DEVELOPMENT OF A CONTINUOUSLY MEASURING
SOIL COMPACTION SENSOR

A Thesis
Presented in Partial Fulfillment of the Requirements for
the Degree Master of Science in the
Graduate School of The Ohio State University

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The Ohio State University
2000

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ABSTRACT

The goal of this project was to develop a continuously indicating sensor to measure soil compaction. The sensor that was developed actually measured air permeability of the soil, which is an indicator of soil compaction. The sensor measured permeability by injecting a constant flow rate of air into the soil from a tine, and measuring the pressure resistance.

The sensor-soil interface was two orifices in a vertical plate mounted on the bottom of a sub-soiling shank. A Global Positioning System receiver was paired with the sensor to record position coordinates for the compaction measurements. LabView software was used to control the sensor and record the data.

The sensor output was compared to data obtained from a recording cone penetrometer. The sensor was capable of measuring compaction trends on a field scale, but is affected by soil type and moisture content.
I want to know God’s thoughts, . . . the rest are details.

Albert Einstein (1879-1955)
ACKNOWLEDGMENTS

First, I must thank the Lord my God for providing everything that allowed this project to be completed.

I would like to thank my adviser, Dr. Timothy Stombaugh, for all of his intellectual support, patient guidance, and nurturing leadership throughout the course of this study. It was only through his help that I was able to accomplish my goals.

I am grateful to Randall Reeder and Barry Allred for serving on my graduate committee and offering their expert advice and support. I would also like to thank Dr. Norm Fausey for his advice in the design of the shank.

A special thanks to Carl Cooper for all of his help in fabricating and building the sensor. Thanks are due to Bill Smith for assistance in wiring the electrical portion of the sensor. I would also like to thank Jon Hothem for assisting in data collection during field testing.

I would like to acknowledge Kale Marketing for their support in providing a subsoiling shank for use in this project. Ohio State University Farm Science Review is also deserving of many thanks for providing the use of a tractor and the land on which the tests were performed.
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CHAPTER 1

INTRODUCTION

Production agriculture in the Eastern Corn Belt has always experienced periods of change, and the 1990's have been no different. This decade has seen the number of farms dwindle while the average farm and equipment size has increased. The large number of acres that producers now try to cover reduces the window of time that is acceptable for field traffic on a per acre basis. This means that more acres experience traffic flow under conditions that render the soil more susceptible to compaction. Producers recognize the need to be efficient in growing crops and finding or developing new practices to maximize their production. One key to maximizing production is to better manage the soil used as the base of the production system. Soil is a very dynamic and unique biological component of the system. Gaining a deeper understanding of the state of the soil and how to better manage this precious resource is essential to improving the practice of efficiently growing field crops.
1.1 Justification for the study

There are many factors of crop production including weather, production inputs (i.e. fertilizer, herbicide, seed, etc.) and soil physical properties that limit yield. An emerging area of technology in agriculture most commonly referred to as Precision Agriculture utilizes Global Positioning Systems (GPS) and Geographic Information Systems (GIS) as aids to quantify and manage spatial variability in farm fields. To this point in time, most work in Precision Agriculture technology has centered around control and optimization of production inputs. However, the identification of soil characteristics is an area of work that needs to be addressed in greater detail. Recently, few significant advances have been made in the measurement and quantification of soil physical properties.

One of the most critical soil physical properties is soil compaction. Hakansson and Reeder (1994) found that subsoil compaction created by high axle loads (10 Mg or more) caused persistent reductions of crop yields, which are partially permanent in nature. Subsoil compaction at depths between 30 and 60 cm (12 and 24 in.) is very difficult to remedy because natural freezing and thawing processes do not typically act that deeply in the soil profile. Mechanical loosening is expensive due to the draft requirements to pull a tillage shank that deep, and it is difficult to achieve the desired results at subsoil depths. In a subsequent study on Hoytville silty clay loam, 9 Mg axle loads and 18 Mg axle loads applied annually for 3 years reduced yields in corn by 24% and 43% and in soybeans by 22% and 65%, respectively (Al-Adawi and Reeder, 1996). Erbach et al. (1992) reported many different agronomic parameters that indicate the
effects of soil compaction on corn production. Using different methods known to ameliorate compaction, they were able to show increased emergence rates, higher yields and lower grain moisture content at harvest compared to non-tillage conditions. It is clear that soil compaction does significantly reduce crop yields in years with few other limiting factors such as soil water and nutrients. Yields are also reduced in years with excessive water. This reduction is probably due to restricted water movement resulting in saturation of the soil and ponding of water on the surface.

Since soil compaction does impose adverse agronomic effects on soil, researchers have explored methods of improving compacted soil. For example, it has been found that the use of both curved and angled subsoil shanks reduced the cone index for multiple soil types (Raper, 1999). The cone index is a measure of the soil’s resistance to mechanical penetration as described in the ASAE Standards (1998). In addition, water infiltration values were shown to increase with the use of subsoiling as a treatment, especially as the frequency of the treatment was increased to an annual level (Clark et al., 1993). Al-Adawi and Reeder (1996) found decreased cone index, decreased dry bulk density, and increased porosity in compacted plots tilled with a Paraplow. Their study also demonstrated agronomic benefits through increased yields in both corn and soybean crops.

Even though farmers do compromise their ability to maximize crop production when they compact the soil under less than ideal trafficking conditions, they are still able to alleviate the problem to some degree through proper subsoil tillage. The ability to manage compaction after it is created is as important of a concept as prevention because farmers continue to practice farming in ways that lead to deep soil compaction even
though they have been warned against it. Control of soil compaction is a continual requirement in modern agriculture (Bowen, 1981), and therefore promotes further understanding of the subject.

Beyond the agronomic considerations, soil compaction can significantly impact the environment. Peters (1982) showed that soil compaction reduces hydraulic conductivity of the soil. Low hydraulic conductivity tends to cause runoff during storm events. The runoff is a major source of soil erosion, which leads to pollution of streams, rivers and lakes.

On a more global scale, soil compaction impacts the environment through soil nitrogen content. O’Sullivan and Simota (1995) showed that denitrification tends to increase with compaction leading to larger emissions of N₂O, a greenhouse gas. Field crops growing in compacted soils cannot use nitrogen as efficiently as those in ideal soil conditions resulting in greater amounts of nitrogen being applied. The subsequent management compensation is over-application of nitrogen.

Another environmental impact of soil compaction is through increased fuel usage during tillage. Increased draft on tillage implements and extra tillage passes necessary to break up the compaction require higher fuel consumption. The consequential energy demands and effects created by soil compaction go well beyond the “common” implications noted by the casual observer. Thereby, proving the worth of finding a means by which to easily and accurately determine the extent of this detrimental soil condition.

If producers are able to know the degree and location of soil compaction, they may be able to more efficiently develop and use techniques to improve the soil’s
condition. These techniques could include different types or shapes of deep tillage shanks. For instance, Raper (1999) evaluated the effects of straight and curved tillage shanks at varying depths on soil disruption and draft requirements. A better compaction measuring technique would lend greater scientific credence to similar tests.

A large-scale soil compaction sensor could also facilitate the creation of soil compaction maps for use in precision agriculture. Clark (1999) considered developing a soil strength map using a cone penetrometer. He found that it is not practical or economical for farmers to create these maps utilizing a cone penetrometer due to the shear number of points that must be collected. He noted that a large amount of variation in cone index values exists on probe spacings as small as 7.5 cm all taken within the crop row.

Although the information seems to be very difficult to gather, a field scale map of soil compaction could be a valuable piece of information to farmers. Producers searching to explain variation in yield maps or for ways to increase the productivity of their fields could utilize compaction maps. Producers could also evaluate the expense of deep tillage to remove compaction or investing in other equipment that could allow them to minimize compaction if they knew the economic impact that the compaction had caused. One example would be to switch to a controlled traffic farming system to limit the area of the field that is covered by machine traffic, thus limiting the amount of soil affected. No matter what changes are implemented, there is a potential management advantage gained by farmers who know the patterns of soil compaction in their fields.
1.2 Concept introduction

The study of soil compaction has been a popular research topic for a significant portion of the last century. Research efforts have focused on the causes of compaction, the effects of compaction and methods to ameliorate compacted agricultural soils. The ability to accurately and reliably quantify soil compaction is critical to any study that attempts to evaluate the causes of compaction, and note the effects of compaction, or to gauge the results of compaction treatments. There are many different ways to quantify soil compaction including the measurement of the soil permeability, porosity, bulk density or soil strength.

The simplicity and principles of probe permeameters used in geological applications (Hurst and Goggin, 1995) have inspired the concept of this project. An adaptation of probe permeameters has been used in agricultural related applications as an indicator of functional pore space in soils (Fish and Koppi, 1993). The relation of functional pore space to soil compaction led to the formation of the project discussed within this work. The use of permeameter principles in a non-stationary application is the fundamental goal of this project. The pressure required to maintain a constant flow rate of air into the soil is measured to determine the relative soil pore space and the continuity of these pores.

The limitation associated with the permeameter used by Fish and Koppi (1993) is the need for stationary measurements. This type of measurement requires a large number of points to be taken and analyzed for variation and averages. With the large degree of variation expressed by Clark (1999), a continuously measuring system would better
identify the true conditions present in a field. The application of a continuously measuring, non-stationary system surrenders the ability to take measurements in a steady-state condition, but does offer a large amount of data.
CHAPTER 2

REVIEW OF LITERATURE

2.1 Compaction

Soil compaction is a decrease in soil volume and re-arrangement of soil particles caused by natural and mechanical means. A soil is considered to be compacted when either the total porosity (in particular, the air-filled porosity) is so low that it restricts aeration, or when the soil is so tight, and its pores so small, that it impedes root penetration, infiltration, and drainage (Hillel, 1998). The numerous detrimental effects of soil compaction in production agriculture, discussed earlier, include yield reductions, increased energy usage in tillage and harmful environmental impacts.

Soil compaction can occur naturally in different forms in an agricultural field. Hillel (1998) described four of these naturally occurring forms of compaction: surface crust, hardpan, fragipan, and claypan. Surface crust is generally formed by the action of raindrops impacting and dispersing soil particles, which then harden as they dry forming an impermeable layer at the soil-atmosphere interface. A hardpan is a naturally occurring
compact subsurface layer composed of densely packed sediments. In extreme cases, hardpans may exhibit rocklike properties that are nearly impenetrable to roots, water, and air, and are thus called fragipans. Fragipans generally form at the union of two distinct soil layers. Claypans are restrictive subsoil layers of high clay content relatively impermeable to air and water. They are formed as depositional layers or in situ as clay particles translocate, accumulating at a certain depth within the soil profile.

A great deal of soil compaction occurs in agricultural fields from mechanical forces applied to the soil. Mechanical compaction comes from livestock and machines. The trampling of livestock will compact the upper soil horizon. However, the most common cause of soil compaction is the effect of machinery (Hillel, 1998). A great deal of compaction results from the passing of heavy equipment over wet soil. Cultivation of wet clayey soils with heavy equipment can lead to smearing of the plow-layer bottom by wheels and plowshares, which creates a plow pan.

Measuring soil compaction has always been challenging. Erbach (1985) stated, “As evidenced by differences of opinion and uncertainties often expressed about compaction issues, such as the degree of compaction present...or the influence of soil compaction on crop production, it is clear that our techniques for measuring soil compaction are inadequate as are our methods of interpreting the results of compaction measurements.” The current practice of measuring compaction includes measuring one or more physical properties of the soil that are thought to be related to compaction. Freitag (1971) lists four general classes of procedures for measurement of soil compaction: volume and weight (soil bulk density), soil strength, fluid conductivity of the soil, and visual observation of the soil fabric.
There are two categories of soil compaction measurement techniques: in situ and laboratory methods. In situ measurements are taken in place, in the field, while laboratory methods require removal of samples from the field to perform the measurements in a laboratory. Each method has advantages and problems. In situ measurements have the advantage of an undisturbed sample, but they do not offer the controlled environment of a laboratory. Laboratory measurements have the disadvantage of needing a sample, which could disturb the inherent properties of the specimen during the sampling process. Laboratory methods do offer the ability to make very precise measurements of the samples collected.

2.2 Soil bulk density

Bulk density of a soil is the ratio of the mass of a sample to the volume it occupies. It gives an indication of the distance between soil particles. The bulk density of a soil will increase as it subjected to a given effort of compaction. The density level depends largely on the particle size distribution, water content and magnitude of loading (Marshall and Holmes, 1988). The water content of a soil has a significant impact on the magnitude of soil compaction (fig. 1). Less compaction occurs at moisture contents above and below a critical value. The soil could exhibit different properties at the same bulk density depending on the soil moisture content at which it was compacted. Freitag (1971) and Campbell (1994) thoroughly discuss the measurement of bulk density.

Bulk density can be expressed in two ways: dry bulk density or wet bulk density. To determine dry bulk density, a soil sample is oven dried before it is weighed. Wet bulk
Figure 1: The relationship between compacted bulk density and soil moisture content for a single compactive effort.

density also includes the effect of the water content of the soil sample. The conversion between dry and wet bulk density can be made by the equations:

\[ \rho_d = \rho_{dw}/(1+w) \]  
\[ \rho_{dw} = W/V \]

Equation 1  
Equation 2

Where:  
\( \rho_d \) = dry bulk density (g/cm³)  
\( \rho_{dw} \) = wet bulk density (g/cm³)  
W = weight of sample (g)  
w = soil water content (wgt. H₂O/wgt. dry soil)  
V = volume of sample (cm³)

The reader should note that dry bulk density is based on the wet volume of the sample.
Laboratory methods to determine bulk density can be performed in a very simple manner. A volume measurement can be obtained by collecting a core sample of known diameter and trimming the ends to a known length. The weight of the soil sample can then be obtained very easily (wet or dry) with an electronic scale or balance.

Field methods are typically more involved as samples are generally irregularly shaped, making volume measurements difficult. The clod method involves measuring the volume of a sample by placing it in a fluid and measuring the amount fluid displaced by the sample (Morgan, 1988). An indication of the bulk density can be obtained by placing the sample in a fluid of known density and observing if the clod floats or sinks. In each experiment, it is very important that the fluid not permeate the sample. Permeation can be prevented by using an immiscible fluid such as mercury or kerosene oil. These fluids can be hazardous, so a preferred method is to coat the sample with paraffin. However, the weight and volume of the paraffin must be taken into account to prevent errors.

Another field method for measuring bulk density involves excavating soil and then measuring the volume of the hole from which the sample was removed. Several techniques have been employed to measure the volume of the excavated hole. Morgan (1988) listed the standard method from Procedures for Testing Soils (1964) as the sand-cone method. In this method the hole is filled with sand that packs to a predetermined density from an apparatus similar to the one in figure 2. This method is susceptible to varying levels of moisture content in the sand, so the sand should be thoroughly dried before each use.
Figure 2: Sand-cone apparatus for volume measurement of excavated soil (Reprinted from Procedures for Testing Soil, 1964).
Nau (1987) employed a modified version of the sand cone method to determine the volume of soil in the coring tubes. His device (fig. 3) utilized a constant head reservoir of glass beads flowing through a burette on a vibrating stand to obtain a uniform and consistent packing density. It was noted that moisture content affected the beads just as it did sand; therefore, the beads were oven-dried before use.

Another technique to measure the volume of an excavated hole is to measure the amount of water needed to fill the hole (Campbell, 1994). A thin, flexible membrane, generally a rubber balloon, is placed in the hole to prevent the water from seeping into the soil. A small amount of air pressure (20 to 50 kPa) can be applied to the water to be sure that the balloon conforms to the irregular shape of the hole. It is important to accurately measure the fluid filling the balloon and to be sure that the balloon is not ruptured by too much pressure or anything in the hole such as stones or roots. Another option is to coat the hole with a plastic spray and then use oil to determine the volume. In either case, it is best to excavate the hole from a level original surface to be sure an accurate observation is being made.

Another technique to measure bulk density measurement utilizes nuclear energy (Freitag, 1971; Marshall and Holmes, 1988; and Campbell, 1994). There are two types of in situ radiation-based bulk density measurements: the backscatter technique and the attenuation technique. Both use gamma rays emitted from a radioactive source, usually cobalt 60 or cesium 137, and a Geiger-Mueller detector. The backscatter technique can be used on the surface of the soil or within the soil. It measures the number of photons that are reflected off of electrons in soil minerals. More photons are reflected from soils with a greater bulk density. Since photons lose energy when they collide with the
Figure 3: Sand column apparatus used to measure the volume of soil cores (Reprinted from Nau, 1987)
electrons, measuring the energy of each photon detected allows only those that have been reflected to be counted eliminating the error created by the photons that find a direct path to the detector.

The attenuation technique is inherently more accurate than the backscatter technique because it is a more direct measurement. Attenuation devices utilize a gamma source and detector placed in the soil. Only the photons that do not collide with electrons in soil minerals will pass through the soil to reach the detector. Soils with greater bulk density will permit fewer photons to pass. The accuracy is increased by counting only the photons that have the same energy level as the source, eliminating any that may have been deflected by soil electrons to the detector.

In either nuclear technique, it is important that the source and detector be calibrated. Lal (1977) found that the concentration and size of gravel present in the soil can substantially effect the density readings of these methods. It should also be noted that these are wet bulk density measurements and a moisture content reading must be taken to convert to dry bulk density.

Electromagnetic induction and ground-penetrating radar are geophysical methods that can be used to find depths to hardpans, fragipans, and claypans. Electromagnetic induction (EM) methods have been used to find the depth to claypans (Doolittle et al., 1994). EM techniques utilize electromagnetic energy to measure apparent conductivity of earthen materials. EM techniques work best in areas where subsurface properties are reasonably homogeneous, and the effects of either clay, moisture, or salt content dominate over the other effects.
Ground-penetrating radar (GPR) has been used to identify subsurface discontinuities (Conyers and Goodman, 1997). GPR involves the transmission of high-frequency electromagnetic radio (radar) pulses into the earth. The reflection of these pulses indicates discontinuities created by changes in electrical properties of the soil, variations in water content, or changes in bulk density at interfaces.

2.3 Soil strength

Soil strength measurement is a popular means for determining soil compaction due to the simplicity of some of the instruments. Guerin (1994) noted that soil strength increased with soil compaction. Freitag (1971), Guerin (1994), and Hillel (1998) discuss some of the traditional methods of measuring soil strength, which include shear tests, strain tests and penetration resistance.

Soil shear strength can be measured using a vane shear test or a direct shear test (Casagrande test). The vane shear test apparatus (fig. 4) measures the torque required to shear the soil at the circular interface created by the vanes inserted into the soil. The vane shear test gives strength measurements in situ; however, moisture content must be considered. Freitag (1971) noted that at higher moisture contents, the vane shear test reveals the cohesiveness of the soil. The effects of compaction are revealed only at lower moisture contents. Unfortunately, the test is much more difficult to perform in dry soil. Also, soil containing substantial gravel does not yield credible results.
Figure 4: Vane shear apparatus (Reprinted from Hillel, 1998).
The direct shear test utilizes a chunk of soil subjected to a perpendicular shear force (fig. 5). A problem with this test is that as the sample is being sheared, its dimensions tend to change resulting in a decrease of shear area, a higher density and thus, a deviation from the original properties of the sample.

Freitag (1971) discussed the use of strain tests to measure compaction. Markers are placed in the soil that will undergo a compactive effort. Examination of the marker positions after compaction will indicate the direction and magnitude of soil movement during compaction. The obvious problem with this approach is the degree to which the soil is disturbed while placing the markers. The natural soil structure that existed is destroyed and is not comparable to the soil that remains around the test area.

The cone penetrometer is a popular device for measuring soil strength. Penetrometers actually measure penetration resistance of soil and are influenced by a
number of factors including soil type, soil strength, moisture content, penetration rate, cone size, surface roughness of the cone, soil-metal friction and soil cohesion (Al-Adawi and Reeder, 1996). To minimize the effects of those influences on measurements, a standard procedure for the use of a cone penetrometer has been established (ASAE standard S313.2, 1998). Specific cone sizes, shaft sizes, cone surface finishes and a constant penetration rate are specified in the standard.

The simplicity of a penetrometer prompted Clark (1999) to try to create soil strength maps on a large scale. As noted earlier, Clark (1999) found that penetrometer readings were not consistent even within close proximity indicating that an overwhelming number of data points would be necessary to create the desired map. Tollner (1985) stated, “It is difficult to interpret penetrometer readings from one soil condition to another soil condition.” It would be a tremendous challenge to create a map of any soil properties using a cone penetrometer considering the variability that exists within agricultural fields.

The principal of the penetrometer has been used in other devices created to indicate soil strength. One of the first was an instrumented tine for deep tillage research (Owen et al., 1987). Alihamsyah et al. (1990) developed a horizontal penetrometer. They found that the resistance on a penetrometer mounted horizontally on a shank correlated well with a traditional Delmi recording penetrometer. Good correlations were observed at both the standard penetration rate of 30 mm/sec and an accelerated rate of 90 mm/sec.

Lui et al. (1996) developed a sensor to map the variability of soil texture/compaction on a field scale. Utilizing three load cells and a soil moisture sensor mounted
on a time, they found that they could create a soil texture/compaction index map by operating the sensor at a constant speed and depth and correcting for moisture content.

2.4 Soil porosity and permeability

The porosity of a material is the ratio of void-space volume to the total volume of a sample. Alakukku (1996) demonstrated that porosity can be used as a measure of soil compaction. He also found that porosity is reduced by the effect of high axle loads, and that pore size distribution changes under the same conditions. Macroporosity (pore sizes >30 μm) was reduced while the microporosity was increased under compactive loading of the soil.

Morgan (1988) reviewed different ways of measuring the porosity of a soil including Boyle’s Law single cell and double cell methods, the Washburn-Bunting method and methods utilizing a pycnometer. Most methods need to be conducted in a laboratory and require either a substantial amount of time or special equipment for the measurements. Boyle’s Law methods involve equalizing pressures of known volumes of a gas, usually helium, with the sample to determine the void volume. In the Washburn-Bunting method, the gas within the pores of the sample is removed through suction and measured. The pycnometer indirectly measures the volume of the solids in the sample, which can be subtracted from the total volume to determine pore volume.

The measurement of soil moisture tension is another quantity indicative of pore size distribution (Marshall and Holmes, 1988). Freitag (1971) listed the tension table as the most popular measure of moisture tensions in the laboratory, while tensiometers can
be used in the field. Moisture tension indicates pore size distribution due to the capillary action of small pores. A large tension required to remove water from a sample indicates that small pores are present while the amount of water removed at different tensions indicates the relative distribution of sizes. Marshall (1958) developed a relation between pore size distribution and permeability in isotropic materials creating another method of measuring soil compaction.

Freitag (1971) stated that a meaningful description of soil compaction can be attained from the ability of a fluid to pass through a soil. This conductivity of a fluid is called permeability and is related to the interconnected pore space of a soil. Permeability characterizes the soil’s ability to conduct mass flow of a fluid in response to pressure gradients (Stepniewski, 1994). The fluid used can be either a gas, such as air, or a liquid such as water. In some conditions, the fluid may interact with the soil and distort the measurements, as is the case with a clayey soil that has a high porosity, but a low water conductivity. The use of air as the permeant should minimize the fluid-soil interactions and yield more consistent relative permeability.

Regardless of the fluid used, the theory governing the flow of fluids through porous material is Darcy’s Law. Muskat (1937) and Scheidegger (1957) thoroughly examined fluid flow through porous media using Darcy’s Law. Morgan (1988) thoroughly reviewed the application of Darcy’s Law to fluid permeability measurements of soil and concluded with the equation:
\[ k = \frac{2\mu Q L P_{\text{Exit}}}{A(P_{\text{In}}^2 - P_{\text{Exit}}^2)} \]  

Equation 3

Where:
- \( k \) = intrinsic permeability \((L^2)\)
- \( \mu \) = viscosity of the fluid \((M/LT)\)
- \( Q \) = volumetric flow rate \((L^3/T)\)
- \( L \) = length of tube \((L)\)
- \( A \) = cross section area of tube \((L^2)\)
- \( P \) = entrance and exit pressures \((F/L^2)\)

Hillel (1988) noted that laminar flow conditions must exist for Darcy’s Law to remain valid. The flow is also assumed to be incompressible. These conditions limit the flow rate and pressures that may be used when applying Darcy’s Law to permeability measurements. However, Rodeck et al. (1994) experimented with air permeability measurements at low and high pressures. Satisfactory results were found with pressures as high as 790 cm of water.

Burris (1985) stated that compaction may be reflected by the changes in hydraulic conductivities measured in the soil profile. Freitag (1971) listed a few techniques to measure the hydraulic conductivity of soils. The simplest in situ method, known as the shallow well method, utilizes a shallow hole filled with water. The rate of flow from the hole is used as the measure of conductivity. A second field measure relies on the use of a double-tube or double-ring apparatus. Double-ring apparati are more accurate because the boundary area of the sample is saturated under controlled conditions by the outer tube/ring allowing the inner tube/ring to measure the saturated hydraulic conductivity.
Laboratory methods are also used for measuring hydraulic conductivity. Peters (1982) developed one of these methods using a falling head permeameter. He found that soils of low strength experience particle migration during the tests. This resulted in pores being clogged by the small migrating particles and distortion of the readings. The laboratory methods offer the advantage of determining the conductivity of different directions through the profile. However, these methods are very time consuming and require a great deal of care in setting up the tests.

Air permeability measurements are also useful measurements related to soil compaction in unsaturated conditions (Nau, 1987). Kirkham (1946) developed an air permeameter that could be used in the field or the laboratory (fig. 6). The device consisted of an air tank with attached manometer, a tire pump and sample holding tube. It was operated by pressurizing the tank, then measuring the rate of decay of the pressure as indicated by the manometer as the air passed through the soil sample. Freitag (1971) mentioned a constant head permeameter using a float to force air into the soil (fig. 7). Freitag (1971) also noted that the major problem with air permeameters is creating a good seal with the soil to avoid the leakage of air. This problem has been addressed by using a paraffin seal poured onto the surface. Another potential problem exists due to moisture present in the soil during air permeability measurements. The higher the moisture content, the lower the permeability readings will be due to the pore space occupied by
Figure 6: Apparatus for measuring air permeability of laboratory samples (a) and undisturbed field samples (b) (Reprinted from Kirkham, 1946).
Figure 7: Float type air permeameter for in situ measurement (Reprinted from Morgan, 1988).

water. Freitag (1971) states that this cannot be corrected analytically, therefore care should be taken in noting the moisture contents associated with measurements of this type. The relative permeability of both water and air are affected by soil moisture content (fig. 8). The relative permeability of water increases with increasing moisture content (Bear, 1979). The relative permeability of air decreases as moisture content increases because the air space is discontinuous due to the water present as previously mentioned. Edwards and Jones (1994) used air permeability measurements to determine site suitability for soil vapor extraction. This process is used in remediation of sites
Figure 8: Relationship between relative permeability, $k_r$, and soil moisture content. Curve $k_{rw}$ is relative hydraulic conductivity, curve $k_m$ is relative air permeability, and the X-axis is water saturation in percent. The air permeability curve shows hysteresis between increasing and decreasing saturation.

contaminated by volatile organic compounds. The major difference in their application is that air is moved through the soil by a vacuum rather than by positive pressure gradient as in most applications of air permeability. Saxton et al. (1993) used an air permeameter to define frozen soil infiltration. They used a device similar to Kirkham's (1946) except that the sample area driven into the soil was larger ($0.25 \text{ m}^2$) to obtain a more representative sample. Fish and Koppi (1993) used an air permeameter with a digital manometer and CO$_2$ as the gas to measure functional pore space. A unique combination of air and hydraulic permeability was used by Whelan et al. (1995) to measure soil
structural stability. The device is similar to the one developed by Kirkham (1946), except both air permeability and hydraulic conductivity measurements were made through the same apparatus. Whelan et al. (1995) used the resulting ratio of air permeability to water conductivity as an indication of structural stability.

2.5 Visual techniques

Roberts (1985) and Freitag (1971) discussed visual techniques for determining soil compaction. Hvorslev (1960) found clay particles to be oriented normal to the direction of the force causing the deformation and that this condition can be observed by slicing and slowly drying compacted soil samples. Samples should also shrink more along the axis of the particle orientation than another when they are dried after being compacted. An uncompacted sample should shrink uniformly. In some cases, an experienced observer can dig a trench and note compacted layers such as hard pans. Freitag (1971) mentioned a technique that utilizes polarized light shined on thin slices of soil. This technique measures the degree of irregularity in the light patterns and the intensity of polarization. None of these methods are practical for large-scale use due to the work involved in obtaining the measurements and the subjectivity of the measurements.
CHAPTER 3

OBJECTIVES

The primary goal of this project was to develop and prove the concept of a sensor that can measure and map soil compaction continuously utilizing a unique technique of air permeability measurement. The sensor should function on a field scale for practicality of on-farm usage. The sensor should also provide quick and easy mounting to typical agricultural tractors.

In operation the sensor measured the flow-rate and pressure of air exiting orifices in a shank designed for acquiring continuous air permeability measurements while moving through a typical Midwestern soil. A suitable data acquisition interface was developed to record the air flow-rate, pressure, and global positioning system coordinate data. The following specific tasks were completed during this study:

1. Evaluate the performance of the sensor relative to a cone penetrometer.
2. Evaluate the performance of the sensor in tilled and untilled field conditions.
3. Evaluate the performance of the sensor in different tillage treatments.
4. Evaluate the performance of the sensor in areas suspected of being highly compacted.
CHAPTER 4

EQUIPMENT AND PROCEDURES

4.1 Development

The basic concept of the sensor (fig. 9a) was to measure the pressure created by a constant flow rate of air into the soil. Air entered the soil through two small orifices in a small vertical plate mounted on the bottom of a subsoiler shank. A laptop computer in the cab of the tractor collected the data from the sensor and the GPS receiver (fig. 9b). The key to the sensor was the development of the shank as discussed in section 4.1.3.
Figure 9: The sensor in operation during preliminary testing (a) and the components and signal flow diagram for the sensor (b).
4.1.1 Instrumentation

The sensor development process was a "ground-up" design with little previous work to build upon. It was an iterative procedure with many obstacles and unknowns influencing the direction and scope of the design. The component specification and design tasks included choosing a mass-flow control valve and a pressure transducer, creating a data collection routine in LabView, a graphical programming software package, and designing an appropriate tine or shank to function as the sensor-to-soil interface.

The first task was to specify and procure a suitable mass-flow control valve. The main challenge was determining the appropriate mass-flow rate for this application. Using some conceptual initial design values, Darcy's Law (Equation 3), and the following equation from Parker (1979):

\[ \text{cfm} = 22 \times c \times d^2 \times \sqrt{P} \]  \hspace{1cm} \text{Equation 4}

Where:
- \( \text{cfm} \) = cubic feet per minute
- \( c \) = orifice coefficient
- \( d \) = orifice diameter (in.)
- \( P \) = pressure (in. of water)

it was determined that a 200 standard liter per minute (SLPM) flow rate was adequate for this application. A standard liter per minute is a flow rate of 1 liter of air at standard temperature, 25°C, and pressure, 0.101 MPa flowing across a boundary in 1 minute. The valve chosen was a 0 to 200 SLPM range Sierra 860 Series Auto-Trak™ with a high-flow body and 9.5 mm (3/8 in.) tubing.
An Omega PX203-100G5V pressure transducer was chosen based on the expected pressure range of 0 to 690 kPa (0 to 100 psig). Other components of the system include a gas-powered generator, a dc power supply, a hydraulically driven air compressor and a global positioning system (GPS) receiver with 1 m (rms) accuracy.

A pentium-based laptop computer equipped with a Computer Boards PCM-DAS16D/12AO data acquisition card (DAQ) was used to control and collect data from the sensor. A significant portion of the sensor development involved creating the LabView (version 5.0.1) program to collect data and control the sensor. The program, or virtual instrument (VI), utilizes two analog input channels and a single analog output channel on the DAQ card as well as the computer's serial port to interface with the transducer and GPS receiver.

4.1.2 Software

The LabView VI created for this project has two windows: a front panel window and a diagram window. The front panel and diagram windows of the VI can be seen in the appendix. The front panel is the user interface with the sensor, very similar to the control panel on a physical instrument. The diagram is the wiring schematic similar to the wiring in a physical control box. The VI is comprised of three basic loops (fig. 10). The data collection loop collected analog voltage readings from the transducer through two channels of the DAQ. Channel one was the flow output of the mass-flow control valve. Channel two was the pressure reading from the pressure transducer. Data collected from these channels were filtered to remove noise and then written to a data
Figure 10: The signal flow diagram used for the LabView VI.

The position collection loop received a GGA data string from the GPS receiver through the serial port of the laptop. The GGA string was disseminated, and the latitude, longitude, and GPS time were written into the data file sequentially with the flow and pressure values.

The control loop used a flow rate set point value established by the user on the front panel to control the airflow rate through the mass flow controller. During initial testing, the airflow rate fluctuated dramatically with changes at the shank-soil interface. The mass flow controller contained an internal feedback that was designed to maintain a constant flow rate established by an external set point. The flow fluctuation that was observed indicated that the internal feedback loop in the mass flow controller was not able to adequately maintain a constant flow rate in this application. The control loop in
the VI utilized a PID controller to supplement the control of the mass flow controller. The PID control insured a more constant flow rate through the valve.

The data collection VI was designed for a forward sensor speed of 1.6 kilometers per hour (1.0 mph). At this speed, the data written to the file represents one sample every 1.2 cm (0.47 inch). The position coordinates are only available from the receiver once each second, which gives one position coordinate for approximately 37 flow and pressure readings. The position coordinates were interpolated in a spreadsheet, assuming a constant speed, to give accurate coordinates for each pressure and flow reading.

4.1.3 Shank design

The design of the shank was an iterative process leading to a very robust and functional shank. The first design consisted of a vertically straight shank made of a common steel bar stock (fig. 11). This design had a number of fundamental problems. The straight design caused a great deal of soil disruption; it did not allow soil to easily flow around the shank resulting in a “lump” of soil being pushed in front of the shank, which disrupted the existing soil structure well ahead of the sensor. The straight design also allowed air to “leak” up and back along the shank to the surface. Essentially, it did not give a good sensor-to-soil seal and resulted in excessive low-pressure readings. The straight design was not structurally durable enough to withstand rugged field conditions for a long period of time.

The final design performed much better than the vertical shank. A commercial sub-soiling shank greatly enhanced the structural durability of the sensor. The sub-
soiling shank could also carry a custom point specifically designed as the main sensor interface with the soil (fig. 12). The custom point was designed to create a better seal with the soil, preventing air leakage and excessive disruption of the soil structure at the point of measurement by the sensor.

The sensor design prevents leakage of air through the use of a thin, vertical plate for the sensor-to-soil interface with a horizontal plate above to seal the sensor vertically. To further seal the interface, the orifice was placed toward the forward edge of the thin plate, which helps prevent air from moving backward and into the void space left behind the path of the sensor.

The shape of the point was designed to minimize soil disruption at the measurement point. The thickness of the vertical plate (1.27 cm, 0.5 in.) was chosen to help the sensor slice through the soil with minimal disruption while maintaining structural durability. The durability of the sensor was an important consideration due to the large number of rocks present in the test area. The sloped point was added to help facilitate flow of displaced soil up over the sensing part of the shank. The soil should slide up along the point, rather than around the edge of the point, which would disturb the existing soil structure. Although, the purpose of a sub-soiling shank is to disturb the soil structure, the sensing point was approximately 3 cm (1.2 in.) below the shank and near the forward edge where little, if any, disturbance is caused.
Figure 11: The initial straight-shank design.

Figure 12: Final shank-tip design with thin plate mounted on the bottom.
4.2 Experimental outline

The goal of this project was to develop a sensor that would measure soil compaction quickly and easily across a field, so an appropriate ground truthing method was chosen as a means to evaluate the performance of the sensor. The author determined that a recording cone penetrometer with GPS interface was the most convenient commercially available device to measure soil compaction quickly. The Investigator™ (Spectrum Technologies) penetrometer with Star Logger GPS interface recorded compaction values in 5 cm (2 in.) increments to a depth of 45 cm (18 in.) along with geo-referenced coordinates.

The test plan for the apparatus included making geo-referenced penetrometer measurements followed by operation of the sensor through the same area. A few soil samples were then taken at the operating depth of the sensor to determine soil moisture content of the soil. The moisture content was determined by weighing and oven drying the samples.

In practice, the penetrometer measurements were taken every 5 to 10 m (16 to 32 ft) with two to three measurements taken at each location. These locations were marked with a flag for identification of the intended path for sensor measurements. The sensor was started and allowed to warm up as required by the mass flow control valve. The sensor was set to a flow rate of 165 SLPM (5.8 cfm) and pulled through the soil at a depth of 30 cm (12 in.) and a forward speed of 1.6 KPH (1.0 MPH). A soil-sampling tool was then used to collect soil samples at the operating depth in the bottom of the narrow trench left by the sensor.
The tests were performed in a variety of field conditions. Surface conditions included wheat stubble, soybean stubble, and corn stalks. The field conditions were dryer than normal throughout the growing season and harvest of the crops; however, there was an adequate amount of rain after harvest, which helped to soften the soil. This was important to allow easier penetration of the sensor into the soil and to prevent large chunks of soil from coming to the surface during testing. The softer soil also made penetrometer use feasible.

The sensitivity of the transducer to different field conditions was evaluated using four specific areas of focus. The first focus evaluated the sensor’s performance differences in tilled and untilled areas of fields. The second focus evaluated the sensor’s performance in different crop covers including wheat stubble, soybean stubble, and corn stalks. The third focus evaluated the sensor’s performance in different tillage treatments. The fourth focus evaluated the sensor’s performance in areas expected to have highly compacted soil. In some tests, a second pass of the sensor was made approximately 3 m (10 ft) from the center of the first pass. The purpose of the second pass was to compare the measurements of two separate transverses through the same area, which should show similar results. A summarization of the tests is provided for ease of reference (Table 1).
<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test A</td>
<td>A single pass from a deep-tilled portion of a corn field to a headland evaluating tilled versus untilled areas</td>
</tr>
<tr>
<td>Test B</td>
<td>A single pass through a swale evaluating a suspected highly compacted area in a wheat field</td>
</tr>
<tr>
<td>Test C</td>
<td>A single pass moving up a hill evaluating wheat as a crop cover</td>
</tr>
<tr>
<td>Test D</td>
<td>Dual passes through different tillage treatments in a soybean field</td>
</tr>
<tr>
<td>Test E</td>
<td>Dual passes from a headland to the center area of a corn field evaluating a suspected highly compacted area</td>
</tr>
<tr>
<td>Test F</td>
<td>Dual passes perpendicular to the direction of tillage in a corn field evaluating different tillage treatments</td>
</tr>
<tr>
<td>Test G</td>
<td>A single pass from the center area of a corn field to a headland evaluating a suspected highly compacted area and different soil type</td>
</tr>
</tbody>
</table>

Table 1: Description of each test performed using the sensor.
CHAPTER 5

RESULTS AND DISCUSSION

Testing of the final design was performed at the Molly Caren Agricultural Center, London, Ohio, during November, 1999. The tests were conducted in soil primarily consisting of Crosby-Lewisburg silt loam and Kokomo silty clay loam.

The measurements made by the sensor indicate its potential to give a continuous indication of soil properties on a field scale. The first notable characteristic of the data is the fact that the sensor does generate trends that one would expect to see. The sensor indicates higher pressures in areas traditionally suspected of having a greater degree of compaction.

A corn field primarily consisting of Crosy-Lewisburg silt loam soil (20% m.c.) that was deep-tilled inside the headlands was tested first. The goal of this test, designated as Test A, was to examine the difference between a presumably compacted headland and soil that was loosened (tilled) using a subsoiler. The shank was operated through a path at an angle of approximately 45° across the end rows moving into the tilled area. The test showed that the headland soil was less permeable to air than the tilled soil (figure 13).
Figure 13: Test A, average air pressure and cone index versus distance, tilled corn < 22 m, corn field headland > 22 m.
In order to filter noisy sensor data, all graphs represent a 51 point running average of the sensor data, i.e., the average of 25 points on each side of point shown. This resulting average represents data collected over a 0.6 m (2 ft) length. The average air pressure of the headland area was 178 kPa (25.8 psi), while the tilled average was 83 kPa (12.0 psi). The results of the cone penetrometer were not consistent with the sensor. The penetrometer gave relatively erratic readings due in part to rocks present in the soil, which follows the work of Clark (1999), as discussed earlier. In the tilled soil, penetrometer measurements were taken in the path of subsoil shanks and between the paths where the surface soil was relatively undisturbed by the tillage. The measurement locations complicate the interpretation due to low and high readings in close proximity to each other. The overall trend of the penetrometer measurements was good with a higher average value of 3.36 MPa (490 psi) in the headland area compared to the 2.79 MPa (405 psi) average in the tilled soil.

The sensor was next tested in wheat stubble (Test B). The soil in this field was also primarily Crosby-Lewisburg. A swale, a path of preferential flow for surface water, was identified in the river bottom portion of the field. A test was performed perpendicular to the direction of the swale. The assumption made was that the area within the swale would be more compacted because it generally has a higher moisture content leaving it more susceptible to compaction by field traffic.

The sensor indicated three distinct compaction levels along the length of the test (fig. 14). The left and right sections are on each side of the swale and the center section is in the swale. The sensor showed higher pressures going through the swale indicating a
Figure 14: Test B, average air pressure and cone index versus distance through a swale in wheat stubble.
more compacted soil. However, the penetrometer did not show the same trend. The penetrometer indicated a fairly uniform cone index across the length of the test. The different sections in the data were not a result of moisture content, since soil moisture content decreased with increasing distance during the test from 26% to 33%.

Test C was performed going up a 5% slope in the same wheat field as Test B where there was no predicted soil compaction (fig. 15). The data presented from this test included linear best-fit lines on the graph. Linear regression of cone penetrometer data showed an increase in cone index going up the slope. Similarly, the sensor indicated an increase in air pressure going up the slope. The best-fit lines had similar slopes suggesting that the sensor and penetrometer measured changes in the same soil characteristics.

These three tests showed that the sensor can indicate trends in soil properties, which is the first step in achieving the objectives of the project. Tests A and C indicated that a penetrometer was a feasible way to quickly check the performance of the sensor under some conditions. It is likely that the swale had a different soil type (Kokomo silty clay loam) than the adjacent areas due to the water flow patterns. A change in soil type often corresponds to a different soil structure and characteristics resulting in a shift of values measured by the sensor. The sensor did accomplish the original goals by indicating the soil structure, which is generally the most significant property of compacted soil.

Test D was conducted in a tillage plot designed to compare the effect of different tillage treatments. Two passes were made side-by-side in opposite directions approximately 3 meters apart. The plot was soybean stubble with side-by-side treatments
Figure 15: Test C, average air pressure and cone index versus distance in wheat stubble.
of no tillage, strip tillage, and sub-soil tillage. Three different parameters of each treatment area were compared in evaluating sensor performance.

The first parameter observed from sensor output was void space percentage. Void space percentage was determined by counting the number of measurements made by the sensor that were less than a threshold value of 58.6 kPa (8.5 psi) and dividing that value by the total number of measurements made in that treatment area. The threshold value is just above the resistance pressure observed when the shank is out of the soil and air is flowing at the set point of 165 SLPM. Utilizing the results of both passes in Test D, the average void space percentage of the no tillage, strip tillage, and the sub-soiled treatments were 3.35, 13.38, and 36.3% respectively (fig. 16).

The second parameter observed from the sensor output was the average pressure measurement of the sensor (fig. 17). The no tillage treatment had the highest average pressure (82.0 kPa; 11.9 psi); the strip tillage treatment was slightly lower (81.6 kPa; 11.8 psi); and the sub-soiled treatment had the lowest average pressure (70.2 kPa; 10.2 psi). These results follow the trend set by the void space percentage parameter, but the no tillage and strip tillage treatments were much closer in average pressure than in void space percentage.

The third parameter examined in Test D was the average cone index for each treatment area. The no tillage area had the highest average cone index (2.69 MPa; 390 psi); the strip tillage area was somewhat lower (2.46 MPa; 357 psi); and the sub-soiled treatment had the lowest average cone index (2.08 MPa; 302 psi). These cone index values follow the trend set by the void space percentage and the average pressure measurements.
Figure 16: Test D, air pressure raw data and void space threshold pressure for different tillage treatments in soybean stubble.
Figure 17: Test D, average air pressure and cone index versus distance for different tillage treatments in soybean stubble.
The sub-soiled treatment was very clearly indicated by the sensor and the cone penetrometer. A large percentage of void space, a lower average pressure and a lower average cone index would be expected from an area that had been tilled by a sub-soiler. The no tillage treatment values were consistent with expectations for an area that had not been tilled since planting. The small percentage of void spaces indicated a relatively consistent soil structure. The high average pressure reading was a result of few void spaces. The high cone index was also expected because the soil was likely compacted during the previous year’s farming practices and no tillage was performed to reduce any compaction that occurred.

The results of the strip tillage treatment are more difficult to understand. The strip tillage was not performed more than 0.1 m (4 in.) deep. The sensor measured the soil at a 0.3 m (12 in.) depth. The increase in void spaces over the no tillage area could have been a result of small vertical fissures generated by the strip tillage implement or the result of the loosened overlaying soil created by the strip tillage operation. Small fissures would allow an open space for the air from the sensor to flow through indicating a void space. The loosened soil theory is a more complex because it requires assumptions as to what is happening below the soil surface. Assuming the loosened soil did not exhibit the same uniform downward pressure as an undisturbed soil, the action of pulling the sensor through the soil could tend to lift “chunks” of soil creating void spaces. The “chunks” of soil would not have been seen because the loosened soil above would have essentially hidden them from view at the surface. The higher number of void spaces in the strip tillage and the closeness of the no tillage average pressure value indicated larger magnitude pressures for the strip tillage treatment compared to the no tillage treatment.
This would tend to suggest more compacted soil in the strip tillage area. It is reasonable to expect more compaction at the 0.3 m depth in the strip tillage area because it had an additional pass of field traffic with no soil disruption near this depth. However, the cone index did not indicate a more compacted soil. One explanation for this could be the small vertical fissure theory discussed above, assuming that the penetrometer measurements were taken in or near these fissures. Otherwise, the strip tillage treatment should have exhibited a cone index at least as high as the no tillage treatment.

Tests E, F, and G were conducted in a harvested corn field. Test F was performed in a subsoiled area, while tests E and G were performed through the end of the field nearly perpendicular to the direction of the end rows. Tests E and F were conducted in Crosby-Lewisburg soil, while Test G was performed in Westland silty clay loam, a darker, “heavier” soil. As with Test D, Test E and Test F consisted of two passes performed next to each other in opposite directions. Test D resulted in good repeatability of measurements through each pass. The same trends were apparent in each pass. Both passes also mirrored each other fairly well across the entire distance of the test. Tests E and F (fig. 18 and 19) also exhibited similar patterns in each pass, but both passes did not mirror each other as observed in Test D.

Examination of the three parameters discussed in Test D revealed some insight into the performance characteristics of the sensor. The only tests resulting in significant
Figure 18: Test E, average air pressure and cone index versus distance in corn field, headland area > 30 m.
Figure 18: Test F, average air pressure and cone index versus distance in a tilled corn field.
void space percentages were those of tilled soil, with an average of approximately 20% void space across all tilled plots. This indicated that the void space percentage is a valid evaluation criteria only in tilled soils and should not be considered in untilled plots. The relationship between corn and soybean sub-soiled plots showed much greater void space percentage in the soybean field by a 30.1% to 18.4% margin.

Table 2 summarizes average pressure values for easy comparison. It is clear that corn gives a higher average pressure reading under both tilled and untilled conditions. The only test performed under significantly different moisture conditions was Test B, which is not included in the table. All tests other than the Test B (30% m.c.) were performed at approximately 20% soil moisture content. The best indication of the pressure differences was the cone index values. For the same tests in the table, the average cone index for tests in corn fields was 3.12 MPa (453 psi) compared to an average cone index for the other crops of 2.41 MPa (350 psi) giving a difference of 0.71 MPa (103 psi). This significant difference suggested that the corn fields are more compact because both the cone penetrometer and the sensor indicate a more compacted soil.

The sensor seems to be sensitive to either soil type or moisture content as exhibited in the differences between tests E and G. The only known difference between Tests E and Test G is the soil type. Test G is a “bottom-land” type soil, darker in color and higher in clay content. The difference in pressures, 121.4 kPa (17.6 psi) in Test E to 153.8 kPa (22.3 psi) in Test G (fig. 20) was significant. The difference was probably caused by the moisture content for which data was not collected in Test G. This became more evident
Figure 20: Test G, average air pressure and cone index versus distance in a corn field, headland area > 20 m.
when considering the cone index values. Test G averaged 2.57 MPa (373 psi) compared to 3.42 MPa (496 psi) for Test E. It is likely that a higher moisture content led to reduced cone penetrometer measurements and increased pressures in the sensor. Tests B and C support this hypothesis. Test B averaged 1.83 MPa (265 psi) in cone index and 30% in moisture content. Test C averaged 2.38 MPa (345 psi) in cone index and 20% in soil moisture content. Typically wetter soils will have a lower cone index, and theoretically, they will have a higher pressure value with this sensor. Cone index is lowered in wetter soils because the shear strength is lower. The water in the soil will “lubricate” the particles allowing them to slide over each other with less friction in the presence of water. The water in the soil occupies void spaces where the air would flow. The presence of water requires a higher pressure to allow air to move through the void spaces by pushing the water out, or the water acts as a solid soil particle not allowing air to move at all.
<table>
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<th>Test</th>
<th>Plot type</th>
<th>Average Pressure (kPa)</th>
<th>Plot Type Average Pressure (kPa)</th>
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<tbody>
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<td>Test C</td>
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<td>95.1</td>
<td>95.1</td>
</tr>
<tr>
<td>Test D</td>
<td>Untilled Soybean</td>
<td>82.1</td>
<td>82.1</td>
</tr>
<tr>
<td>Test D</td>
<td>Strip Tilled Soybean</td>
<td>81.6</td>
<td>81.6</td>
</tr>
<tr>
<td>Test D</td>
<td>Sub-soiled Soybean</td>
<td>70.5</td>
<td>70.5</td>
</tr>
<tr>
<td>Test A</td>
<td>Untilled Corn</td>
<td>194.4</td>
<td></td>
</tr>
<tr>
<td>Test E</td>
<td>Untilled Corn</td>
<td>121.4</td>
<td>147.7</td>
</tr>
<tr>
<td>Test G</td>
<td>Untilled Corn</td>
<td>153.8</td>
<td></td>
</tr>
<tr>
<td>Test A</td>
<td>Tilled Corn</td>
<td>95.1</td>
<td>91.5</td>
</tr>
<tr>
<td>Test F</td>
<td>Tilled Corn</td>
<td>89.7</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Table of average pressure values.
CHAPTER 6

CONCLUSIONS

The primary objective of this project was to develop and prove the concept of a sensor that could measure soil compaction continuously utilizing a unique technique of air permeability measurement. A sensor was developed to indicate soil compaction using air permeability measurements. Commercially available devices capable of measuring the flow-rate and pressure of air moving through an orifice were found for use on the sensor. A robust shank capable of making continuous air permeability measurements was developed by utilizing a sub-soiling shank fitted with a custom designed point. A LabView based data acquisition interface was developed to record air flow-rate, air pressure, GPS coordinates, and to control the air flow-rate. The results of this study yielded the following conclusions:

1. A cone penetrometer was not a good method to evaluate the sensor’s performance due to the different soil properties measured (soil strength versus air permeability).
2. The sensor indicated changes in soil properties including soil structure/compaction, soil moisture content, and soil type.
3. The sensor indicated higher average air pressure values and void space percentages in untilled soils. Higher void space percentages were indicated in tilled soybean than tilled corn fields. Few void spaces were indicated in untilled soils.

4. The sensor indicated higher average pressures in areas suspected of having highly compacted soils.
CHAPTER 7

RECOMMENDATIONS FOR FURTHER STUDY

The development of the sensor in this project was improved through iteration of the design process. Further progress toward a more robust design can be made by considering the following recommendations.

1. Sensor performance should be evaluated under controlled conditions such as in a soil bin to evaluate the response to a homogeneous soil.

2. Sensor outputs should be compared to laboratory and in situ air permeability measurements.

3. The thickness of the sensing plate should be reduced to 9.525 mm (3/8 in.) to minimize soil disturbance in the vicinity of the sensing point.

4. A range of flow rates should be evaluated to determine if soil structure is affected by high flows.

5. A soil moisture content sensor should be incorporated with the sensor so that permeability measurements can be appropriately adjusted.
REFERENCES


APPENDIX
Control Panel

Master Switch: OFF ➡ ON

Data Collection
Flow: 0.0
Pressure: 0.0

Setpoint Control
Output Date Value: 0.165

Input Range: 0 - 5 V
Output Range: ±5 V

Note: The Master Switch must be ON before running the VI or the entire VI must be stopped and restarted to function properly.

Figure 21: The front panel window from the main LabView program, Sensor VI, developed to record data and control the sensor's operation.
Figure 22: The first sequence frame of the diagram window from the Sensor VI LabView program developed for the sensor.
Figure 23: The second sequence frame from the LabView Sensor VI diagram. This frame closes the program file and sets the sensor output to zero SLPM.

Figure 24: The front panel window from the GPS VI used in the LabView program.
Figure 25: View of sequence frames zero and one from the GPS VI diagram used in the Sensor VI LabView program.