the results from this work is inconclusive. However, based on an understanding of dielectric properties of a soil, water and air mix as well as the way that a capacitance probe uses this property to estimate a soil moisture content, it is assumed that the higher the moisture content in the soil the smaller the thickness of soil required surrounding the access tube

Literature suggests that an increase in temperature is likely to cause the sensor to over predict the volumetric soil moisture content. This was not comprehensively determined in this experimental work because the variation in moisture content between the control (dry) and the treatment (hot and dry) soils.

Increasing electrical conductivity in the water based experiments increased the scaled frequency. Therefore capacitance probe reading in saline soils or following irrigation with saline water may over predict the actual volumetric soil moisture content. It is recommended that the water intended for use in irrigation should be used to take the water reference counts.

Air gaps adjacent to the access tube in the water based experiments representing soil cracks had a profound effect on the sensor response. Air gaps of >11 mm produced a 90% reduction in the scaled frequency.

5.3 Further investigations

Further developing the knowledge surrounding the behaviour of capacitance probes with respect to environmental variables will allow increased confidence in the sensors response.

A direct extension of the work presented above could include a water based experiment involving the draining of sleeves 2 and/or 3. This would represent a crack of varying width at some distance (11 mm or 22 mm) from the access tube, while still maintaining direct contact between water and the access tube. However, it may be possible to undertake this analysis mathematically using the data collected in the above experiments with respect to the amount of response obtained from varying soil thicknesses.

It may be of benefit to users of capacitance probes in clay soils if a table of scaling factors was developed. The table should show a factor to be used when cracks are present surrounding the access tube. If the parameters used in the table are the crack width and the distance between the access tube and the crack (Table 6), scaling factors can be determined which the user can multiply the probes response by to achieve a closer representation of the actual volumetric moisture content.

Other scaling factor tables could be developed for the electrical conductivity of the soil surrounding the access tube or temperature flux.

Table 6 Possible product of experimental work

Crack width (mm)	Distance between access tube and crack (mm)		
	1	2	3
1	scale	factors	scale
2	factors	scale	factors
3	scale	factors	scale

List of References

Australian Bureau of Statistics (ABS), 2005, *Water Use on Australian Farms: 2003–04,* Commonwealth of Australia, Canberra, Australia.

Baumhardt R, Lascano R, and Evett S, 2000, '*Soil Material, Temperature, and Salinity Effects on Calibration of Multisensor Capacitance Probes'*, Soil Science Society of America Journal, Vol 64, pp. 1940-1946.

Blake G, 1965, 'Bulk Density', In Black, C (Ed), *Methods of Soil Analysis, Part 1 – Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling*, American Society of Agronomy Inc, Madison, Wisconsin, USA.

Bolvin, H., Chambarel, A., Chanzy, A, 2004, *Three Dimensional Numerical Modelling of a Capacitance Probe: Application to Measurement Interpretation*, Soil Science Society of America Journal. Vol 68 pp. 440 -446, Wisconsin, USA

Brady, N. and Weil, R., 1999, *The Nature and Properties of Soil, 12th ed.,* Prentice-Hall, New Jersey, USA.

Clipper controls (2005), *Dielectric Constants of materials,* Retrieved 18 June 2005, from http://www.clippercontrols.com/info/dielectric_constants.html

Craig R, 1997, *Soil Mechanics 6th Ed*, E & FN Spon, New York, USA.

Dane J, and Topp G (Eds), 2002, *Methods of Soil Analysis , Part 4 – Physical Methods*, Soil Science Society of America Inc, Madison, Wisconsin, USA.

de Hayr, R and Gordon, I, 2005, *Irrigation water quality - Salinity & soil structure stability*, Queensland Natural Resources and Mines Fact Sheets, Brisbane, Queensland

de Rosny G, Chanzy A, Parde M, Gaudu J, Frangi J, and Laurent J, 2001, '*Numerical Modelling of a Capacitance Probe Response',* Soil Science Society of America Journal, Vol 65, pp. 13-18.

Fares A, and Alva A, 2000 '*Soil Water Components Based on Capacitance Probes in a Sandy Soil*', Soil Science Society of America Journal, Vol 64, pp.311-318.

Hubble G, 1984, '*The Cracking Clay Soils: definition, distribution, nature, genesis and use*', In McGarity J, Hoult E, and So H, (Eds), The Properties Utilisation of Cracking Clay Soils, University of New England, Armidale, Australia.

Jabro J, Leib B, and Jabro A, 2005, '*Estimating soil water content using site specific calibration of capacitance measurements from Sentek EnviroSCAN systems*', American Society of Agricultural Engineers, Vol 21;3, pp. 393-399.

Kelleners T, Soppe R, Ayars J, and Skaggs T, 2004, '*Calibration of Capacitance Probe Sensors in a Saline Silty Clay Soil*', Soil Science Society of America Journal, Vol 68, pp. 770-778.

Lane P, and Mackenzie D, 2001, '*Field and laboratory calibration and test of TDR and capacitance techniques for indirect measurement of soil water content*', Australian Journal of Soil Research, Vol 39, pp. 1371-1386.

Leib, B, Jabro, J, and Mathews, G, 2003, *Field evaluation and performance comparison of soil moisture sensors*, Lippincott, Williams and Wilkins, WA, USA.

McKenzie N, Isbell R, Brown K, and Jacquier D, 1999, 'Major Soils Used for Agriculture in Australia', In Peverill K, Sparrow L, and Reuter D, (Eds), *Soil Analysis and Interpretation Manual*, CSIRO Publishing, Collingwood, Victoria, Australia.

Marshall, T, and Holmes, J, 1998, *Soil Physics* 2nd ed, Cambridge University Press, Cambridge, U.K.

McDonald R, Baker D, and Tucker R, 1984, 'Cracking Clays of the Emerald Irrigation Area, Central Queensland', In McGarity J, Hoult E, and So H, (Eds), *The Properties Utilisation of Cracking Clay Soils*, University of New England, Armidale, Australia.

Meyer, W, 1985*, Irrigation Scheduling – Principals*, Irrigation Association of Australia Journal, August, pp. 7, 8, 10.

Morgan K, Parsons L, Wheaton T, Pitts D, and Obreza T, 'Field Calibration of a Capacitance Water Content Probe in Fine Sand Soils', *Soil Science Society of America Journal*, Vol 63, pp. 987-989.

Roberts J, 1996, *Understanding Soil Mechanics*, Delmar Publishers, Albany, New York, USA.

Sentek, 2001, *Calibration of Sentek Pty Ltd Soil Moisture Sensors,* Sentek Sensor Technologies, Stepney, South Australia.

Singer M, and Munns D, 1996*, Soils – An Introduction 3rd Ed*, Prentice Hall Inc, Upper Saddle River, New Jersey, USA.

Smiles, D. 1984, 'Water Relations of Cracking Clay Soils', In McGarity, J. Hoult, E. and So, H. (Eds). *The Properties Utilisation of Cracking Clay Soils*, University of New England, Armidale, Australia.

Tan K, 1996*, Soil Sampling, Preparation and Analysis*, Marcel Dekker Inc, New York, USA.

Upshur, J, Terry, J, Holoka, Goff, R, Cassar, G, 2002, *World History Volume 1,* Wadsworh-Thompson Learning, California, USA

Appendices

Appendix A Project Specification
Appendix B Soil to water calculation for moisture content and bulk density
Appendix C Laboratory data sheet
Appendix D Paired T-test for raw counts taken with and without polycarbonate or acrylic sleeves in place
Appendix E Typical chemical parameters from Toowoomba City Council Municipal Water Supply
Appendix F Sequence of filling and draining sleeves sealed onto apparatus platform.

Appendix A Project Specification

University of Southern Queensland

Faculty of Engineering and Surveying

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: **MICHAEL SCOBIE**

TOPIC: Sensitivity of Capacitance Probes to Soil Moisture in Clay Soils

Project Aim: This project aims to investigate the performance of capacitance probes in detecting soil moisture

Sponsorship: Sentek Pty Ltd, South Australia

Programme: ISSUE B, 16 MAY 2005

1. Research the background information on the behavior and sensitivity of soil moisture measurement focusing on time domain and frequency domain (capacitance) probes.
2. Design a suitable apparatus to create compacted soil of known bulk density and water content which will allow successive reductions in the diameter of the apparatus in order to detect any variation in readings by the sensor
3. Develop suitable methods to collect, characterize and process soil materials for testing the sensitivity of capacitance probes
4. Investigate the effects of volumetric water content and bulk density of soil on the measured water content by a capacitance probe
5. Analyze results to evaluate the sensitivity of the capacitance probe to soil moisture within varying volumes of soil
6. Discuss the application of results to measurement of soil moisture in cracking clay soils

As time permits

7. Expand the investigation to detect the effect of cracks of various geometry and orientation on readings from the capacitance probe
8. Examine the possible application of models in dielectric behavior of materials to the project data

Agreed

___________________Student ________________________Supervisor

____/____/____ ____/____/____

Appendix B Soil to water calculation for moisture content and bulk density

Water Content of Air Dryed soil

1	M1	Mass of tin (g)	40.97
	M2	Mass of air dried soil and tin (g)	93.12
	M3	Mass of oven dried soil and tin (g)	91.68
	M4	Mass of water = M2-M3	1.44
	M5	Mass of soil = M3-M1	50.71
	Gravimetric W.C. (%) = M4/M5*100		2.84
2	M1	Mass of tin (g)	38.88
	M2	Mass of air dried soil and tin (g)	94.56
	M3	Mass of oven dried soil and tin (g)	92.96
	M4	Mass of water = M2-M3	1.6
	M5	Mass of soil = M3-M1	54.08
	Gravimetric W.C. (%) = M4/M5*100		2.96
3	M1	Mass of tin (g)	41.4
	M2	Mass of air dried soil and tin (g)	96.23
	M3	Mass of oven dried soil and tin (g)	94.69
	M4	Mass of water = M2-M3	1.54
	M5	Mass of soil = M3-M1	53.29
	Gravimetric W.C. (%) = M4/M5*100		2.89
		average	2.90

WC 2.9% = 2.9g water /100g air dried soil

To create 5% WC we need to add 2.1ml of water to each 100g soil
To create 10% WC we need to add 7.1ml of water to each 100g soil
To create 15% WC we need to add 12.1ml of water to each 100g soil
To create 20% WC we need to add 17.1ml of water to each 100g soil
To create 25% WC we need to add 22.1ml of water to each 100g soil

Bulk density

BD=Mass of oven dried soil/packing volume

where packing volume = (pi x 0.293^2)/4 x 0.1 per 100mm depth
- 0.006486 m^3 -access tube
= 6486.493 cm^3

	so for a 120g sample with BD of 1.0 (g/cm^3) & WC of 20% we need	
	100g OD soil x volume (6486.49cm^3/100mm depth)=	6486.493
+	20g water or	
	102.9g AD soil +	6674.601
=	17.1g water	1109.19
	120g wet soil	7783.791

for BD= 1.0

MC	soil required (g)	Water Required (ml)
5	6486.49	142
10	6486.49	466
15	6486.49	791
20	6486.49	1115
25	6486.49	1439

for BD= 1.05

MC	soil required (g)	Water Required (ml)
5	6810.82	149
10	6810.82	490
15	6810.82	830
20	6810.82	1171
25	6810.82	1511

for BD= 1.10

MC	soil required (g)	Water Required (ml)
5	7135.14	156
10	7135.14	513
15	7135.14	870
20	7135.14	1227
25	7135.14	1583

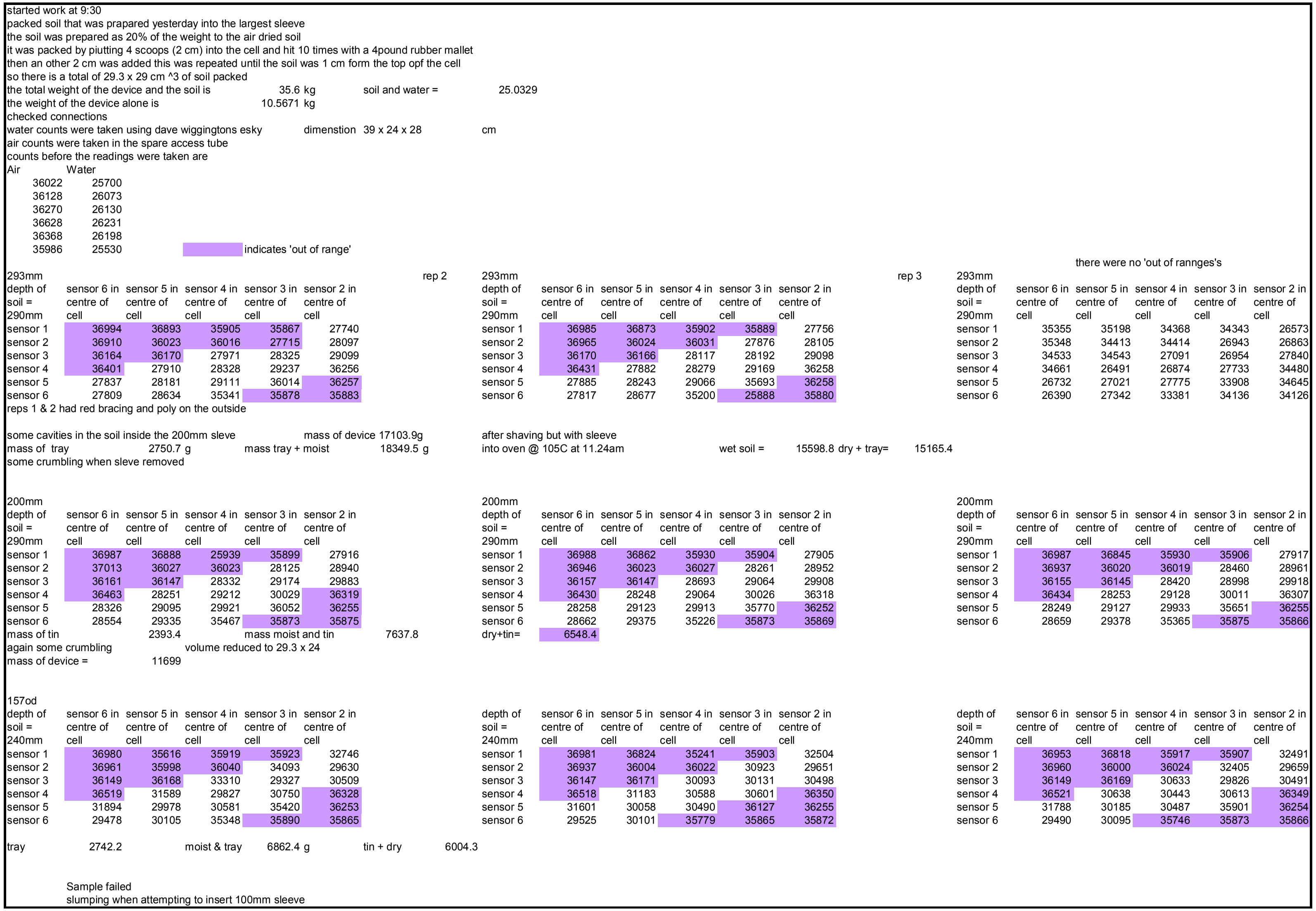
for BD= 1.15

MC	soil required (g)	Water Required (ml)
5	7459.47	163
10	7459.47	536
15	7459.47	909
20	7459.47	1282
25	7459.47	1655

for BD= 1.20

MC	soil required (g)	Water Required (ml)
5	7783.79	170
10	7783.79	560
15	7783.79	949
20	7783.79	1338
25	7783.79	1727

Appendix C Laboratory data sheet



started work at 9:30
packed soil that was prapared yesterday into the largest sleeve
the soil was prepared as 20% of the weight to the air dried soil
it was packed by piutting 4 scoops (2 cm) into the cell and hit 10 times with a 4pound rubber mallet
then an other 2 cm was added this was repeated until the soil was 1 cm form the top opf the cell
so there is a total of 29.3 x 29 cm ^3 of soil packed
the total weight of the device and the soil is 35.6 kg soil and water = 25.0329
the weight of the device alone is 10.5671 kg
checked connections
water counts were taken using dave wiggingtons esky dimenstion 39 x 24 x 28 cm
air counts were taken in the spare access tube
counts before the readings were taken are

Air	Water
36022	25700
36128	26073
36270	26130
36628	26231
36368	26198
35986	25530

▨ indicates 'out of range'

293mm

depth of soil = 290mm	sensor 6 in centre of cell	sensor 5 in centre of cell	sensor 4 in centre of cell	sensor 3 in centre of cell	sensor 2 in centre of cell
sensor 1	36994	36893	35905	35867	27740
sensor 2	36910	36023	36016	27715	28097
sensor 3	36164	36170	27971	28325	29099
sensor 4	36401	27910	28328	29237	36256
sensor 5	27837	28181	29111	36014	36257
sensor 6	27809	28634	35341	35878	35883

reps 1 & 2 had red bracing and poly on the outside

rep 2

293mm

depth of soil = 290mm	sensor 6 in centre of cell	sensor 5 in centre of cell	sensor 4 in centre of cell	sensor 3 in centre of cell	sensor 2 in centre of cell
sensor 1	36985	36873	35902	35889	27756
sensor 2	36965	36024	36031	27876	28105
sensor 3	36170	36166	28117	28192	29098
sensor 4	36431	27882	28279	29169	36258
sensor 5	27885	28243	29066	35693	36258
sensor 6	27817	28677	35200	25888	35880

rep 3

there were no 'out of rannges's

293mm

depth of soil = 290mm	sensor 6 in centre of cell	sensor 5 in centre of cell	sensor 4 in centre of cell	sensor 3 in centre of cell	sensor 2 in centre of cell
sensor 1	35355	35198	34368	34343	26573
sensor 2	35348	34413	34414	26943	26863
sensor 3	34533	34543	27091	26954	27840
sensor 4	34661	26491	26874	27733	34480
sensor 5	26732	27021	27775	33908	34645
sensor 6	26390	27342	33381	34136	34126

some cavities in the soil inside the 200mm sleve mass of device 17103.9g
mass of tray 2750.7 g mass tray + moist 18349.5 g
some crumbling when sleve removed

after shaving but with sleeve
into oven @ 105C at 11.24am wet soil = 15598.8 dry + tray= 15165.4

200mm

depth of soil = 290mm	sensor 6 in centre of cell	sensor 5 in centre of cell	sensor 4 in centre of cell	sensor 3 in centre of cell	sensor 2 in centre of cell
sensor 1	36987	36888	25939	35899	27916
sensor 2	37013	36027	36023	28125	28940
sensor 3	36161	36147	28332	29174	29883
sensor 4	36463	28251	29212	30029	36319
sensor 5	28326	29095	29921	36052	36255
sensor 6	28554	29335	35467	35873	35875

mass of tin 2393.4 mass moist and tin 7637.8
again some crumbling volume reduced to 29.3 x 24
mass of device = 11699

200mm

depth of soil = 290mm	sensor 6 in centre of cell	sensor 5 in centre of cell	sensor 4 in centre of cell	sensor 3 in centre of cell	sensor 2 in centre of cell
sensor 1	36988	36862	35930	35904	27905
sensor 2	36946	36023	36027	28261	28952
sensor 3	36157	36147	28693	29064	29908
sensor 4	36430	28248	29064	30026	36318
sensor 5	28258	29123	29913	35770	36252
sensor 6	28662	29375	35226	35873	35869

dry+tin= 6548.4

200mm

depth of soil = 290mm	sensor 6 in centre of cell	sensor 5 in centre of cell	sensor 4 in centre of cell	sensor 3 in centre of cell	sensor 2 in centre of cell
sensor 1	36987	36845	35930	35906	27917
sensor 2	36937	36020	36019	28460	28961
sensor 3	36155	36145	28420	28998	29918
sensor 4	36434	28253	29128	30011	36307
sensor 5	28249	29127	29933	35651	36255
sensor 6	28659	29378	35365	35875	35866

157od

depth of soil = 240mm	sensor 6 in centre of cell	sensor 5 in centre of cell	sensor 4 in centre of cell	sensor 3 in centre of cell	sensor 2 in centre of cell
sensor 1	36980	35616	35919	35923	32746
sensor 2	36961	35998	36040	34093	29630
sensor 3	36149	36168	33310	29327	30509
sensor 4	36519	31589	29827	30750	36328
sensor 5	31894	29978	30581	35420	36253
sensor 6	29478	30105	35348	35890	35865

depth of soil = 240mm	sensor 6 in centre of cell	sensor 5 in centre of cell	sensor 4 in centre of cell	sensor 3 in centre of cell	sensor 2 in centre of cell
sensor 1	36981	36824	35241	35903	32504
sensor 2	36937	36004	36022	30923	29651
sensor 3	36147	36171	30093	30131	30498
sensor 4	36518	31183	30588	30601	36350
sensor 5	31601	30058	30490	36127	36255
sensor 6	29525	30101	35779	35865	35872

depth of soil = 240mm	sensor 6 in centre of cell	sensor 5 in centre of cell	sensor 4 in centre of cell	sensor 3 in centre of cell	sensor 2 in centre of cell
sensor 1	36953	36818	35917	35907	32491
sensor 2	36960	36000	36024	32405	29659
sensor 3	36149	36169	30633	29826	30491
sensor 4	36521	30638	30443	30613	36349
sensor 5	31788	30185	30487	35901	36254
sensor 6	29490	30095	35746	35873	35866

tray 2742.2 moist & tray 6862.4 g tin + dry 6004.3

Sample failed
slumping when attempting to insert 100mm sleeve

Appendix D Paired T-test for raw counts taken with and without polycarbonate or acrylic sleeves in place

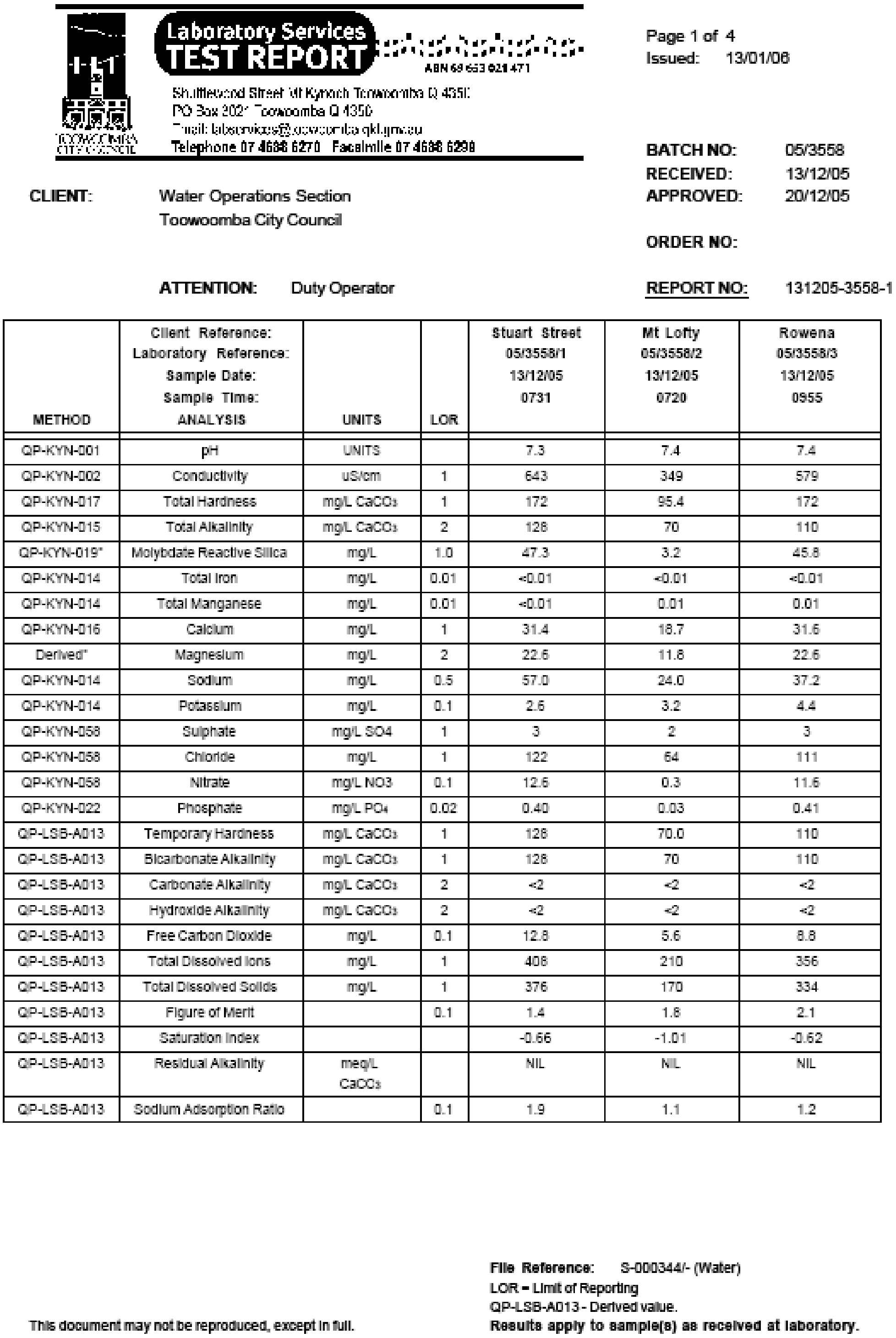
t-Test: Two-Sample Assuming Unequal Variances
for wet soil with and without sleeves in place

	with	*without*
Mean	28820.63	28845.94
Variance	1547718	1477259
Observations	48	48
Hypothesized Mean Difference	0	
df	94	
t Stat	-0.10083	
P(T<=t) one-tail	0.45995	
t Critical one-tail	1.661226	
P(T<=t) two-tail	0.919899	
t Critical two-tail	1.985523	

t-Test: Two-Sample Assuming Unequal Variances
for moist soil with and without sleeves in place

	with	*without*
Mean	31116.47	31064.88
Variance	551372.1	577330.6
Observations	59	59
Hypothesized Mean Difference	0	
df	116	
t Stat	0.373017	
P(T<=t) one-tail	0.354908	
t Critical one-tail	1.658096	
P(T<=t) two-tail	0.709816	
t Critical two-tail	1.980626	

Appendix E Typical chemical parameters from Toowoomba City Council Municipal Water Supply



Laboratory Services
TEST REPORT
ABN 69 653 021 471
Shuttleworth Street Mt Kynoch Toowoomba Q 4350
PO Box 2021 Toowoomba Q 4350
Email: labservices@toowoomba.qld.gov.au
Telephone 07 4688 6270 Facsimile 07 4688 6298

Page 1 of 4
Issued: 13/01/06

BATCH NO: 05/3558
RECEIVED: 13/12/05
APPROVED: 20/12/05

CLIENT: Water Operations Section
Toowoomba City Council

ORDER NO:

ATTENTION: Duty Operator

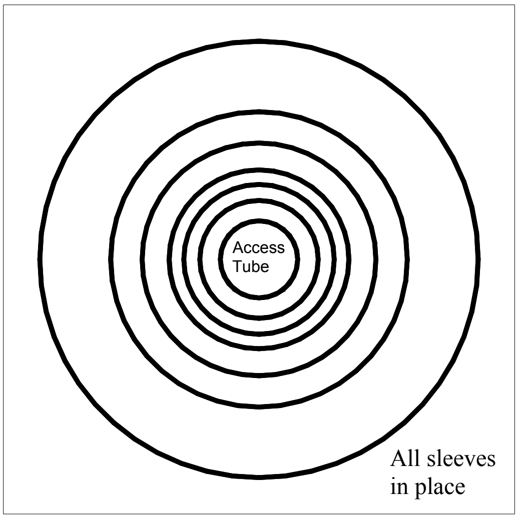
REPORT NO: 131205-3558-1

METHOD	Client Reference: Laboratory Reference: Sample Date: Sample Time: ANALYSIS	UNITS	LOR	Stuart Street 05/3558/1 13/12/05 0731	Mt Lofty 05/3558/2 13/12/05 0720	Rowena 05/3558/3 13/12/05 0955
QP-KYN-001	pH	UNITS		7.3	7.4	7.4
QP-KYN-002	Conductivity	uS/cm	1	643	349	579
QP-KYN-017	Total Hardness	mg/L $CaCO_3$	1	172	95.4	172
QP-KYN-015	Total Alkalinity	mg/L $CaCO_3$	2	128	70	110
QP-KYN-019*	Molybdate Reactive Silica	mg/L	1.0	47.3	3.2	45.8
QP-KYN-014	Total Iron	mg/L	0.01	<0.01	<0.01	<0.01
QP-KYN-014	Total Manganese	mg/L	0.01	<0.01	0.01	0.01
QP-KYN-016	Calcium	mg/L	1	31.4	18.7	31.6
Derived*	Magnesium	mg/L	2	22.6	11.8	22.6
QP-KYN-014	Sodium	mg/L	0.5	57.0	24.0	37.2
QP-KYN-014	Potassium	mg/L	0.1	2.6	3.2	4.4
QP-KYN-058	Sulphate	mg/L SO4	1	3	2	3
QP-KYN-058	Chloride	mg/L	1	122	64	111
QP-KYN-058	Nitrate	mg/L NO3	0.1	12.6	0.3	11.6
QP-KYN-022	Phosphate	mg/L PO_4	0.02	0.40	0.03	0.41
QP-LSB-A013	Temporary Hardness	mg/L $CaCO_3$	1	128	70.0	110
QP-LSB-A013	Bicarbonate Alkalinity	mg/L $CaCO_3$	1	128	70	110
QP-LSB-A013	Carbonate Alkalinity	mg/L $CaCO_3$	2	<2	<2	<2
QP-LSB-A013	Hydroxide Alkalinity	mg/L $CaCO_3$	2	<2	<2	<2
QP-LSB-A013	Free Carbon Dioxide	mg/L	0.1	12.8	5.6	8.8
QP-LSB-A013	Total Dissolved Ions	mg/L	1	408	210	356
QP-LSB-A013	Total Dissolved Solids	mg/L	1	376	170	334
QP-LSB-A013	Figure of Merit		0.1	1.4	1.8	2.1
QP-LSB-A013	Saturation Index			-0.66	-1.01	-0.62
QP-LSB-A013	Residual Alkalinity	meq/L $CaCO_3$		NIL	NIL	NIL
QP-LSB-A013	Sodium Adsorption Ratio		0.1	1.9	1.1	1.2

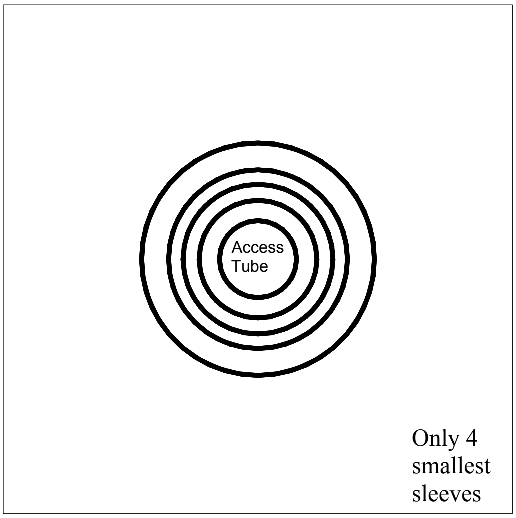
File Reference: S-000344/- (Water)
LOR = Limit of Reporting
QP-LSB-A013 - Derived value.
Results apply to sample(s) as received at laboratory.

This document may not be reproduced, except in full.

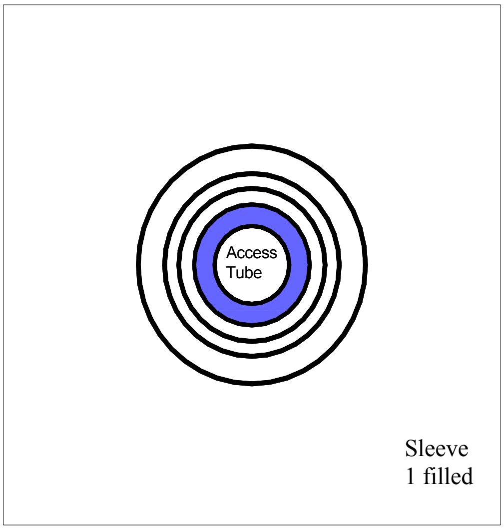
Appendix F Sequence of filling and draining sleeves sealed onto apparatus platform.



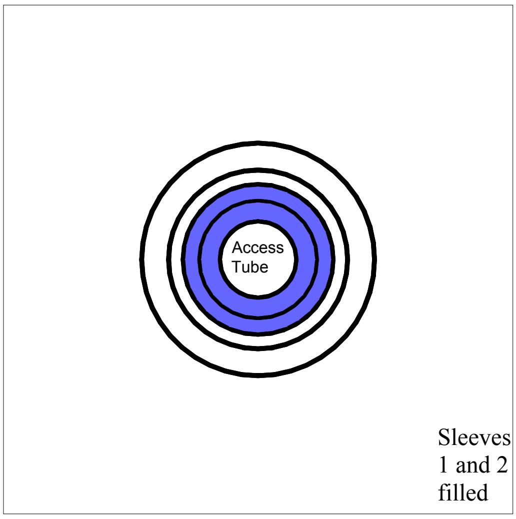
All sleeves
in place



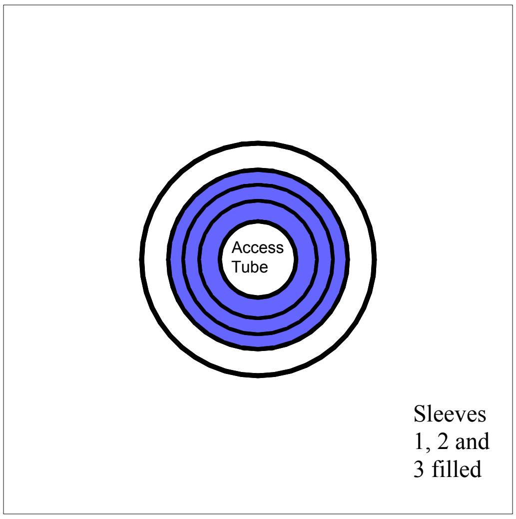
Only 4
smallest
sleeves



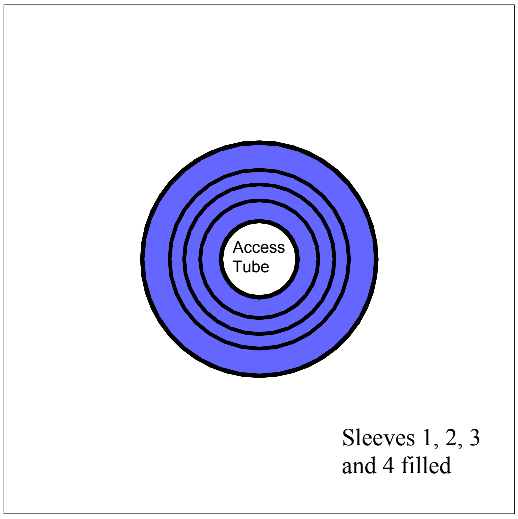
Sleeve
1 filled



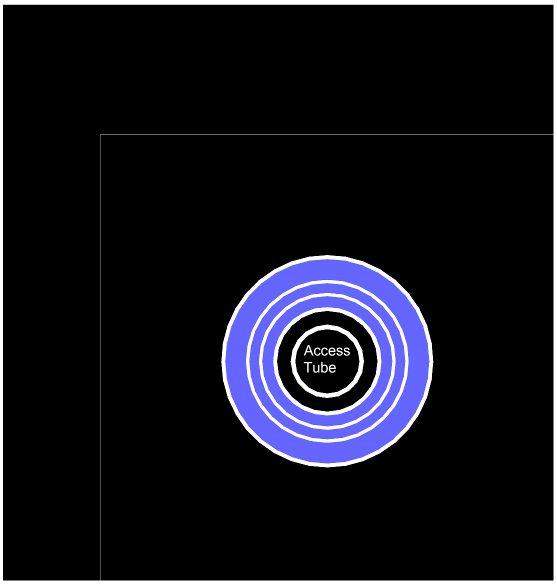
Sleeves
1 and 2
filled

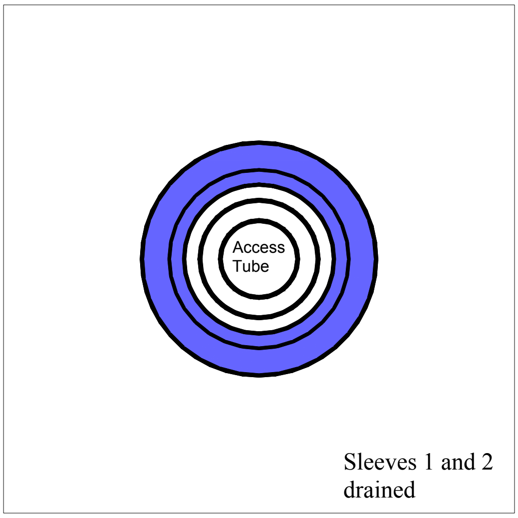


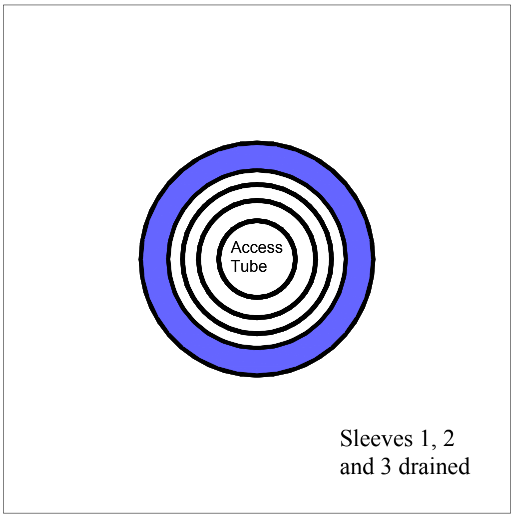
Sleeves
1, 2 and
3 filled

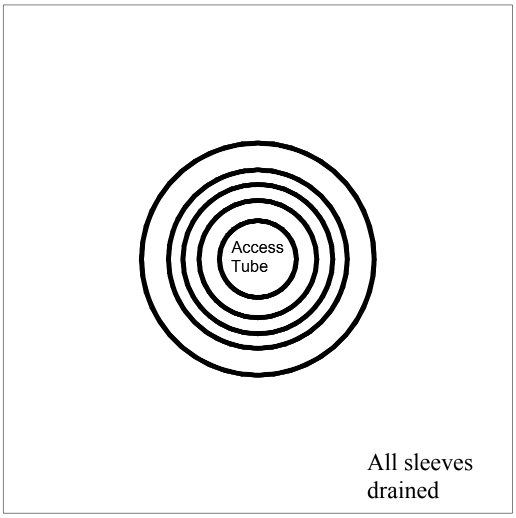


Sleeves 1, 2, 3
and 4 filled


Access
Tube


Access
Tube
Sleeves 1 and 2
drained


Access
Tube
Sleeves 1, 2
and 3 drained


Access
Tube
All sleeves
drained