Tillage Effects on Soil-Water-Air Matrix and Prediction of Soil Bulk Density From Cone Index Data

by

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(ABSTRACT)

Conventional farming systems create socio-economic problems through increased production costs and loss of the soil and chemicals that are washed from the farmlands. Even though no-till farming systems can increase farm profit and reduce environmental degradation, soil compaction can negate the advantages of no-till farming when no-till systems are used continuously under certain soil and climatic conditions.

One objective of this study was to evaluate the long-term effects of the no-till method on bulk density, capillary porosity, noncapillary porosity, void ratio, and cone index of the soil. Although tillage affected cone index significantly, moisture variations caused difficulty in interpreting the results. No statistically significant differences in other parameters were found among no-till, conventional till, and control fallow treatments within each of three cropping seasons. However, within each tillage treatment these parameters showed significant variations between test seasons.

When the soil bulk density data is required at close depth intervals, the core sample method becomes laborious while its use is limited by soil type and moisture conditions. The neutron probe densitometer is difficult to use in tillage studies due to practical problems. Among the predictive models for bulk density, some require parameters determined through expensive laboratory procedures while others have not been proven to work in field conditions. Therefore, the second objective was to develop a model to predict soil bulk density using cone index and moisture content data for a Virginia soil.

Two separate models have been developed for top and subsoil layers using remolded natural soil samples. The topsoil model predicted bulk density close to the actual data taken in recently disturbed soils. One cropping season after plowing, predicted values were about 10% higher than the actual, a result which could be due to the ageing effect. The subsoil model, on the other hand, under-predicted soil bulk density by about 15%.

After the model coefficients for a particular soil are determined through laboratory tests, cone index and moisture data can be used to predict bulk density in that soil. This procedure may save time and expense in future research on soil compaction.

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1.0 INTRODUCTION

Agricultural production in the United States is threatened by high prices for farm inputs and low market prices for farm products. Even with governmental subsidies and loans, farm profits have decreased significantly in the United States. With these high production costs, farm goods from the United States are unable to compete in the world market. Therefore, for U.S. agriculture to continue to be a viable industry, the costs of crop production must be reduced. Conventional tillage systems used to prepare the land generally demand more energy inputs than newer no-tillage systems (Sin et al., 1979). If the number of operations associated with land preparation can be minimized without affecting crop yield, the farmer may realize substantial savings.

Soil and moisture conservation has become a major issue in the United States because of the reduced capacity of streams and reservoirs due to deposition of eroded soil particles, the pollution of public streams with chemicals and nutrients washed from farm lands, floods caused by increased surface runoff, and the high cost of irrigation. Due to high soil erodability attributed to the lack of surface cover at the beginning of the cropping seasons, conventionally tilled land is responsible for a major portion of these problems. Many research studies have proven the effectiveness of surface cover in reducing soil erosion and surface runoff. Therefore, leaving plant residue on the soil surface is the most economical method of soil and moisture conservation.

In order to reduce the severity of the socio-economic and environmental problems caused by agriculture, alternative farming systems must be adopted on farms where conventional tillage systems are currently used and are currently contributing to these problems. It has been shown that no-till farming systems are effective in handling the above problems. Many studies have shown higher or comparable yields in no-till systems compared to conventional systems. In addition, reducing the number of operations for land preparation saves energy inputs while improving timeliness. Reduced nutrient losses increase fertilizer efficiency in no-till systems. Some research studies have shown favorable changes in the soil-water-air matrix due to continuous use of no-till farming. Because of these advantages, more and more farmers are changing their cropping systems to no-till farming.

Even though many research studies have shown the advantages of no-till farming, some studies have shown disadvantages under certain soil and climatic conditions. Excessive soil moisture conditions in clay soils during wet cropping seasons, and the associated soil compaction under no-till systems can reduce crop yield. Soil compaction problems may occur sooner or later, depending on soil type, equipment used, and the soil moisture conditions at the times of field operations. If soil compaction occurs, poor infiltration can cause an increase in surface runoff and soil erosion. Due to the restricted moisture movement and poor root growth in compacted soils, plant growth may be affected. Therefore, several advantages of using no-till practices can be lost in the long run if soil compaction problems occur. Because of these potential compaction problems, some farmers who use no-till practices till their fields periodically and thus do not enjoy all the advantages of no-till practices. Others neglect the compaction problem and suffer from reduced farm income. Therefore, it is necessary to study the effects of the continuous use of no-till practices on the structural characteristics of soils and how and where the soil compaction problems occur when using no-till systems. The long term effect of no-till systems on Virginia soils has not been investigated completely even though similar studies have been conducted in some other regions of the United States.

Soil bulk density data is used widely to assess the level of soil compaction. The core sample procedure used to determine the soil bulk density involves tedious work, especially when samples have to be collected from subsurface layers at close depth intervals. The radiation techniques used for predicting soil bulk density require site-specific calibrations. The single and the dual probe configurations of the gamma-ray densitometer have specific constraints and advantages associated with them. Because of the radiation hazard potential, the use of these nuclear devices has been limited even though the soil bulk density can be measured about three to five times faster with the densitometer compared to the core sample method. The strict safety regulations regarding the operation and storage of these devices result in a considerable increase in the total cost. Therefore, an alternate method is needed to predict soil bulk density using less laborious, inexpensive, and quickly determinable parameters.

Even though some models have been developed for predicting soil bulk density using the cone index with some other soil properties, these models are not widely used either because they utilize many soil properties that require expensive laboratory analysis procedures or because they have not been proven to work under field conditions. However, cone index and soil moisture content have been shown to be related to soil bulk density under laboratory conditions. These two parameters can be determined accurately and quickly using low cost procedures. So far, no models for predicting soil bulk density using only cone index and moisture content data have been evaluated under field conditions.

2.0 OBJECTIVES

Soil compaction can occur under continuous use of no-till practices in some soil types under certain climatic regions. Even though there have been a few studies on the effects of continuous use of no-till practices on soil physical properties, similar studies have not been conducted in Virginia. In order to provide information for advising farmers in this region on the use of no-till farming in place of conventional tillage farming, a knowledge of the structural changes associated with these tillage practices is needed.

There are problems associated with both the core sample method and the neutron probe method used for determining soil bulk density. The models developed in the past for predicting soil bulk density using cone index data require additional parameters determined through expensive laboratory procedures. A model that uses only cone index and moisture content data for predicting soil bulk density in the field would save time and money in future research studies. Therefore, the specific objectives of this study were to:

1. Evaluate the effects of no-till and conventional tillage practices on soil dry bulk density, capillary porosity, noncapillary porosity, and penetration resistance, and to compare those results with a control fallow treatment.

2. Develop a model that predicts soil bulk density using only cone index and moisture content data under laboratory conditions, and to evaluate it using data collected in the field.

3.0 TILLAGE EFFECTS ON THE SOIL-AIR-WATER MATRIX

3.1 *Introduction*

> "Soil compaction from wheel traffic of modern machinery is an increasing world-wide concern. Soil compaction has been identified as one of the leading causes of soil degradation threatening future productivity of American farm land. Compaction has the potential to affect crop growth and production directly, and also indirectly by increasing soil erosion and/or water runoff," said Voorhees (1987).

One purpose of tillage is alleviating soil compaction. However, the effectiveness of different tillage practices in removing soil compaction may depend on soil type, level of soil compaction, location of compaction zone, tillage system, tillage depth, climatic conditions, and other field operations required by the crop being grown in that system. Therefore, the effects of wheel traffic on soil compaction and crop response vary widely around the world (Voorhees, 1987). There have been numerous studies on the effects of tillage practices on soil properties and crop growth under different geographic and climatic conditions.

Information on changes in soil physical properties due to the continuous use of any tillage practice is essential to explain the crop response to that particular tillage practice. Many approaches have been proposed by researchers to quantify the changes in those soil physical properties.

3.2 Literature Review

3.2.1 Tillage

Tillage in conventional farming systems is carried out to obtain a better crop response by accomplishing the following:

1. Pulverize and mix soil layers to incorporate plant residue into soil,
2. Control weeds,
3. Control pests,
4. Loosen the soil for:
    - Increased aeration
    - Increased infiltration
    - Better seed/soil contact
    - Better root growth

In order to get good soil tilth and to reduce the energy required in the field operations, primary and secondary tillage preparations should be performed when the soil moisture content is favorable. Therefore, farmers may have to wait for at least one or two rain storms before starting land preparation at the beginning of the season. Unpredictable weather patterns, especially prolonged wet or dry periods at the beginning of the season, can delay planting dates and lead to crop losses under conventional farming systems. Farmers tend to work long hours to plant the crop as early as possible, while soil moisture content is favorable. But, continuous use of equipment reduces the life span of the machine components and increases the frequency of breakdowns. Therefore, conventional tillage systems may result in poor timeliness in field operations.

Since all farmers who use conventional tillage systems start field work simultaneously, equipment, labor, seeds, and fertilizers are in high demand at the beginning of the season. Therefore, labor, fuel, machinery, and other inputs may be more expensive when using conventional tillage systems, and this greater expense may lead to reduced profits or net losses if the crop yield is affected by environmental factors such as high temperature and drought.

3.2.2 Tillage Effects on Soil Properties and Plant Growth

3.2.2.1 Soil Compaction

Initially, the general assumption among researchers was that reduced tillage practices would reduce soil compaction because of reduced traffic in the field (Phillips, 1973). However, studies have shown that 75-90 percent of the compaction due to multiple passes by a vehicle is caused during the first few passes (Canarache et al., 1984; Soane et al., 1981; Taylor et al., 1982; Trouse, 1966). Soils which are initially loose experience maximum compaction during the first pass, whereas on soils with higher initial strength, the compaction resulting from the first pass differs little from that of subsequent passes (Soane et al., 1981). However, because of reduced land preparation, the soil compaction by vehicular traffic during subsequent cultural practices may not be removed before the next cropping season. The cumulative effect of compaction may change the soil properties in the long run and may affect the crop yield.

An increase in soil compaction is indicated by increased bulk density, reduced porosity, and increased soil strength under a given moisture content. Bulk density and porosity are closely related and various researchers have used these interchangeably to describe the effects of tillage and traffic on soil compaction.

3.2.2.1.1 Bulk Density

The dry bulk density of soil is measured as the weight of dry soil per unit volume. Even though the bulk density can change from one soil to another at a given compaction level, depending on the mineral composition, it is a good indicator of soil compaction for a given soil. Therefore, soil bulk density has been widely used by researchers to express the degree of compaction. Re-orientation of soil particles and/or soil aggregates under a compressive force creates a densely packed structure. The degree of re-orientation depends on the intensity of the external force, moisture content, particle size distribution, and soil type. Therefore, the contact pressure between the tire and the soil surface influences the change in bulk density of a given soil. An increase in soil moisture content reduces the soil strength and makes it easy for the soil particles to re-orient. Thus, according to Gameda et al. (1987b), moisture content during compaction has a significant effect on soil bulk density. According to their study, an axle load of 10 t was enough to compact wet soil and significantly reduce crop yield, whereas a load of 20 t was required to produce similar results in dry soil.

The depth to which compaction occurs for a given load also increases with increasing moisture content (Kayombo and Lal, 1986). On the other hand, Burger et al. (1985) found that even at the

21% moisture level, soil density at 15-cm depth was not affected by the tractor type or the contact pressure, and that the bulk density at the surface was significantly increased by increased moisture content, contact pressure, and the number of passes of the tractor.

The volumetric strain (compaction) in the soil at a given depth is proportional to the pressure applied at the soil surface. The contact pressure between the tire and the soil is inversely proportional to the contact area. Therefore, soil compaction due to vehicle loads can be reduced by increasing the contact area through the use of larger tires and/or reduced tire inflation pressures. However, Campbell et al. (1984) reported that the increase in contact area at low inflation pressures was very small due to the carcass stiffness of the tires. Therefore, the effectiveness of reduced inflation pressures in increasing contact area is very small. The use of larger tires also has practical limits. Therefore, Hakansson et al. (1987) recommended that axle-loads above 10 t should never be used in agricultural field operations.

Vehicular traffic has a cumulative effect on soil compaction (Campbell et al., 1986; Hakansson et al., 1987; Soane et al., 1981; Taylor et al., 1982; Trouse, 1966). The surface layer of loose soil absorbs most of the compactive energy initially. Thus, the surface layer compacts more than the bottom layers do. During subsequent passes of vehicles, the compacted layer will absorb less and less energy while more is transmitted to deeper layers. Thus, the depth of the compacted layer increases with repeated loading (Kayombo and Lal, 1986). Therefore, it is reasonable to expect higher bulk density values in no-till fields compared to fields of similar soils that are conventionally tilled (Derpsch et al., 1986; Ehlers et al., 1983; Floyd, 1984; Heard et al., 1988; Ike, 1986; Lal, 1985; Mielke et al., 1986; Roth et al., 1988). However, due to the elasto-plastic behavior of soils, the increase in soil compaction due to multiple passes of a vehicle may not be significant after a few passes (Lenhard, 1986).

In addition to wheel traffic, reactive forces around the cutting edges of tillage tools cause soil compaction below the plowing depth. Therefore, the layers below the plowing depth are subjected to higher compactive forces and become more dense under conventional tillage systems than in no-till systems (Gameda et al., 1987b; Ehlers et al., 1983). The highly compacted soil layer immediately below the plowing depth is called a hardpan (plowpan). This layer in plowed plots had the highest level of compaction than in any layer in untilled soil in the study by Ehlers et al. (1983). Floyd (1984) reported that the effect of plowpan is more visible in low moisture conditions.

3.2.2.1.2 Porosity

Voids or pore spaces within the soil are needed to store moisture, and to provide paths for growing roots and for movement of air and moisture within the soil. The total pore space in the soil is divided into capillary and noncapillary spaces. The capillary pore spaces are small and, therefore, are capable of holding moisture at tensions greater than that equivalent to a 50-cm water column. These spaces are primarily used for moisture storage. On the other hand, the noncapillary pores are larger and can be used for all the purposes listed above. However, the noncapillary pores are not very effective in storing moisture against the gravitational forces because of their larger diameters. Therefore, it is important to have some balance between the volumes of these two pore types for better plant growth.

When soil is compacted, total porosity reduces due to re-orientation of soil aggregates. During this process, the total volume of noncapillary pores decreases while the total volume of capillary pores increases because of the shrinkage of noncapillary pores to the sizes of capillary pores (Roth et al., 1988). Thus, many researchers have observed reductions in both total porosity and noncapillary porosity in no-till plots compared to plowed plots (Campbell et al., 1986; Derpsch et al., 1986; Douglas and Goss, 1987; Hamblin, 1984). Mielke et al. (1986) observed low air permeability because of a 10 percent reduction in total porosity in the surface layer in no-till plots. Blackwell et al. (1986) found that axle loads exceeding 5 t can reduce the soil noncapillary porosity in topsoil below 5% (v/v) and that an axle load of 13 t can reduce the porosity to a depth of 50 cm. This reduction in noncapillary porosity restricted oxygen supply during wet and warm periods.

As far as air permeability and hydraulic conductivity are concerned, continuity among noncapillary pores in the soil is more important than the total pore volume. Elongated, cylindrical noncapillary pores (channel type), commonly known as transmission pores, transmit moisture to deeper layers rapidly during rain storms as well as oxygen to the root zone. Dead plant roots from previous crops and soil fauna (earth worms and arthropods) help in creating these transmission pores, while plowing disrupts them (Douglas and Goss, 1987; Douglas et al., 1980; Ehlers et al., 1983; Lal, 1985). Pagliai et al. (1984) observed a higher total porosity in conventionally tilled plots that was represented by few, large, and very irregular elongated pores. They showed that the number and the proportional area of elongated pores of 30-500 μm width and the number of long and regularly shaped elongated pores were clearly larger in no-till plots. More root remains were also found in thin sections from no-till plots than in conventionally tilled plots. Hamblin (1984), Maurya (1986), Mielke et al. (1986) and Stengel et al. (1984) observed the presence of more organic matter on the soil surface in no-till plots. This organic matter cover on the soil surface in no-till plots helps the activities of earthworms and arthropods (Derpsch et al., 1986). Maurya (1986) reported higher porosity values in the surface layers of no-till plots with residue, compared to tilled plots. According to Heard et al. (1988), the continuous channels from 10-cm depth to 20 and 30-cm depths were maximum in no-till plots. They also observed highest air permeability at 20-30-cm depth in no-till plots. Therefore, even if the total noncapillary pore volume declines in the no-till plots, the presence of more transmission pores and the increase in capillary pore volume counteract the effect of high bulk density and produce a better environment for plant roots of subsequent crops (Ehlers et al., 1983).

3.2.2.1.3 Penetration Resistance (Cone Index)

Strength of inter-particle bonds, arrangement of soil particles, and moisture content of the soil affect the soil's resistance to a penetrating probe. Where the soil structure is loose and the bulk density is low, there is a low penetration resistance at a given moisture content because soil particles can rearrange easily to make a path for the penetrating probe. Conversely, where bulk density is high, the resistance of compacted soils to deformation at the same moisture content is considerably higher (Potapov, 1985). On the other hand, the penetration resistance reduces with increasing moisture content. The penetration resistance against the cone head of an ASAE standard cone penetrometer (ASAE Standard S313.2) divided by the base area of the cone is called the 'cone index'.

The effectiveness of different tillage systems in loosening soil may depend on the type of equipment used for soil loosening, the number of passes, the weight of the vehicle driven through the field, and the moisture content of the soil at the times of field operations. Usually, soils that are conventionally tilled exhibit the lowest penetration resistance (cone index) up to the depth of plowing (Hamblin, 1984), whereas no-till systems exhibit the highest values in similar layers (Ehlers et al., 1983; Floyd, 1984). However, due to the cumulative effect of soil compaction by vehicular traffic, cone resistance increases with increasing traffic (Campbell et al., 1986; Hakansson et al., 1987; Canarache et al., 1984), and is more marked in tilled soil, due to low initial soil strength, than in no-till soil (Kayombo and Lal, 1986).

3.2.2.2 Hydraulic Properties and Soil Moisture Content

Moisture migrates through the interconnected pores in the soil. Therefore, one can assume that soils with higher total porosity values have higher infiltration rates and hydraulic conductivities.

According to the Carman-Kozeny equation (Foust et al., 1967), soil hydraulic conductivity should be proportional to $n^3/(1-n)^2$, where n is defined as the porosity. However, resistance to the flow of water increases drastically as the cross-sectional area of the passage decreases. Therefore, a unit increase in total porosity in the form of noncapillary pores has a much higher influence on the hydraulic properties than does a similar change in the forms of the capillary pores. According to Potapov (1985), compacting a loamy soil to bulk densities in the range 1.0-1.2 g/cm^3 reduces the infiltration rate. An increase in bulk density to 1.4 g/cm^3 reduces the infiltration rate to the minimum by complete destruction of the macrostructure. This result emphasizes the importance of noncapillary pores in soil. In soils loosened by tillage, the infiltration rate has a higher value, due to higher noncapillary porosity, than that of wheel-tracked soils (Voorhees et al., 1985). Negi et al. (1982) observed lower hydraulic conductivity during the second year cycle of the no-till practice than in conventionally tilled plots, a result which could be due to low noncapillary porosity and fewer transmission pores during the first few years using no-till.

Continuity of these noncapillary pores is also important for fast movement of moisture within the soil. As explained earlier, the number of elongated cylindrical transmission pores in no-till plots increases over time, while plowing disrupts the continuity. Thus, a higher infiltration rate and hydraulic conductivity is often found in no-till plots compared to conventionally tilled plots after a few cropping seasons (Derpsch et al., 1986; Maurya, 1986; Lal, 1985). However, Heard et al. (1988) found the saturated hydraulic conductivity to be higher within the top soil layer in plowed plots compared to no-till plots in the tenth year of their experiment in Chalmers soil. In the same experiment in Clermont soil, saturated conductivity was higher in plowed plots compared to other conservation tillage treatments after the fifth year. The difference in saturated conductivity was greater between soils than between tillage treatments.

Moisture evaporation from the soil is proportional to the wind velocity at the surface. Standing crop residue reduces the wind velocity near the soil surface and thereby reduces the moisture evaporation loss (Smika, 1983).

The combined effects of more water infiltration into the soil, the presence of continuous transmission pores, and less evaporation from the surface using no-till systems helps to store more moisture in the soil profile to a greater depth compared to conventionally tilled plots (Hamblin, 1984; Derpsch et al., 1986; Ike, 1986; Grevers et al., 1986; Ojeniyi, 1986; Al-Darby et al., 1987; and Lal, 1985). However, Voorhees et al. (1985) disagreed with the above finding, and reported that in a dry season, the 0-15-cm layer of a loose soil which had no wheel traffic on it lost excessive amounts of water through evaporation, and became drier than a compacted soil.

3.2.2.3 Plant Growth

Many attempts have been made to relate individual soil physical characteristics to plant growth, although plant growth is influenced by many soil and climatic factors. Among all the physical characteristics, soil strength, moisture availability, aeration, and soil temperature appear to be the most important for the development of a healthy root system. However, the response to the above factors may depend on the crop and the crop variety.

In compacted soils, proper seed placement is difficult because of the poor performance of furrow openers. The presence of large quantities of crop residues on the soil surface produce similar results unless special tools are used (Izaurralde et al., 1986). Improper seed placement leads to reduced seedling emergence due to destruction of seeds by ants, rodents, and birds, and to delayed germination (Voorhees et al., 1985; Kayombo and Lal, 1986).

Low mechanical impedance, good aeration, and a good supply of moisture enhance the development of a better root system. Therefore, even after proper seed placement, crop growth is affected in highly compacted soils due to poor root growth caused by high mechanical impedance and poor aeration (Willatt, 1986; Graham et al., 1986). Poor aeration and high mechanical impedance in the plow pan layer could be the reasons for high rooting density above and low rooting density below the plow pan layer, as observed by Ehlers et al. (1983) in a Loess soil. Many have observed low crop yields because of reduced crop growth due to increased bulk densities (Adams et al., 1960; Canarache et al., 1984; Chaudhary and Prihar, 1974; Cornish and Fettell, 1977; Froehlich, 1979; Gameda et al., 1987c; Pollard and Elliott, 1978; and Wert and Thomas, 1981). Stibbe and Terpstra (1982) related penetrometer resistance to emergence of seedlings, plant height, and dry matter yield, and found that penetration resistance was linearly related to the time required for 50% emergence of seedlings. Percent emerged seedlings, plant height, and dry matter yield decreased linearly with increasing penetration resistance. Plant height and dry matter yield increased when moisture content changed from 15% to 25% (v/v), but the effect of penetration resistance remained unchanged. According to Graham et al. (1986), cone resistances exceeding 1.4 MPa can slow wheat root growth in dry autumn in silt loam soils. When seed germination and crop growth are affected by higher levels of soil compaction, weed competitiveness may be increased. Thus, early establishing weeds can reduce farmers' profits either by reduced crop yields or by added cost of weed control.

Potapov (1985) stated that the water-air regime in newly cultivated soils deteriorates when compacted mechanically. Since it takes time for the transmission pores to develop and for the water-air regime to become favorable for crop growth, crop growth and crop yield can be affected by soil compaction during the early years of using the continuous no-till practice, as observed by Campbell et al. (1986), Gerik and Morrison (1985), Zantinge et al. (1986), and Zugec (1986). However, Wagger (1988) reported an increase of 24 bu/A (1500 kg/ha) in corn yield in the first season using no-till practice compared to continuous conventional tillage.

Graham et al. (1986) found the optimum noncapillary porosity to be approximately 14% for wheat yields. Higher noncapillary porosity (16 - 20%) generally restricts nutrient uptake due to low moisture uptake. Plant growth differences diminish, however, when the soil is re-wetted by heavy rains.

Due to a buildup of continuous channels and an increase in capillary porosity after a few years of continuous no-till farming, the soil may support root growth regardless of increased bulk density or penetration resistance. Ehlers et al. (1983) found that the limiting penetration resistance for oat root growth was 3.6 MPa in the tilled Ap-horizon. The limiting value for the untilled Ap-horizon and the subsoil was in the range of 4.6 - 5.1 MPa. Favorable soil conditions in continuous no-till plots results in higher root densities compared to tilled plots (Kayombo and Lal, 1986). Continuous channels extending to deeper layers provide paths for growing roots to reach greater depths (Lal, 1985). Roots extending to deeper layers can provide enough moisture to the crop during dry periods. Due to low moisture stress, crops produced using no-till compared to conventional farming systems can produce similar or better yields in dry seasons after a few cropping seasons (Al-Darby and Lowery, 1986; Al-Darby et al., 1987; Campbell et al., 1986; Derpsch et al., 1986; Freebairn et al., 1986; Hamblin, 1984; Herbek et al., 1986; Izaurralde et al., 1986; and Wagger, 1988).

Wagger (1988) found tillage influence on corn yield to be significant in moderately dry years. In extremely dry years, both tillage systems produced low yields due to moisture stress. In the years with adequate rainfall, both tillage systems produced comparable corn yields. Gerik and Morrison (1985) reported similar results for wheat.

Even though no-till systems produce good results in terms of crop growth and yield in dry seasons, they can lead to reduced crop growth and yields in wet seasons, especially in poorly drained soils, due to excessive moisture conditions which increase root diseases (Dick and Van Doren, 1985) and restrict oxygen supply to the root system (Kladivko et al., 1986; Campbell et al., 1986; Griffith et al., 1982). According to Dick and Van Doren (1985) and Griffith et al. (1982), yield reduction in poorly drained soils using no-till practices can be reduced by using crop rotations. Heard et al. (1988) suggested that surface cover be used for rapid improvement of poorly structured soils.

3.2.3 Recovery of Compacted Soils

The recovery of heavily compacted soil is caused by drying/wetting cycles (Blackwell et al., 1986) and by freezing and thawing cycles (Taylor et al., 1981; Gameda et al., 1987b). Freeze/thaw cycles are not very effective in alleviating soil compaction because the lenses formed during freezing disappear during the thawing period and leave the soil compacted at the pre-freezing level (Blackwell et al., 1986; Kay et al., 1985). Because of the incomplete amelioration of compacted soil by natural forces during the winter season, no-till practice can result in higher bulk densities, aggregate densities, and penetration resistances (Voorhees, 1983). Wetting and drying can regenerate compacted soil by creating planar voids (Bullock et al., 1985) that can increase noncapillary porosity by at least 3% (Blackwell et al., 1986). Due to little moisture changes in subsoil layers, regeneration of compacted subsoil layers takes a considerably longer time (Gameda et al., 1987c; Hakansson et al., 1987; Froehlich et al., 1985).

3.2.4 No-Till Advantages

3.2.4.1 Effects of Residue Cover

Having a cover on the surface helps to reduce the adverse effects of changing atmospheric conditions on the soil while conserving soil and moisture. Even though artificial covers can be used to achieve this purpose, they are not practical economically on large U.S. farms. Plant residue and crop mulches can be used to cover the surface more economically.

3.2.4.2 Temperature Control

Residue cover greatly influences the soil temperature in temperate regions as well as in tropical regions. In temperate regions during the winter season, standing crop residues increase the accumulation of snow on the surface. Both the residue cover and the snow layer act together to reduce soil freezing when the air temperature drops sharply in severe winter seasons (Conn, 1987; Cox et al., 1986; and Kay et al., 1985). Tall stubble helps to reduce the wind velocity near the soil surface; therefore, the heat loss from the surface is reduced during the winter season. Cox et al. (1986) pointed out that a comparatively warmer soil temperature due to reduced soil freezing reduces the duration of time that the soil temperature drops within the range responsible for winter crop injury. Therefore, percent winter survival of winter wheat was greatest in no-till plots with tall stubble. According to Cox et al. (1986), winter wheat yields after a severe winter from conventional tillage, mulch tillage, no-till with 0.05-m high stubble, and no-till with 0.20-m high stubble were 455, 2203, 2270 and 4073 kg/ha, respectively. Winter wheat yield differences after a mild winter were not significant. However, because soil warming is delayed by crop residues through insulating effects and greater reflection of solar radiation (Gupta, 1985), crop planting may be delayed and crop yield reduced if planting is done early in wet and cool seasons (Herbek et al., 1986).

In tropical regions where soil temperature in bare soils exceeds 40°C, seeds, crop roots and soil capillary fauna can be damaged by extreme temperatures (Derpsch et al., 1986). Lal (1974) observed an 8°C reduction in soil temperature at the 5-cm depth with an application of 2 Mg/ha residue. Izaurralde et al. (1986) reported a 3°C reduction in maximum soil temperature at the 5-cm depth in no-till plots compared to conventionally-tilled plots. Therefore, residue cover can be beneficial in the tropical regions in reducing seed injuries caused by extreme temperature levels in the seeding zone.

3.2.4.3 Moisture and Erosion Control

When crop residue decomposes, more organic matter is added to the surface layer. Organic matter (humus) binds soil particles together to form stable aggregates. Therefore, a high concentration of organic matter in the surface layer reduces the detachment of soil particles by traffic, livestock, and rain drop action (Hamblin, 1984; Biggerstaff and Moore, 1982; and Derpsch et al., 1986). Residue or mulch cover also absorbs most of the kinetic energy stored in rain drops and further reduces particle detachment at the surface. These detached particles deposit in the openings created by dead roots and soil fauna and thereby create a surface seal. Therefore, through the reduction of particle detachment and creation of a surface seal, residue or mulch cover increases the soil's ability to absorb water or at least maintain it at a capacity nearer to its maximum potential (Biggerstaff and Moore, 1982; Wagger, 1988). Maurya (1986) also reported higher infiltration rates and accumulated infiltration within a 4-hour period using no-till with a residue cover. When the residue cover was removed, however, the volume of moisture dropped to the minimum value. Low hydraulic conductivity and aggregate instability in tilled soil is indicated by reduced depth to wetting front and reduced amount of water stored in top 120-cm of soil (Hamblin, 1984).

Crop residue acts as a barrier to surface water flow and reduces the runoff flow velocity, and thus allows more time for water to infiltrate into the soil. The net result is that less water is lost from the field in the form of surface runoff. The reduced flow velocity allows more detached particles to deposit on the surface, reducing the sediment yield in runoff water (Blackwell et al., 1986; Freebairn et al., 1986). Derpsch et al. (1986) indicated that the extent of soil cover significantly affects infiltration rate and surface runoff, compared to the tillage method. The significant effect of soil cover could be due to the presence of more earthworms and arthropods under that cover, which help to build up transmission pores in the soil. Roth et al. (1988) stated that 4-6 t/ha of plant residue is needed to reduce runoff and erosion effectively. Since no-till farming systems leave a residue cover on the surface, these systems help to control soil erosion while increasing the volume of moisture stored in the soil.

Many studies dealing with the effectiveness of different cropping systems on erosion control have been reported. When the soil is exposed after plowing using conventional tillage systems, it is very vulnerable to erosion until the crop canopy develops to cover the surface. Therefore, soil erosion is considerably higher in conventional farming systems. According to Harrold (1972), soil erosion from a conventionally-tilled plot was 242,000 kg/ha, compared to 330 kg/ha from a no-till plot. A 20-year study at Millan Tennessee Experimental Station showed that no-till prevents soil erosion and improves water quality. Freebairn et al. (1986) said that soil erosion was reduced to 2 t/ha/yr using no-till compared to 30-60 t/ha/yr from bare fallow plots.

Many farmers who use conventional tillage systems do not adopt erosion control procedures in order to reduce the cost of production. Therefore, the amount of soil eroded from farm lands is extremely high. It has been estimated that the soil loss from cropland in the United States alone amounts to about 2.3 billion tons per year. This very high rate of soil erosion causes many socio-economic problems. Therefore, some governments have taken legislative steps to identify those lands vulnerable to erosion and to force the farmers to adopt erosion control measures and/or to deviate from conventional farming in order to maintain and extend the productivity of farm lands. One example of this effort is the 1985 Farm Bill in the United States. Of 327 million acres of farmland in the United States, 165 million acres are classified as highly erodible land. The federal conservation rules in the 1985 Farm Bill cover 99 million acres of farmland, and force farmers to develop conservation plans for their farms by the end of 1989 and to implement the plans by 1995, or face cuts in federal farm subsidies.

According to the Southeast Farm Press (1988), no-till farming is the most economical and simplest solution most farmers can adopt in order to reduce erosion. However, farmers should not divert their cropping systems to no-till without a full knowledge of the long-term effects of the no-till system, since it has been proven to cause compaction problems under some soil and climatic conditions.

3.2.5 Cone Penetrometer and Penetration Resistance

The widespread use of penetrometers in soil compaction studies can be attributed to the following: (1) penetrometers are quick, easy, and economical to use; (2) test data can be analyzed easily; (3) they can be used to investigate sandy soils where undisturbed sampling is difficult; and (4) it is possible to collect data from the deeper layers. On the other hand, a disadvantage of this test is the inability to observe the soil samples at the depth where data is collected.

Energy required to reposition soil particles by the cone tip of the cone penetrometer is greatly influenced by the compactness of particle arrangement, strength of the inter-particle bonds, rate of penetration, and soil moisture content. The force required to push the cone penetrometer into the soil is called the penetration resistance. Penetration resistance divided by the base area of the cone is called the "cone index". The cone index value can be stated at a particular depth or averaged over a depth range.

3.2.5.1 Factors Affecting Penetration Resistance

The soil properties, together with the size and shape of the cone and the rate of penetration, influence the penetration resistance (Frietag, 1967; and Gill, 1967). Frietag (1967) stated that for fine-grained soils an increase in the diameter of a 30-degree right circular cone resulted in a decrease in cone index value, while an increase in the rate of penetration produced an increase in the index value. Nowatzki and Karafiath (1972) reported that, for air-dried sand, increasing the apex angle from 15.5 to 150 degrees increased the penetration resistance. According to Gill (1967), in fine-grained soils the penetration resistance decreases when apex angle increases from 7.5 to 30 degrees, but increases slightly for the range of 30 to 60 degrees. Therefore, it is important that the results of penetration tests be compared carefully with regard to the equipment and procedures used for the tests.

The resistance of a given soil to penetration represents the combined influence of both the cohesional and frictional characteristics of the soil. When a frictional component exists, the relationship of cone index to the state of the soil depends on the level of soil compaction as well as other physical properties of the soil (Frietag, 1971). Mulqueen et al. (1977) investigated the relationship among density, moisture content, cohesion, and penetration resistance. For clay, the influence of cohesion on penetration resistance was greater at lower moisture contents.

Soil moisture acts as a lubricant when the soil particles are displaced by the penetrating cone head. Therefore, in addition to bulk density, soil moisture content influences the cone index data (WES, 1958; Knight, 1961; Smith, 1964; Turnage, 1970; Voorhees and Walker, 1977; Collins, 1971; WES, 1964; Melzer, 1971; Turnage, 1974; Wells and Treesuwan, 1977; Hayes and Ligon, 1977; Wells and Baird, 1978; and Ayers and Perumpral, 1982).

3.2.5.2 Cone Penetrometer Types

Since penetration resistance is influenced by several factors, the American Society of Agricultural Engineers (ASAE) developed a standard for cone penetrometers (ASAE Standard S313.2) to make the comparison of penetration resistance data more meaningful. This cone penetrometer was originally developed by the Waterways Experiment Station (WES) of the US Army Corps of Engineers to predict the trafficability of vehicles over a particular terrain (WES, 1948). Its cone, which has an apex angle of 30 degrees and a base area of 3.2 cm^2 , is mounted on a 91-cm long, 15.9-mm diameter graduated shaft. A proving ring with a dial gauge is provided between the handle and the shaft to indicate the penetration resistance. The proving ring is calibrated so that the reading on the dial gauge represents the penetration resistance in pounds per square inch. The zero-depth reading is taken with the base of the cone flush with the soil surface. According to the ASAE Standard, a penetration rate of 3 cm/s (72 in/min) is recommended for the cone penetrometer tests (ASAE, 1988). ASAE Standard S313.2 is widely used to measure the cone index for tillage and traction tests, soil mobility research, soil compaction studies, and plant growth investigations. Many configurations of the cone penetrometer built according to the ASAE standard are available for research use.

During penetration tests, readings are taken at every 2.5-cm (1-in.) penetration of the cone. Usually, 2-3 persons are required to conduct the test and record data accurately. In addition, manually maintaining a constant penetration rate of 3 cm/s during the test is practically impossible. To overcome these shortcomings, many have developed recording penetrometers with an appropriate mechanism for maintaining a constant rate of penetration.

Carter (1967) developed a simple hand-held recording penetrometer with a calibrated spring and a spring-loaded frame to graph the soil resistance on a 7.5 by 12.7-cm card. Hendrick (1969) described a recording penetrometer consisting of a calibrated spring with moving chart paper. Carter (1969) developed an integrating penetrometer to provide average soil strength; it consisted of a force transducer, an operational amplifier, and a signal generator. The continuous recording and integrating circuitry, which eliminated the laborious task of manual integration, made it possible to obtain the average penetration force. Prather et al. (1968) used an X-Y plotter with a hand-held penetrometer to plot the penetration resistance versus depth of penetration. Howson (1977) constructed a recording penetrometer with a calibrated spring and rotating chart paper. The penetrometer developed by the Scottish Institute of Agricultural Engineering recorded a limited number of readings (15) per penetration, which had to be transferred to paper or electronic memory after each penetration test (Anderson et. al. 1980). By placing strain gauges on the proving ring, Phillips and Perumpral (1983) modified a conventional cone penetrometer to provide an electrical signal corresponding to penetration resistance. A microcomputer-based data logger was developed to collect and store the penetration resistance data. However, this design required two persons to conduct the test and record data. Woodruff and Lenker (1984) designed a hand-held digital penetrometer with a data logger that could store data from 60 to 70 penetrations of 48 readings each. All of these hand-held penetrometers lacked the provision for controlling the rate of penetration. To overcome this drawback, Lowery (1984) designed a tripod-mounted portable cone penetrometer which could be driven into the soil at a constant rate using an electric motor. Heslop et al. (1989) described a portable cone penetrometer with a data acquisition module; it was powered by a 110 V AC motor.

Williford et al. (1972) developed a tractor-mounted penetrometer. A hydraulic cylinder was used to push the penetrometer probe into the soil. An X-Y plotter recorded the force-depth relationship during the penetration test. Smith and Dumas (1978) collected data at specific depth intervals in the soil profile using a tractor-mounted recording penetrometer. The power to push the probe into the soil was supplied by an electric motor. This unit measured cone index values in the range of 0-14000 kPa. Wilkerson et al. (1982) developed a more elaborate test unit for soil strength measurements. It consisted of a tractor-mounted hydraulically-operated cone penetrometer designed to operate to a depth of 61-cm (24-in.) over a 4-row width. A microprocessor-based control unit was used to activate all moving mechanisms and to automatically record data on a magnetic tape. Threadgill (1982) used an electronically-recording, tractor-mounted, hydraulically-operated cone penetrometer. This penetrometer was later modified by Cromer and Threadgill (1985) to use a personal computer with dual disk drives and a monitor for field data collection and analysis. The depth-versus-force relationship displayed on the monitor helped the operator with the decision to save or reject the data and repeat the test. Recording across 2-m wide sections was possible, and lateral movement of the unit was accomplished using an electric gear motor connected to a portable generator.

In 1986, Jayatissa developed a tractor-mounted, hydraulically-operated, recording penetrometer. It consisted of a load cell, a depth sensor, an analog to digital (A/D) converter, an operational amplifier, a microcomputer and a cassette recorder. Using a hand-cranking mechanism, the penetrometer could be positioned at any location in a vertical (or horizontal) section 2-m wide and could be operated up to 60-cm depth. The microcomputer recorded the A/D converter output of depth and penetration resistance during each penetration and transferred those values onto the cassette tape. All the electric power needed by the components was supplied by the 12 V DC tractor battery through a DC/DC converter. The hydraulic power to push and retract the penetrometer probe was supplied by hydraulic circuitry connected to the tractor hydraulic system.

Sirois and Stokes (1988) reported the design and method of operation of a hydraulically-operated cone penetrometer mounted on a four-wheel-drive, all-terrain cycle. The unit was comprised of a 6.35-cm diameter hydraulic ram, which was powered by a hydraulic accumulator-based system, and an electronic data recorder. The system measured penetration forces in excess of 890 N over depths of 0 to 35.5-cm for up to 100 penetrations without recharging the system's batteries or dumping data to a computer.

Sirois et al. (1989) compared four different cone penetrometers in two soil types at different depths and reported significant differences among the penetrometer methods. The variation among the methods was less than the variation from the soil types and depths. They observed a higher variation among the penetrometer methods at higher resistance levels.

3.3 Methodology

From the previous discussion it is clear that the effects of the continuous use of no-till practices on structural characteristics of soils are not fully known. Even though a limited number of studies has been conducted to address this problem in certain geographic regions, it is important that such assessment be made under Virginia soil conditions because the effects can vary based on geographic location and climatic conditions. Therefore, the objective of this part of this study was to assess the changes in soil physical properties due to continuous use of no-till practices under one Virginia soil condition.

3.3.1 Experimental Plots and Treatments

The field study was conducted at the Virginia Tech Prices Fork Research Farm located about 5 km from the main campus. A rectangular area 36-m wide and 84-m long was selected for the experiment. The plot layout was such that the longest dimension was in the north-south direction. The northern half of the area selected had a gentle slope ($< 5\%$) towards both the east and the south. The southern half was steeper (10 - 15%) towards the south. The 20-cm topsoil was a sandy loam and the subsoil was clay. In order to nullify or minimize the effects of previous tillage practices, the entire area was plowed using a moldboard plow and then rotary tilled to pulverize the soil at the beginning of 1987 cropping season when this study was initiated.

Since the goal of this part of the study was to assess the changes in soil physical properties in continuous no-till systems, the following three treatments were selected:

1. Conventional tillage - (CT)

2. Zero tillage (no-till) - (NT)

3. Fallow (control) - (F)

The fallow treatment was included in the study to evaluate the changes in soil physical properties when the soil is compacted through natural consolidation due to soil overburden. When changes in the physical characteristics in the fallow treatment are subtracted from the other two treatments, the results reflect the pure effects of those tillage treatments and the traffic conditions on the soil-air-water matrix.

For the conventional tillage treatment, the test plots were moldboard plowed parallel to the longest dimension and then rotary tilled to pulverize the soil and to smooth the surface. Soon after, a systemic herbicide mixed with nitrogen fertilizer solution was sprayed on the plots to destroy germinating weeds and to add nutrients to the soil. Corn was planted in these plots about 2 weeks after the chemical application.

For the zero-tillage (no-till) treatment, the soil was not disturbed by any form of tillage operation after the initial land preparation at the beginning of this study. At the beginning of each cropping seasons, the same herbicide/fertilizer mixture used in the conventionally-tilled plots was sprayed on the no-till plots to kill weeds and to add nutrients to the soil. The spraying and corn planting operations in the no-till plots were synchronized with the similar operations in the conventionally-tilled plots.

For the fallow treatment, the plots were left alone after the initial land preparation allowing natural weed growth. Traffic through these plots was avoided except at the time of data collection. Weeds were controlled manually.

In order to minimize the effect of variations within the test area, a randomized block design was used for establishing the test plots. As illustrated in Figure 1, the total test area selected was divided into four 18-m sections with 4-m wide buffer strips between sections. Each section was then divided into six 6-m wide plots, and three adjacent plots in each section were grouped to form a block. The three treatments selected were randomly assigned to the plots in each block. This procedure resulted in a total of 24 plots within 8 blocks.

In the 1987 cropping season, CT and NT plots were planted with corn in rows 0.9-m apart in the north-south direction, using a 4-row conventional corn planter. In the 1988 and 1989 cropping seasons of this study, corn was planted in rows 0.8-m apart using a 2-row no-till corn planter. The buffer strips were used to access each plot to prevent traffic over the other plots.

3.3.2 Data Collection and Analysis

To accomplish the stated objective, changes in soil bulk density, capillary porosity, noncapillary porosity, void ratio, and penetration resistance (cone index) were evaluated. Since the changes due to the treatments selected could vary as a function of depth and time, data was collected at various depths twice during the year.

3.3.2.1 Penetration Resistance (Cone Index)

The cone index values were collected from three 2.1-m wide, 60-cm deep vertical sections in each test plot as indicated in Figure 1 during each test period. One vertical section was located at the

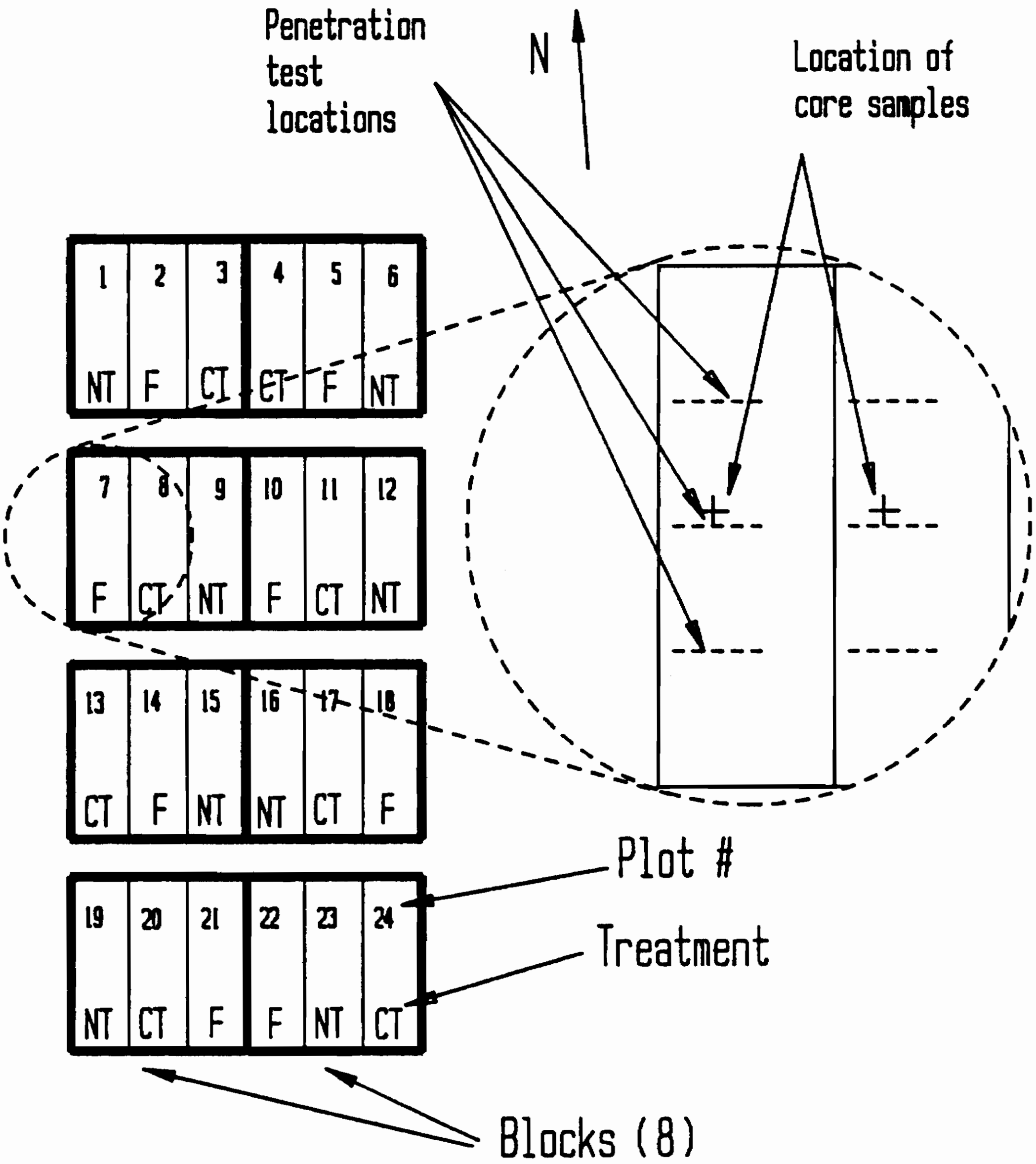


Figure 1. Layout of the Test Plots

midpoint while the other two sections were about 4-m from each end of the test plot and 0.6-m away from the boundary, so as to reduce any influence from the treatment in the adjacent plot. The tractor-mounted, hydraulically-operated recording penetrometer developed by Jayatissa (1986) was modified and used to collect cone index data. The data acquisition system was modified using a dedicated Analog/Digital (A/D) converter and an IBM Convertible microcomputer for data collection and storage. The design details of the new configuration and the operating procedure are given in the Appendix A.

During each test period and at each location, 15 penetration tests were conducted 15-cm (6-in.) apart. During each penetration test, the resistance data were collected at each 1.27-cm (0.5-in.) displacement of the cone. The program used to record the A/D converter output data on the micro diskettes is listed in Appendix B. Soil moisture samples were collected from two locations in each vertical section up to 25-cm (10-in.) at 5-cm (2-in.) depth intervals. After these moisture samples were dried for a 24-hour period at 105 °C, the soil moisture content of each sample was determined. The data files containing A/D output were transferred to the Micro VAX computer. Using the data reduction program listed in Appendix C, the A/D converter output data were converted to cone index values.

3.3.2.2 Determination of Bulk Density, Capillary Porosity, Noncapillary Porosity and Void Ratio

Core samples were taken from the plots to assess the changes in bulk density, capillary porosity, noncapillary porosity, and void ratio at various depths. Soil bulk density is defined as the dry weight per unit volume of undisturbed soil. The void space that can hold moisture against a tension equivalent to a 50-cm water column divided by the undisturbed volume of the soil sample is called 'capillary porosity'. The remaining void space is known as noncapillary porosity. The ratio of total pore volume to the total volume of soil particles (solids) is known as the void ratio.

The core sampler illustrated in Figure 2 was used to extract undisturbed soil samples. This core sampler consisted of a 0.5-m long tubular shaft and handle with a threaded base and a stainless steel cup. One end of this cup was threaded while the other was machined to provide a sharp cutting edge. The inside diameter of the cutting edge was 6-cm. The brass rings having a 6-cm inside diameter were inserted into the cup from the side opposite the cutting edge. Two narrow rings (0.75-cm thick) were inserted before the 6-cm long ring, and another narrow ring followed the wide one. Then, the cup with brass rings was screwed onto the base. After the core sampler was positioned over the point where the soil samples were to be collected from each plot, as indicated in Figure 1, it was driven into the soil by repeatedly dropping the 4 kg weight from a height of 30 cm. A 6-cm diameter soil column was collected within the brass rings as the core sampler penetrated into the soil. When the base of the core sampler touched the soil surface, the core sampler was extracted from the soil and the cup was unscrewed from the base. The brass rings were pushed out of the cup by inserting a cylindrical object into the side having the cutting edge. After the small brass rings were carefully removed, the soil column was cut across the edges of the large brass ring with a sharp knife. Then, the soil sample was secured in the brass ring by closing the ends of the ring with two plastic caps.

Another large brass ring (6-cm long) was placed in the cup with the small rings as previously described. Using a hand-operated post-hole digger, a 20-cm diameter, 12.5-cm deep hole was excavated. Then the soil core sample from the 12.5-20-cm depth layer was extracted using the core sampler in the same manner as described above. This procedure was repeated to collect two more soil core samples from 25-32.5-cm and 37.5-40-cm depth layers in the plot. Samples were collected from the other plots in the same manner. A total of 96 soil core samples were collected for each test period. The soil core samples were brought to the laboratory for parameter assessment.

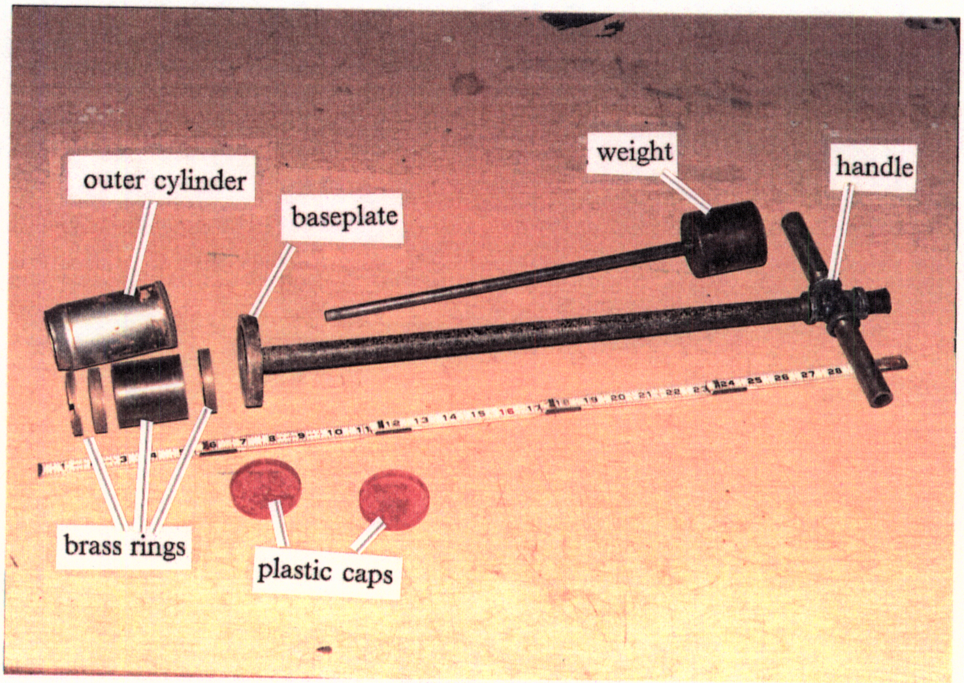


Figure 2. Core Sampler Used to Extract Undisturbed Soil Samples

Using the tension table procedure, it is possible to determine the dry weight and the total pore volume of undisturbed soil samples and to differentiate the volume of capillary pores from the total pore volume of these samples. The tension table removes soil moisture held at lower moisture tensions than that equivalent to a 50-cm water column from saturated samples. The arrangement of components in the tension table setup is schematically presented in Figure 3. First, the plastic caps around the brass rings were removed, and a cap with a small hole at the center was placed over the bottom of each core. The soil samples, which were still in the brass rings, were placed in a tray and the tray was filled with water to cover about 1-cm at the bottom of the soil cores. After 12 hours the water level was brought near the top of the rings without submerging them. After another 12 hour period, more water was added to the tray to submerge the rings, before the soil cores were transferred to the tension table.

Before the saturated soil samples were transferred from the water tray to the tension table, the total length of the plastic tubing and water reservoirs (Figure 3) were filled with water, and the drain valve was closed completely.

The surface of the tension table was then flooded with water. Two layers of plastic mesh similar to that used in window screens were placed in water covering the center area of the tension table. All air bubbles trapped in the mesh were removed. A large filter paper was then laid over the mesh so that the filter paper extended at least 3-4-cm beyond the mesh. Excess moisture was removed from the edges of the tension table top, and the filter paper was then pressed onto the surface. A small roller was pulled radially over the filter paper toward the outer edge to squeeze out the moisture and air bubbles trapped under the filter paper and to form a seal between the table surface and the filter paper. The drain valve was opened completely. The valve between the water reservoirs was adjusted to add water into the lower reservoir at a very slow rate. The elevation of the lower reservoir was adjusted so that the difference in height from the middle of a soil core sample on the table to the water level in the reservoir was 50-cm. The prepared table was left for about 12 hours before the soil core samples were loaded, to check for air leaks into the system.

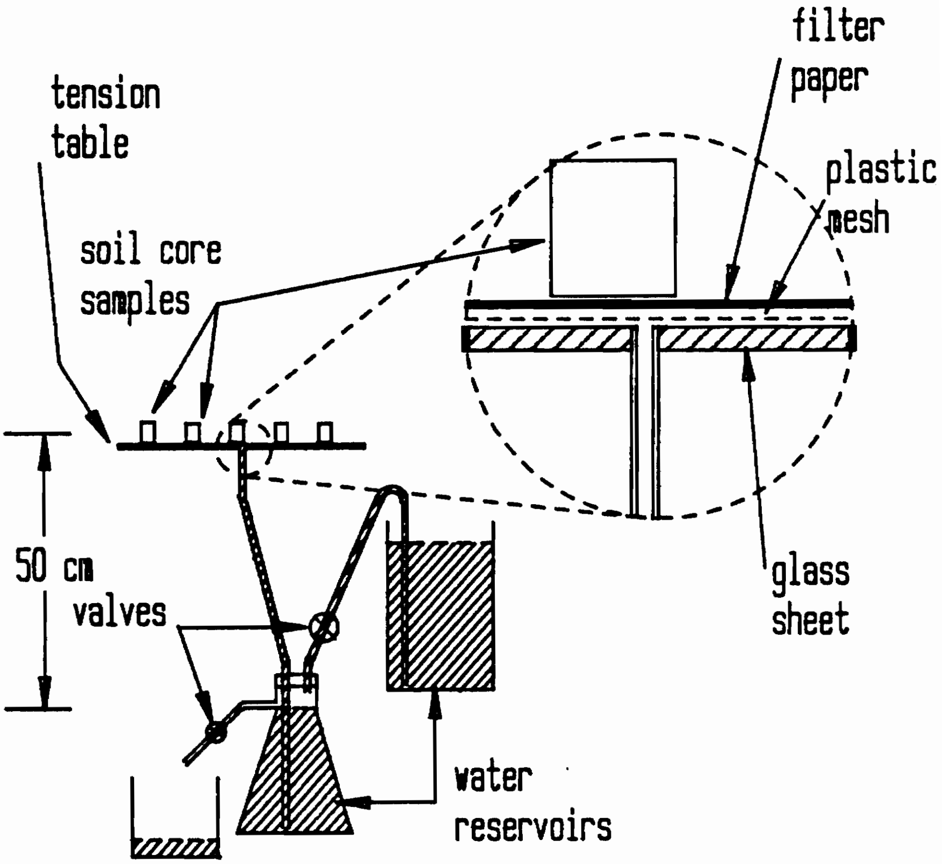


Figure 3. Schematic Diagram of the Tension Table Setup

Each soil core was then kept on the tension table with the cap at the bottom for about 10 minutes. The soil cores were then turned over and the caps were removed. The soil cores were left on the tension table for a 24-hour period to reach equilibrium. The tension table was covered during the equilibrating period to reduce moisture evaporation from the top of the soil cores and to prevent the filter paper from drying. The weight of each soil core at equilibrium was then recorded, the cores were dried at 105 °C for 24 hours, and the dry weight of each soil core was recorded. After the soil was removed from the rings, the weights of the brass rings were also recorded.

Soil bulk density, capillary porosity, noncapillary porosity, and void ratio for each soil core sample were determined using the following equations:

$$\text{Bulk Density (BD)} = \frac{\text{ODW}}{\text{V}} \qquad [3.1]$$

$$\text{Total Porosity (TP)} = \frac{2.65 - \text{BD}}{2.65} \times 100 \qquad [3.2]$$

$$\text{Capillary Porosity (CP)} = \frac{\text{EW} - \text{ODW}}{\text{V}} \times 100 \qquad [3.3]$$

$$\text{Noncapillary Porosity (NCP)} = \text{TP} - \text{CP} \qquad [3.4]$$

$$\text{Void Ratio (VR)} = \frac{2.65}{\text{BD}} - 1 \qquad [3.5]$$

where:

ODW = Wdrd - Wr - Wd = oven dry weight of soil (g),

EW = Werd - Wr - Wd = weight of soil at equilibrium (g),

V = inner volume of the cylinder (132.36 cm^3),

2.65 = average particle density (g/cm^3),

Wr = weight of brass ring,

Wd = weight of drying dish,

Werd = total weight of the soil at equilibrium, the brass ring, and the drying dish,

Wdrd = total weight of the oven-dry soil, the brass ring, and the drying dish, and

V = inner volume of the cylinder (132.36 cm^3).

These data are given in Appendix D.

3.3.2.3 Data Analysis

Soil bulk density, capillary porosity, noncapillary porosity, and void ratio determined from each soil core sample were analyzed statistically using the Analysis of Variance (ANOVA) procedure in the SAS package (SAS, 1985). Data from each layer were analyzed separately for the effects of treatments and test periods on the parameters stated above. The variations in each parameter tested were compared between test periods under each treatment and between treatments within each test period using Duncan's multiple range test. Then, the treatment averages from each depth layer were plotted separately for visual comparisons.

The cone index data from all 15 penetration tests in each vertical section were averaged in 5-cm (2-in.) layers. The average value of moisture contents determined from two soil samples collected from each 5-cm layer was used with the average cone index value in statistical analyses. The general linear models (GLM) procedure in the SAS program package (SAS, 1985) was used to determine the significance of the effects of tillage treatments, test periods, and treatment-test period interactions on the variation of cone index values, considering the moisture content as the covariate.

3.4 Results and Discussion

Soil bulk density, capillary porosity, noncapillary porosity, void ratio, and cone index were analyzed to evaluate the effects of treatments and test periods on the variations in those physical characteristics. However, cone index data from the 1987 cropping season were not included in the analysis because most of the penetration tests conducted in that season were incomplete due to very high soil resistance associated with low moisture conditions. The PR > F values from the analysis of variance tests give the probability of the null hypothesis "H0 = no differences between population variances" being true. The variations in those parameters within each soil layer are discussed separately with the help of observations made on the soil properties and field conditions at the times of sample collections and during various other field operations.

3.4.1 Field Observations

The observations which could be helpful in interpreting the results are as follows:

- The topsoil layer down to 15-20-cm depth contains less clay when compared to the subsoil.
- The subsoil layer below the 25-cm depth contains mainly clay.
- During sample preparation for the tension table procedure, it was observed that the subsoil samples expanded when moistened. The changes in volume were not uniform for all subsoil samples. When these subsoil samples were dried, the samples shrank. The reduction in volume also was not uniform. The topsoil samples did not show changes in volume when moistened or dried.

- According to NOAA (1987), the total rainfall from May through October in 1987 was only 16.65 inches, of which 6.6 inches was received during September. During the month of May, 1987, only 2.09 inches of rain were received; therefore, the soil remained very dry at the time of land preparation.
- Sample collection during the 1987 cropping season (first test period) was performed about three weeks prior to harvesting the corn crop for silage.
- At the time of harvesting in the 1987 season, the soil was moist due to the heavy rainfall received in September.
- During the winter months in 1987-88, very little or no soil cover remained on the surface of the no-till (NT) and conventionally-tilled (CT) plots. Fallow (F) plots had a small surface cover at the end of the 1987 cropping season.
- According to NOAA (1988), the total rainfall during the period from May through October in 1988 was 21.55 inches. Only 1.68 inches of rain was received during May 1988. Therefore, the soil was very dry at the time of land preparation and planting for the 1988 cropping season.
- Due to very low moisture content in the CT plots, the moldboard plow did not penetrate more than 10-12.5-cm (4-5-in.) at the beginning of the 1988 season.
- Due to very high soil strength and poor weed control in the NT plots, the furrow opener of the corn planter could not penetrate far enough into the soil. Many of the corn seeds were left on the surface and were destroyed by birds and ants. Even when the gaps were filled by hand planting, those plants could not compete with weeds; therefore, a poor plant stand in the no-till plots resulted.
- The second sample collection was performed about one month after the corn was planted in the 1988 season.
- At the end of the 1988 cropping season, corn ears were harvested using a pull-type cone picker connected to a small farm tractor. The corn stalks were left on the surface.

- At the time of harvest in the 1988 season, soil was moist due to high rainfall amounts received during the months from July through September.
- The third sample collection was performed about one week after the harvest in the 1988 season.
- The soil surface was completely covered with crop residue in the CT and NT plots, and with dead weeds in the fallow plots during the 1988 winter.
- In mid-December 1988 it was observed that the soil was frozen down to about the 5-cm depth.
- During May and June of 1989, the total monthly rainfall received was 4.4 and 7.08 inches, respectively. Because of this heavy rainfall, the soil was very moist when the land was prepared, and when spraying and corn planting operations were conducted at the beginning of the 1989 cropping season.
- During the land preparation for the 1989 season, the moldboard plow penetrated to a depth about 20-25-cm from the surface due to favorable soil moisture conditions; as a result some clay from the subsoil was brought up to the surface in some of the CT plots.

3.4.2 Results from the Analysis of Core Sample Data

With the help of the above-mentioned observations, the changes in bulk density, noncapillary porosity, capillary porosity, and void ratio for each depth layer are discussed below.

3.4.2.1 Changes Within the 0-7.5-cm Depth Layer

The results of Duncan's multiple range test are summarized in Table 1. The treatment means are presented graphically in Figure 4.

Table 1. Treatment Means and Duncan's Multiple Range Test Results from the 0-7.5-cm Depth Layer

Variable	Treatment	Year			
		1987(1)	1988(1)	1988(2)	1989(1)
Bulk Density	CT	1.25195 b (A)	1.27997 b (A)	1.30611 b (A)	1.42020 a (A)
	F	1.18875 b (A)	1.21878 b (A)	1.33941 a (A)	1.33042 a (A)
	NT	1.19293 b (A)	1.18898 b (A)	1.34834 a (A)	1.40188 a (A)
Noncapillary Porosity	CT	20.713 a (A)	15.642 b (B)	15.147 b (A)	11.899 b (A)
	F	23.561 a (A)	22.702 a (A)	12.823 b (A)	13.097 b (A)
	NT	21.637 a (A)	24.440 a (A)	12.533 b (A)	11.798 b (A)
Capillary Porosity	CT	32.043 b (A)	36.057 a (A)	35.566 a (A)	34.508 ab(B)
	F	31.581 b (A)	31.307 b (B)	36.633 a (A)	36.699 a (A)
	NT	33.347 bc(A)	30.693 c (B)	36.586 a (A)	35.301 ab(AB)
Void Ratio	CT	1.1287 a (A)	1.0769 a (A)	1.0341 a (A)	0.8779 b (A)
	F	1.2349 a (A)	1.1852 a (A)	0.9833 b (A)	1.0005 b (A)
	NT	1.2366 a (A)	1.2417 a (A)	0.9740 b (A)	0.8929 b (A)

Means with the same lower case letter in each row are not significantly different at the $\alpha = 0.05$ level (test periods within each treatment)

Means with the same capital letter within each Year-Variable set are not significant at the $\alpha = 0.05$ level (treatments within each test period)

Numbers in parentheses following the year indicate when the data were collected (1 = after planting; and 2 = after harvest).

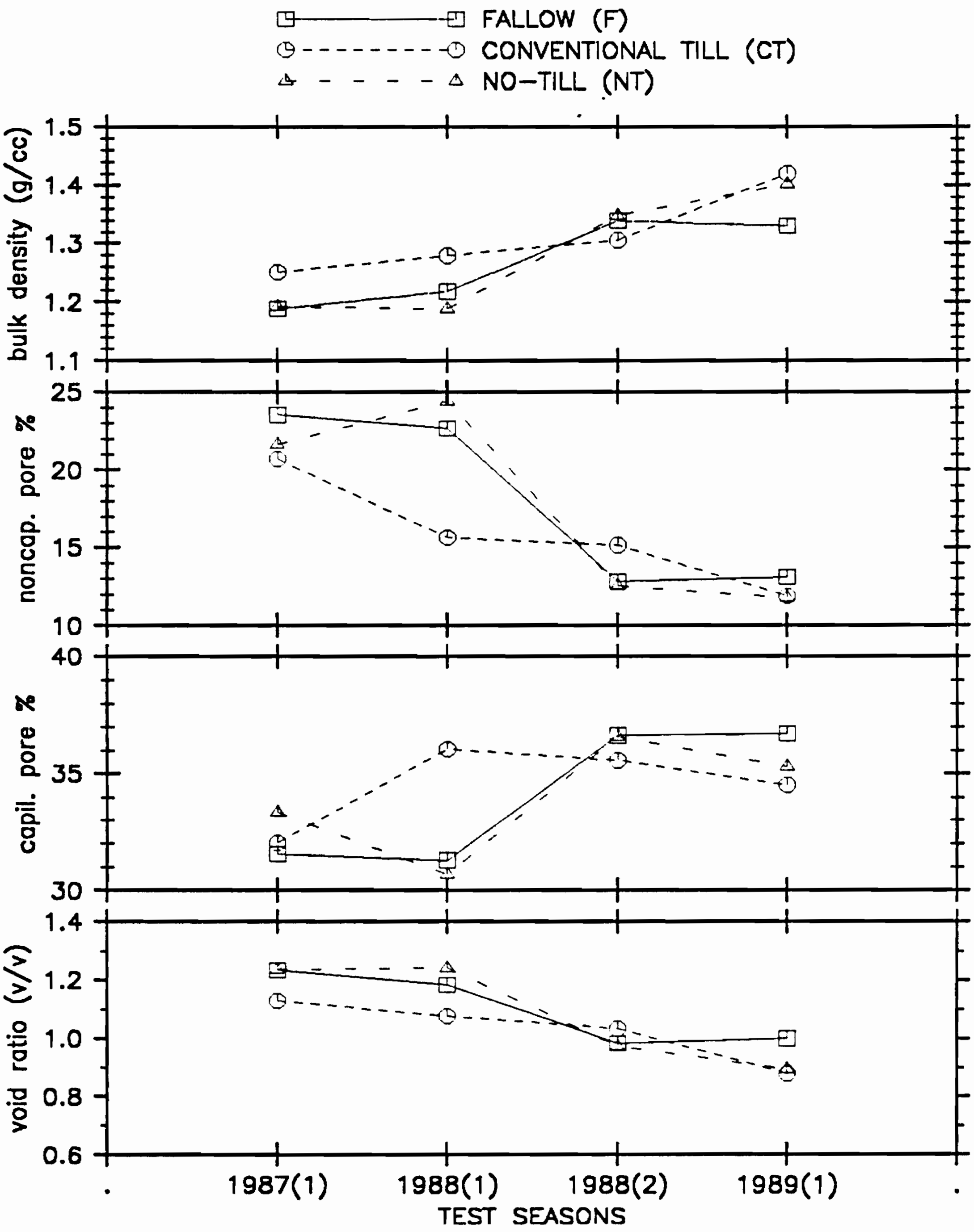


Figure 4. Parameter Changes Within the 0-7.5-cm Depth Layer for the 4 Test Periods

According to the ANOVA test results, tillage treatments had n significant effects on the bulk density variations within each test period. The PR > F values for the treatment effects in chronological order, at close to the end of 1987 cropping season, the beginning of the 1988 cropping season, the end of the 1988 cropping season, and the beginning of the 1989 cropping season, were 0.397, 0.1753, 0.1501, and 0.195, respectively. Duncan's multiple range test showed no significant differences in the treatment averages within test periods. Within each treatment, bulk density varied significantly between test periods. The PR > F values for the effects of test periods for CT, F, and NT treatments were 0.0075, 0.001, and 0.0002, respectively.

As seen in Figure 4 and Table 1, the bulk density of the soil in the surface layer increased significantly in the NT and F plots at the end of 1988 cropping season. Similar changes in the CT plots occurred only at the beginning of the 1989 cropping season.

Within the period from the end of the 1987 cropping season to the beginning of the 1988 cropping season, average bulk density in CT and F plots increased by equal amounts while those in NT plots remained unchanged. Within the 1988 cropping season, average bulk density increased in all treatments at different rates. The rates of increase in average bulk density during this period was on the order NT > F > CT. Lower moisture conditions in CT plots could have reduced the soil compaction in those plots. From the end of 1988 to the beginning of the 1989 cropping season, F plots indicated no change in average bulk density. NT and CT plots showed similar average bulk densities at the beginning of the 1989 cropping season. However, the change in bulk density within CT plots was greater than that in NT plots.

The very dry soil conditions during 1987 and the first part of the 1988 cropping season could have delayed changes in soil structure. Land preparation under dry soil conditions for the 1987 cropping season could have left large soil clods in the soil. These soil clods may not have collapsed during the growing season due to low soil moisture conditions. Even though the soil moisture content was a little higher at the beginning of the 1988 cropping season, it was still considered to be dry. This improved moisture condition did not help to crush the soil clods in CT plots when they were rotary-tilled at the beginning of the 1988 cropping season. Therefore, the average bulk density in CT plots remained unchanged. The low moisture levels in NT plots prevented soil compaction from vehicular traffic during crop harvesting in the 1987 cropping season and during the spraying and planting operations in the 1988 cropping season. The high soil moisture contents at the end of the 1988 cropping season helped soil compaction during harvesting operations. Since the degree of soil compaction due to a given load is influenced by the soil moisture content, these different rates of increase in dry bulk density can be explained by the soil moisture status at the time of harvest.

Even though soil moisture data at the time of harvest were not collected, soil moisture data collected after harvest in the 1988 cropping season showed that CT plots had lower soil moisture contents compared to NT and F plots. These lower moisture contents could have reduced the amount of compaction under a given traffic condition. Therefore, the increase in bulk density in CT plots was small compared to NT and F plots. On the other hand, higher amounts of moisture in NT plots would have increased the vulnerability of the soil to compaction under similar traffic conditions. Therefore, the NT plots were probably compacted more during the harvesting operation. Even though the operator had special instructions not to travel over the F plots, some F plots were traversed during harvesting due to maneuvering difficulties. Therefore, fallow plots indicated soil compaction similar to NT plots.

Between the last two test periods there was no traffic through the F plots. Therefore, any soil compaction which occurred in F plots should have been due to natural consolidation. The reduction in average bulk density could be due to either the loosening effect of the freeze/thaw and drying/wetting cycles, and/or creation of void spaces by dead roots and by soil fauna (earthworms), which overcame the natural consolidation.

Large increases in average bulk density were observed in CT plots as compared to the NT plots at the beginning of the 1989 cropping season. Most of the moisture from rainfall before and after plowing could have been collected in the topsoil layer of CT plots because of a lack of transmission pore spaces to carry moisture to the subsoil, and this retained moisture could have kept the moisture content of the topsoil layer of CT plots close to the optimum moisture content for maximum compaction during spraying and planting operations. Even if land preparation on wet soil increased the noncapillary porosity, subsequent traffic during spraying and planting operations could have severely compacted the soil at the high moisture levels. Therefore, the average bulk density in CT plots after planting in the 1989 cropping season could have surpassed the density level at the end of previous season.

The topsoil layer of NT plots could have been loosened by the effects of freeze/thaw and drying/wetting cycles during the winter months following the 1988 cropping season. On the other hand, soil in NT plots could have had a higher strength as a result of being undisturbed for two years, which would have increased the bonding between soil particles. Since the NT plots also had a higher average bulk density at the end of the previous cropping season, additional compaction due to traffic at planting should have been small. Therefore, the topsoil layer in NT plots could have been compacted less compared to CT plots under similar traffic conditions at planting in the 1989 season. These different levels of compaction left the average bulk densities of both CT and NT treatments equal at the end of planting in 1989 season.

Noncapillary porosity showed significant differences between treatments only at the beginning of 1988 cropping season. The PR > F values for treatment effects over four test periods, taken chronologically, were 0.5512, 0.0054, 0.2162 and 0.7514, respectively. Noncapillary porosity significantly varied between test periods within each treatment. The PR > F values for the effects of test periods were 0.0121, 0.0001, and 0.0001, for CT, F, and NT treatments, respectively. As shown in Figure 4 and Table 1, noncapillary porosity showed a reduction that occurred in steps and at different rates throughout the experiment. Average noncapillary porosity in the top layer was in the range of 20 to 25% at the end of the 1987 cropping season. The F plots contained the highest value, while NT and CT plots had similar values. At the beginning of the 1988 cropping season, noncapillary porosity in CT plots reduced significantly, while F plots showed a small reduction and NT plots indicated an increase. The reduction in noncapillary porosity in CT plots at the beginning of the 1988 cropping season could have been caused by tillage, spraying, and planting operations under improved soil moisture conditions. Reduction in noncapillary porosity in NT and F plots occurred only at the end of the 1988 cropping season when it decreased below the level in the CT plots. This reduction in noncapillary porosity was caused by vehicular traffic during harvesting operations. During the time between the end of the 1988 season and the beginning of the 1989 season, F plots indicated a minute increase in noncapillary porosity due to the loosening effects of freeze/thaw and drying/wetting cycles during the winter months. Noncapillary porosity in CT plots were reduced by the field operations, at high moisture conditions, to the level of NT plots at the beginning of the 1989 cropping season.

Capillary porosity in the top layer significantly varied between treatments at the beginning of each cropping season, and the differences diminished by the end of the cropping season. The PR > F values for the treatment effects for the four test periods were 0.3613, 0.021, 0.3948, and 0.0365, respectively. Capillary porosity in each treatment varied significantly between test periods. The PR > F values for the effect of test periods were 0.042, 0.0002, and 0.0012, respectively.

As seen in Figure 4 and Table 1, capillary porosity was at a minimum at the end of the 1987 cropping season in CT and F plots, but increased significantly in the 1988 cropping season within CT plots, while NT plots show a reduction larger than the reduction in F plots. Within the 1988 season, capillary porosity in F and NT plots increased significantly, but only a small amount in CT plots. At the end of the 1988 cropping season, F and NT plots had equal capillary porosity values, which were higher than in CT plots. From the end of the 1988 season to the beginning of the 1989 season, F plots retained their capillary porosity while NT and CT plots showed a small reduction. These large increases in capillary porosity along with the decreasing noncapillary porosity values reflected the soil compaction caused by tillage and traffic in the plots. Small reductions in capillary porosity along with decreasing noncapillary porosity values show soil compaction from the natural overburden.

The increases in void ratio indicate soil loosening, while the reductions indicate soil compaction. Tillage treatments had no significant effects on the void ratio in the top layer. The $PR > F$ values for the treatment effects on void ratio for the four test periods were 0.3977, 0.194, 0.4737, and 0.2345, respectively. Within each treatment, void ratio showed significant variations between the test periods. The $PR > F$ values for the effects of test periods for CT, F, and NT treatments were 0.015, 0.0013, and 0.0004, respectively. According to Duncan's test results, treatment means within each test period were not significantly different. The same test on treatment means between test periods revealed that the reduction in void ratio in CT plots was significant only at the beginning of the 1989 cropping season whereas significant changes in void ratio in F and NT treatments occurred only at the end of the 1988 cropping season.

3.4.2.2 Changes Within the 12.5-20-cm Depth Layer

Results from the Duncan's multiple range tests and the treatment means of bulk density, capillary porosity, noncapillary porosity, and void ratio data collected from core samples from 12.5-20-cm depth layer are summarized in Table 2 and presented graphically in Figure 5.

Soil bulk density in this layer showed significant differences between tillage treatments only at the beginning of 1988 cropping season. The $PR > F$ values for treatment effects were 0.8862, 0.0293, 0.68, and 0.5714, respectively, for the four test periods taken chronologically. Significant differences

Table 2. Treatment Means and Duncan's Multiple Range Test Results from the 12.5-20-cm Depth Layer

Variable	Treatment	Year			
		1987(1)	1988(1)	1988(2)	1989(1)
Bulk Density	CT	1.43643 a (A)	1.45234 a (A)	1.47213 a (A)	1.46085 a (A)
	F	1.4171 a (A)	1.3111 b (B)	1.4411 a (A)	1.4349 a (A)
	NT	1.44392 a (A)	1.43239 a (A)	1.47327 a (A)	1.40562 a (A)
Noncapillary Porosity	CT	13.969 a (A)	13.822 a (B)	12.414 a (A)	12.377 a (A)
	F	14.794 b (A)	19.729 a (A)	12.218 b (A)	13.517 b (A)
	NT	13.469 ab(A)	15.529 a (AB)	10.463 b (A)	13.866 ab(A)
Capillary Porosity	CT	31.8261 a (A)	31.3728 a (A)	32.0338 a (A)	32.4966 a (A)
	F	31.7316 ab(A)	30.7967 b (A)	33.4032 a (A)	32.3361 ab(A)
	NT	32.043 ab(A)	30.419 b (A)	33.942 a (A)	33.092 ab(A)
Void Ratio	CT	0.8659 a (A)	0.8353 a (B)	0.8088 a (A)	0.8279 a (A)
	F	0.893 b (A)	1.03728 a (A)	0.8453 b (A)	0.8598 b (A)
	NT	0.8398 a (A)	0.8524 a (B)	0.8159 a (A)	0.8944 a (A)

Means with the same lower case letter in each row are not significantly different at the $\alpha = 0.05$ level (test periods within each treatment)

Means with the same capital letter within each Year-Variable set are not significant at the $\alpha = 0.05$ level (treatments within each test period)

Numbers in parentheses following the year indicate when the data were collected (1 = after planting; and 2 = after harvest).

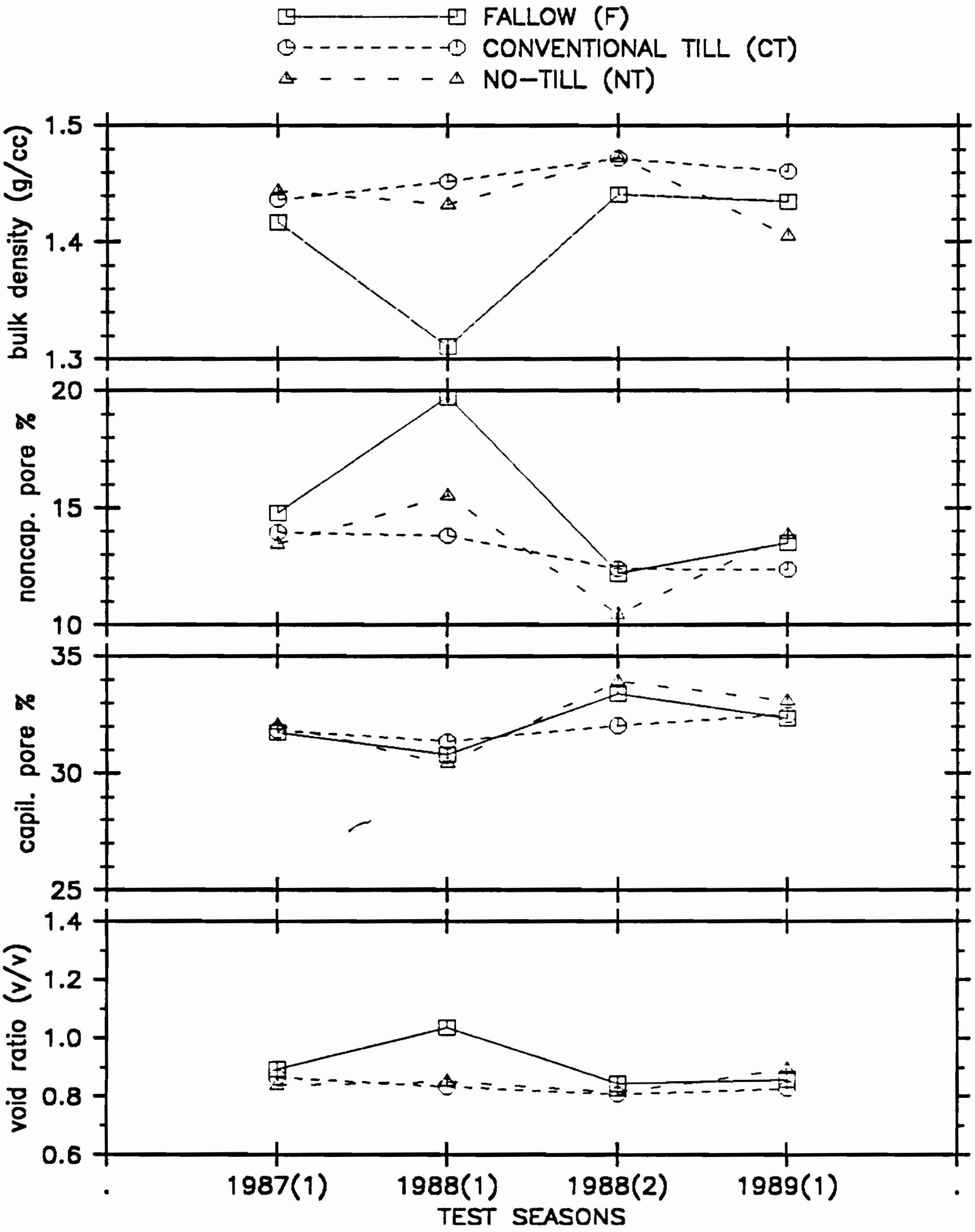


Figure 5. Parameter Changes Within the 12.5-20-cm Depth Layer for the 4 Test Periods

in bulk density between test periods were found only in F plots. The PR > F values for the effects of test periods were 0.9273, 0.0126, and 0.6018, respectively, for CT, F, and NT treatments. Duncan's multiple range tests concluded that the average bulk density of F plots at the beginning of the 1988 cropping season was significantly lower compared to other tillage treatments and test periods (Table 2). Figure 5 also shows lower bulk density values for F plots at the beginning of the 1988 cropping season. This large reduction in bulk density in the F plots could have been caused by decaying plant residue buried during land preparation at the beginning of 1987 cropping season. NT plots also showed a small reduction in bulk density at the beginning of the 1988 cropping season. Reduction in soil bulk density in NT plots due to decay of plant residue had been reduced by the soil compaction by vehicular traffic during spraying and planting operations. The greater reduction in bulk density in NT plots at the beginning of the 1989 cropping season could be due to the loosening effect of drying/wetting cycles. Soil compaction below the plowing depth may have cancelled this loosening effect in CT plots.

Variations in noncapillary porosity between tillage treatments were not significant. The PR > F values were 0.8561, 0.0879, 0.436, and 0.7426, respectively, for the treatment effects in the four test periods. Noncapillary porosity varied significantly between test periods within the F plots only. The PR > F values for the effects of test periods were 0.783, 0.0024, and 0.1616, respectively, for the CT, F, and NT treatments. However, according to Duncan's multiple range test, NT and F plots had significant variations in noncapillary porosity in this layer. The significant increases in noncapillary porosity in NT and F plots at the beginning of each season from the levels at the end of previous season could be due to dead roots, earthworm activity, and the effect of drying/wetting cycles. The large reduction in this parameter in the NT and F plots, at the end of the 1988 season could be due to soil compaction caused by the use of heavy equipment for harvesting. The soil moisture content in NT and F plots at harvest time may have been greater than that in CT plots and would have caused more soil compaction in the NT and F plots. The reduction in noncapillary porosity in F plots could have resulted from vehicular traffic through these plots at harvest, as explained earlier. The recovery of noncapillary porosity in NT and F plots, at the beginning of the 1989 season, could be due to the effect of drying/wetting cycles, dead roots, and earthworm activity.

The ANOVA tests concluded that the tillage treatments had no significant effects on capillary porosity. The PR > F values for treatment effects were 0.9324, 0.7531, 0.1918, and 0.6079, respectively, in the four test periods, taken chronologically. Differences in capillary porosity data were significant only in the F plots. The PR > F values for the effects of test periods were 0.4359, 0.0248, and 0.0544 for the test periods for CT, F, and NT plots, respectively. From Duncan's multiple range test, capillary porosity in CT plots at this depth showed no significant differences for the duration of this study, even though F and NT plots showed significant variations between test periods. At the end of the 1987 season, all three treatments had equal values of capillary porosity. The reductions in capillary porosity between the 1987 and 1988 seasons were in the order CT < F < NT. When the CT plots were plowed, the moldboard plow did not penetrate into this layer during the 1988 season because the soil was dry. Therefore, it is assumed that the loosening effect of drying/wetting cycles had been overcome by natural consolidation and the small compactive effect of traffic and tillage. The gradual increase in capillary porosity in CT plots from the beginning of the 1988 season could be due to high soil strength combined with lower moisture levels at this depth along with the absorption of compactive energy by the loose soil layers above this depth. The significant increase in capillary porosity in F and NT plots at the end of the 1988 season could be due to traffic at higher soil moisture levels. The reduction in capillary porosity at the beginning of 1989 season could be due to the loosening effect of drying/wetting cycles.

Treatments showed significant differences in void ratio only at the beginning of the 1988 cropping season. The PR > F values for treatment effects were 0.8128, 0.0253, 0.436, and 0.6364 for the four test periods, respectively. The PR > F values for the effects of test periods were 0.8917, 0.0262, and 0.6931 in CT, F, and NT treatments, respectively. Duncan's multiple range test also indicated seasonal differences in the void ratio in the F plots. The differences in void ratio between tillage treatments were significant only at the beginning of the 1988 cropping season (Table 2).

3.4.2.3 Changes Within the 25-32.5-cm Depth Layer

Results of Duncan's multiple range test on the measured variables are summarized in Table 3. The graphical presentation of test means is given in Figure 6.

The analysis of variance test on bulk density indicated insignificant treatment effects in all test periods. The PR > F values for treatment effects were 0.4413, 0.6046, 0.3936, and 0.5883, respectively, for the four test periods. The effects of test periods within each treatment also was insignificant. The PR > F values for seasonal effects on bulk density were 0.1856, 0.9713, and 0.208 for CT, F, and NT treatments, respectively. Duncan's test results also showed no significant differences within treatments or within test periods. Since the moldboard plow did not penetrate into this layer, the lack of significant effects from tillage treatments on bulk density was expected. Since this layer is 25-cm below the surface, the influence of traffic was minimal. The fluctuations in soil bulk density in this layer, between beginnings and ends of cropping seasons, should relate to the fluctuating moisture levels.

Treatments significantly affected noncapillary porosity values only at the beginning of the 1989 cropping season. The PR > F values for treatments were 0.2679, 0.5634, 0.2239, and 0.0081 for the four test periods, respectively. The effects of test periods were significant only in F and NT treatments. The PR > F values for test periods were 0.0529, 0.0386, and 0.0276 for CT, F, and NT treatments, respectively. According to Duncan's test, the lower values of noncapillary porosity occurred at the end of each cropping season in all the treatments. The high noncapillary porosity

Table 3. Treatment Means and Duncan's Multiple Range Test Results from the 25-32.5-cm Depth Layer

Variable	Treatment	Year			
		1987(1)	1988(1)	1988(2)	1989(1)
Bulk Density	CT	1.61049 a (A)	1.54020 a (A)	1.59421 a (A)	1.56631 a (A)
	F	1.57002 a (A)	1.57287 a (A)	1.58039 a (A)	1.58220 a (A)
	NT	1.56807 a (A)	1.57581 a (A)	1.62265 a (A)	1.55749 a (A)
Noncapillary Porosity	CT	6.806 b (A)	10.157 a (A)	6.447 b (A)	7.689 ab(B)
	F	7.247 b (A)	12.541 a (A)	8.178 b (A)	9.214 ab(AB)
	NT	8.934 ab(A)	10.957 a (A)	7.405 b (A)	10.732 a (A)
Capillary Porosity	CT	32.421 a (A)	31.722 a (A)	33.394 a (A)	33.205 a (A)
	F	33.507 a (A)	28.105 b (A)	32.185 ab(A)	31.080 ab(AB)
	NT	31.894 a (A)	29.578 b (A)	31.363 ab(A)	30.494 ab(B)
Void Ratio	CT	0.6509 a (A)	0.7246 a (A)	0.6657 a (A)	0.6986 a (A)
	F	0.6909 a (A)	0.6904 a (A)	0.6818 a (A)	0.6774 a (A)
	NT	0.6932 a (A)	0.6854 a (A)	0.6385 a (A)	0.7052 a (A)

Means with the same lower case letter in each row are not significantly different at the $\alpha = 0.05$ level (test periods within each treatment)

Means with the same capital letter within each Year-Variable set are not significant at the $\alpha = 0.05$ level (treatments within each test period)

Numbers in parentheses following the year indicate when the data were collected (1 = after planting; and 2 = after harvest).

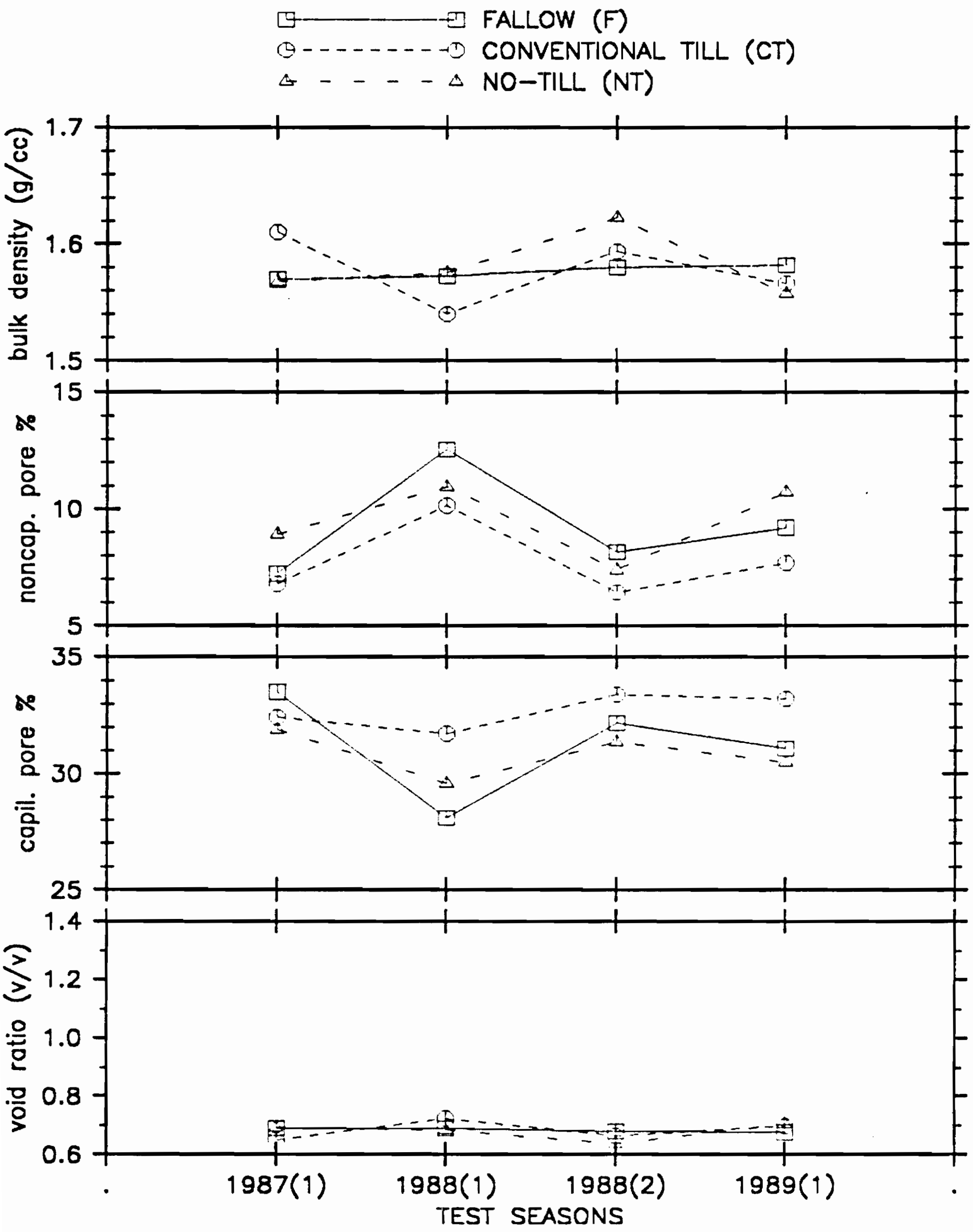


Figure 6. Parameter Changes Within the 25-32.5-cm Depth Layer for the 4 Test Periods

values were found at the beginning of each season. At the beginning of 1989 cropping season, NT plots had the highest values while CT plots had the lowest values for noncapillary porosity.

Variations in capillary porosity had no significant effects from treatments for all test periods. The PR > F values were 0.4954, 0.2967, 0.2247, and 0.0837 for treatments in the four test periods, respectively. Test periods had no significant effects on capillary in any treatment. The PR > F values were 0.4143, 0.0839, and 0.0991 for the test periods in CT, F, and NT treatments, respectively. According to Duncan's multiple range test, F and NT plots contained significantly different capillary porosity values between test periods. Significantly different capillary porosity values between treatments were observed only at the beginning of the 1989 season. The capillary porosity in F and NT plots were reduced from the highest values in the 1987 season to the lowest levels at the beginning of the 1988 season. Then the capillary porosities increased to intermediate values at the end of that season and remained at those levels until the 1989 season.

The void ratio data were not significantly affected by treatments in all seasons. The PR > F values were 0.4663, 0.5995, 0.4347, and 0.5708 for the treatments, respectively, in the four test periods. The variations in void ratio were not significantly affected by test periods within treatments. The PR > F values were 0.1774, 0.9669, and 0.2333 for test periods, respectively, for CT, F, and NT treatments. Duncan's test results of treatment means showed no significant differences between test periods and between treatments.

Because the plow did not penetrate into this layer, differences in the measured parameters could not have resulted from soil loosening by tillage. Since a small farm tractor was used for all field operations, the compactive effect of traffic at this depth was very small. The penetration resistance data indicate the presence of a plowpan at this depth. Due to higher initial bulk density in this layer, additional soil compaction by natural consolidation and vehicular traffic is assumed to be very small.

The soil core samples indicated the presence of high amounts of clay in the soil at this depth. Because this clay expands and contracts when moistened and dried, respectively, as observed during core sample analysis, the changes in these parameters must be due to fluctuations in soil moisture contents between test periods.

Generally, clay soils contain more charged particles. When the soil is wet, the distance between these charged particles increases as the gaps fill with water. Due to the increase in volume occupied by a unit mass of clay, the bulk density of the soil decreases. When the moisture is removed from the soil, these gaps between particles reduce and an increase in soil bulk density results. In the field, when soil moisture content is reduced by small amounts, cracks may develop between soil aggregates due to the volume changes in individual aggregates. The development of these cracks is represented by increased noncapillary porosity. The changes in total volume occupied by the soil mass will not be visible until these cracks develop to a certain limit, at which point the soil structure collapses, causing an increase in soil bulk density and a reduction in noncapillary porosity. When the moisture content is increased to the initial level, total soil volume is also increased to the initial level. Using the above theory, the changes in the measured parameters can be explained.

Because of the high weed population and more roots penetrating into this layer, NT and F plots probably lost more moisture from this layer through evapo-transpiration. The CT plots could have retained more moisture in this layer due to better weed control through tillage operations. This higher moisture level may have caused the lower bulk density observed in CT plots at the beginning of the 1988 season. The NT plots were full of weeds during the 1988 cropping season due to poor weed control. This high plant population in NT plots could have resulted in a higher moisture loss and therefore a structural collapse in these plots compared to other plots. Most of the weeds in F plots were dead at the time of data collection after harvest in the 1988 season. Therefore, F plots could have maintained the moisture level by allowing more moisture from the rainfall to reach this depth at the end of the 1988 season; the increased moisture could have caused the soil bulk density to be equal to that at the beginning of the season.

At the last sample collection, the average bulk density of all treatments came closer. Heavy rain had supplied enough moisture to eliminate the moisture deficiency in this layer. The CT plots had the lowest noncapillary porosity and the highest capillary porosity while the NT plots had the highest noncapillary porosity and the lowest capillary porosity at this time.

3.4.2.4 Changes Within the 37.5-45-cm Depth Layer

Sample means and the Duncan's multiple range test results on the variables determined from core samples are summarized in Table 4. These results are also presented graphically in Figure 7.

Variations in bulk density in this layer was significantly affected by treatments only at the beginning of 1988 cropping season. The PR > F values for treatments were 0.3176, 0.0148, 0.3552, and 0.5315, respectively, for the four test periods. The effects of test periods on bulk density were not significant. The PR > F values for test periods 0.1563, 0.3083, and 0.0811 in CT, F, and NT treatments, respectively. Even though Duncan's multiple range test found significant differences between test periods only in the CT plots and between treatments at the beginning of 1988 season, this layer was not disturbed tillage. The weight of the small tractor could not have caused soil compaction at this depth. Therefore, it was assumed that these bulk density variations were due to fluctuations in moisture contents in this layer.

The treatment effects on the noncapillary porosity were not significant. The PR > F values were 0.4549, 0.3159, 0.2738, and 0.1989 for treatment effects, respectively, for the four test periods. The effects of test periods on noncapillary porosity were also not significant. The PR > F values were

Table 4. Treatment Means and Duncan's Multiple Range Test Results from the 37.5-45-cm Depth Layer.

Variable	Treatment	Year			
		1987(1)	1988(1)	1988(2)	1989(1)
Bulk Density	CT	1.49815 ab(A)	1.47569 ab(B)	1.45279 b (A)	1.52361 a (A)
	F	1.42006 a (A)	1.45028 a (B)	1.48256 a (A)	1.50098 a (A)
	NT	1.48717 a (A)	1.55626 a (A)	1.49738 a (A)	1.55304 a (A)
Noncapillary Porosity	CT	6.191 ab(A)	8.521 a (A)	5.381 ab(A)	4.739 b (A)
	F	6.182 a (A)	10.339 a (A)	4.758 a (A)	10.116 a (A)
	NT	8.116 a (A)	8.635 a (A)	6.579 a (A)	7.142 a (A)
Capillary Porosity	CT	37.275 ab(A)	35.793 b (A)	39.797 a (A)	37.766 ab(A)
	F	40.231 a (A)	34.933 ab(A)	39.296 a (A)	33.243 b (A)
	NT	35.764 ab(A)	32.638 b (A)	36.916 a (A)	34.253 ab(A)
Void Ratio	CT	0.7953 a (A)	0.809 a (A)	0.8369 a (A)	0.7593 a (A)
	F	0.882 a (A)	0.834 a (A)	0.7987 a (A)	0.7744 a (A)
	NT	0.7878 a (A)	0.7063 a (B)	0.7751 a (A)	0.7142 a (A)

Means with the same lower case letter in each row are not significantly different at the $\alpha = 0.05$ level (test periods within each treatment)

Means with the same capital letter within each Year-Variable set are not significant at the $\alpha = 0.05$ level (treatments within each test period)

Numbers in parentheses following the year indicate when the data were collected (1 = after planting; and 2 = after harvest).

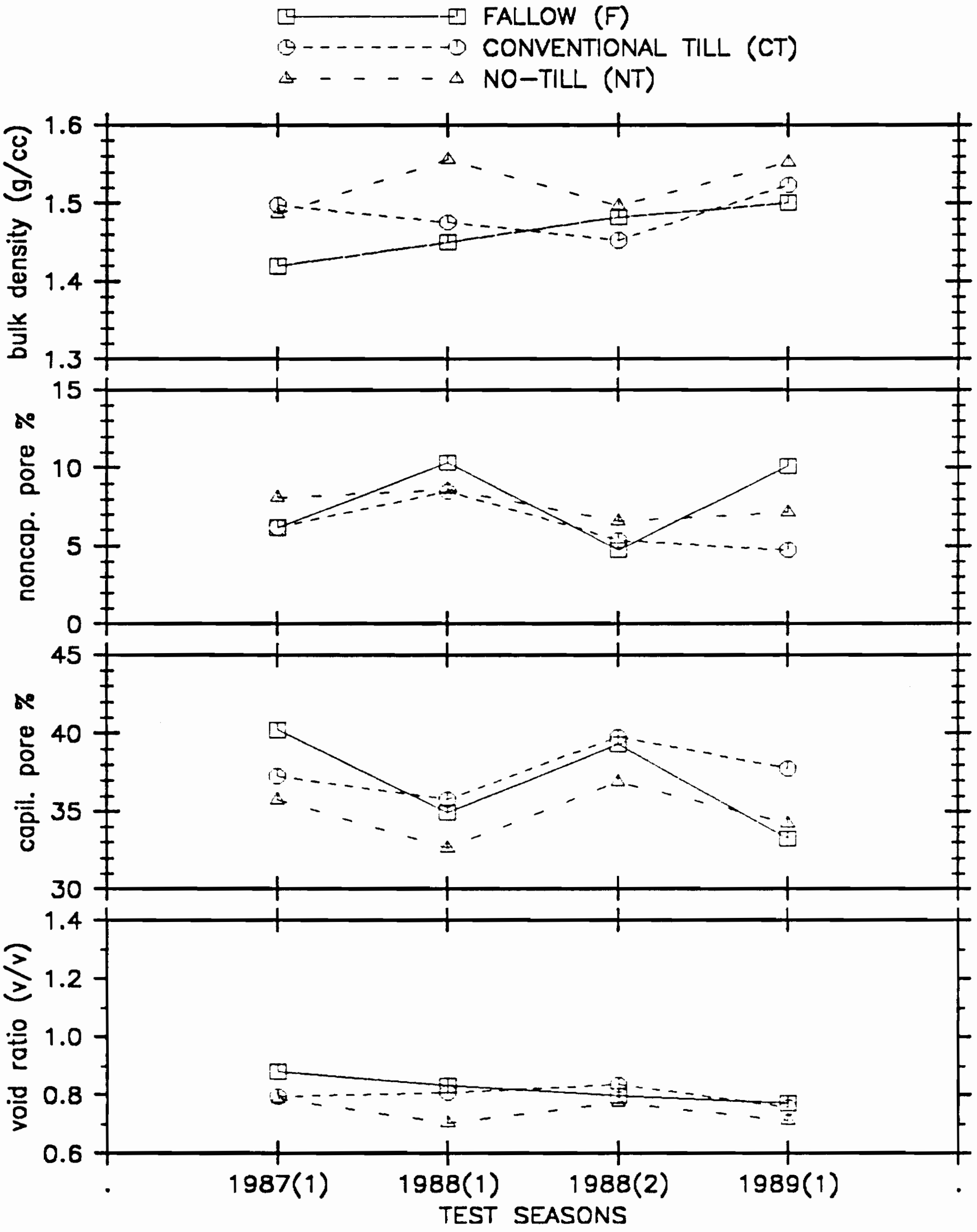


Figure 7. Parameter Changes Within the 37.5–45-cm Depth Layer for the 4 Test Periods

0.1312, 0.0921, and 0.3354 for test periods, respectively, for CT, F, and NT treatments. However, Duncan's multiple range test indicated significant seasonal differences between noncapillary porosity values only in CT plots.

Treatment effects on capillary porosity were not significant for all test periods. The PR > F values were 0.1323, 0.1912, 0.2004, and 0.223 for treatments, respectively, for the four test periods. The effect of test periods on capillary porosity was significant only in the F treatment. The PR > F values were 0.1152, 0.028, and 0.138 for test periods, in CT, F, and NT treatments, respectively. Duncan's multiple range test indicated significant differences between test periods in all treatments and insignificant differences between treatments in all test periods.

Void ratio was significantly affected by the treatments only at the beginning of the 1988 cropping season. The PR > F values were 0.2952, 0.0196, 0.2471, and 0.4569 for treatments, respectively, for the four test periods. The effects of test periods on void ratio were not significant. The PR > F values were 0.2504, 0.2759, and 0.0845 for seasonal effects, respectively, for CT, F, and NT treatments. Duncan's multiple range test found significantly different void ratios between treatments only at the beginning of the 1988 season.

Based on results of ANOVA tests and Duncan's multiple range tests on the different soil parameters presented above, significant differences exist between and within some test periods. Since a small farm tractor was used for the field operations and most of the significant differences between treatments occurred during dry seasons, these differences could not have been caused by vehicular traffic. Therefore, it is suspected that these differences were caused by differences in moisture contents in the soil, as previously explained.

Although this layer in F plots shows fluctuations in noncapillary porosity and in capillary porosity similar to those in the above layer, data on both parameters during the last two test periods were lower than for those in first two test periods. Therefore, the gradual increase in the average bulk density in this layer was probably due to the process of natural consolidation. However, the high noncapillary porosity and low capillary porosity of F plots, at the beginning of the 1989 season, showed that the moisture content in this layer had not been increased by the heavy rainfall received prior to data collection in that season, caused either by heavy loss of moisture through evapo-transpiration due to thick weed cover or by storing the moisture by the upper layers.

3.4.3 Cone Index Data

As described earlier, the cone index data were averaged in 5-cm layers down to the 25-cm depth for each vertical section. The average cone index values in each tillage treatment increased with depth. Using the F statistics and the null hypothesis: "there is no significant effect of the parameter/interaction on cone index", the average cone index values in each 5-cm layer were tested for the effects of tillage treatments, test periods, and the treatment-by-season interaction on the variation of cone index data. The probability of the null hypothesis being true is indicated by the PR > F value. The results are summarized in Table 5. According to these results, the effect of tillage treatment on cone index was significant only within the top 5-cm layer.

Then, the cone index means adjusted for moisture contents (least squares means) were compared between tillage treatments using t tests. Results indicated that at the beginning of the 1988 cropping season, F plots had significantly high cone index values within all layers, as given in Tables 6 through 10. But, moisture data presented in Table 11, shows that the F plots had the lowest moisture contents within all depth layers. Thus the higher cone index values are associated with low moisture contents in all depth layers. Average soil moisture contents in each layer significantly varied between treatments and test periods. In future research, if the effects of treatments on the

Table 5. Summary of Statistical Tests on Cone Index Data

Parameter	PR > F				
	0-5-cm	5-10-cm	10-15-cm	15-20-cm	20-25-cm
Tillage Treatment	0.0002	0.3383	0.6202	0.2180	0.0923
Test Season	0.0025	0.0001	0.0001	0.0001	0.0001
Treatment * Season	0.0001	0.0001	0.0164	0.0001	0.0001

Table 6. Statistical Test Results on Cone Index Data from the 0-5-cm Layer

TREATMENT	CONE INDEX LSMEAN	PROB > |T| H0: LSMEAN(I)=LSMEAN(J) I/J	1	2	3
CT	714.530354	1	.	0.0001	0.1597
F	825.269123	2	0.0001	.	0.0267
NT	757.251967	3	0.1597	0.0267	.

TEST PERIOD	CONE INDEX LSMEAN	PROB > |T| H0: LSMEAN(I)=LSMEAN(J) I/J	1	2	3
1988(1)	935.135525	1	.	0.0006	0.0015
1988(2)	656.670488	2	0.0006	.	0.0792
1989(1)	705.245432	3	0.0015	0.0792	.

TEST PERIOD	TRT	CONE INDEX LSMEAN	LSMEAN NUMBER
1988(1)	CT	651.07478	1
1988(1)	F	1199.19264	2
1988(1)	NT	955.13916	3
1988(2)	CT	647.44882	4
1988(2)	F	642.63741	5
1988(2)	NT	679.92523	6
1989(1)	CT	845.06746	7
1989(1)	F	633.97732	8
1989(1)	NT	636.69151	9

PROB > |T| H0: LSMEAN(I) = LSMEAN(J)

I/J	1	2	3	4	5	6	7	8	9
1	.	0.0001	0.0001	0.9613	0.9140	0.7026	0.0002	0.8113	0.8713
2	0.0001	.	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
3	0.0001	0.0001	.	0.0001	0.0002	0.0008	0.0475	0.0001	0.0009
4	0.9613	0.0001	0.0001	.	0.9158	0.4740	0.0006	0.7671	0.8242
5	0.9140	0.0001	0.0002	0.9158	.	0.4121	0.0008	0.8508	0.8995
6	0.7026	0.0001	0.0008	0.4740	0.4121	.	0.0043	0.3141	0.3686
7	0.0002	0.0001	0.0475	0.0006	0.0008	0.0043	.	0.0001	0.0025
8	0.8113	0.0001	0.0001	0.7671	0.8508	0.3141	0.0001	.	0.9566
9	0.8713	0.0001	0.0009	0.8242	0.8995	0.3686	0.0025	0.9566	.

Table 7. Statistical Test Results on Cone Index Data from the 5-10-cm Layer

TREATMENT	CONE INDEX LSMEAN	PROB > |T| H0: LSMEAN(I) = LSMEAN(J)			
		I/J	1	2	3
CT	1270.19620	1	.	0.1426	0.7422
F	1361.81715	2	0.1426	.	0.3090
NT	1289.17744	3	0.7422	0.3090	.

TEST PERIOD	CONE INDEX LSMEAN	PROB > |T| H0: LSMEAN(I) = LSMEAN(J)			
		I/J	1	2	3
1988(1)	1724.78484	1	.	0.0001	0.0001
1988(2)	1071.40681	2	0.0001	.	0.3469
1989(1)	1124.99914	3	0.0001	0.3469	.

TEST PERIOD	TRT	CONE INDEX LSMEAN	LSMEAN NUMBER
1988(1)	CT	1497.93055	1
1988(1)	F	2064.52915	2
1988(1)	NT	1611.89483	3
1988(2)	CT	1068.38909	4
1988(2)	F	1038.00212	5
1988(2)	NT	1107.82923	6
1989(1)	CT	1244.26897	7
1989(1)	F	982.92019	8
1989(1)	NT	1147.80827	9

PROB > |T| H0: LSMEAN(I) = LSMEAN(J)

I/J	1	2	3	4	5	6	7	8	9
1	.	0.0002	0.2592	0.0012	0.0007	0.0042	0.0177	0.0001	0.0242
2	0.0002	.	0.0005	0.0001	0.0001	0.0001	0.0001	0.0001	0.0004
3	0.2592	0.0005	.	0.0005	0.0003	0.0017	0.0031	0.0001	0.0105
4	0.0012	0.0001	0.0005	.	0.7514	0.6812	0.0963	0.3816	0.4313
5	0.0007	0.0001	0.0003	0.7514	.	0.4665	0.0552	0.5758	0.2714
6	0.0042	0.0001	0.0017	0.6812	0.4665	.	0.2058	0.2065	0.6875
7	0.0177	0.0001	0.0031	0.0963	0.0552	0.2058	.	0.0090	0.4289
8	0.0001	0.0001	0.0001	0.3816	0.5758	0.2065	0.0090	.	0.1280
9	0.0242	0.0004	0.0105	0.4313	0.2714	0.6875	0.4289	0.1280	.

Table 8. Statistical Test Results on Cone Index Data from the 10-15-cm Layer

TREATMENT	CONE INDEX LSMEAN	PROB > |T| H0: LSMEAN(I)=LSMEAN(J)			
		I/J	1	2	3
CT	1640.99016	1	.	0.3375	0.8558
F	1723.60955	2	0.3375	.	0.4777
NT	1656.02815	3	0.8558	0.4777	.

TEST PERIOD	CONE INDEX LSMEAN	PROB > |T| H0: LSMEAN(I)=LSMEAN(J)			
		I/J	1	2	3
1988(1)	2488.70889	1	.	0.0001	0.0001
1988(2)	1248.67331	2	0.0001	.	0.6668
1989(1)	1283.24567	3	0.0001	0.6668	.

TEST PERIOD	TRT	CONE INDEX LSMEAN	LSMEAN NUMBER
1988(1)	CT	2253.43956	1
1988(1)	F	2834.56910	2
1988(1)	NT	2378.11801	3
1988(2)	CT	1255.67630	4
1988(2)	F	1186.07690	5
1988(2)	NT	1304.26672	6
1989(1)	CT	1413.85463	7
1989(1)	F	1150.18265	8
1989(1)	NT	1285.69973	9

PROB > |T| H0: LSMEAN(I)=LSMEAN(J)

I/J	1	2	3	4	5	6	7	8	9 9
1	.	0.0048	0.3905	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
2	0.0048	.	0.0101	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
3	0.3905	0.0101	.	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
4	0.0001	0.0001	0.0001	.	0.6238	0.7306	0.2606	0.4493	0.8422
5	0.0001	0.0001	0.0001	0.6238	.	0.3960	0.1221	0.7982	0.4841
6	0.0001	0.0001	0.0001	0.7306	0.3960	.	0.4520	0.2713	0.8969
7	0.0001	0.0001	0.0001	0.2606	0.1221	0.4520	.	0.0643	0.4213
8	0.0001	0.0001	0.0001	0.4493	0.7982	0.2713	0.0643	.	0.3588
9	0.0001	0.0001	0.0001	0.8422	0.4841	0.8969	0.4213	0.3588	.

Table 9. Statistical Test Results on Cone Index Data from the 15-20-cm Layer

TREATMENT	CONE INDEX LSMEAN	PROB > |T| H0: LSMEAN(I)=LSMEAN(J) I/J	1	2	3
CT	1978.63383	1	.	0.2244	0.5115
F	2081.36616	2	0.2244	.	0.0826
NT	1929.85734	3	0.5115	0.0826	.

TEST PERIOD	CONE INDEX LSMEAN	PROB > |T| H0: LSMEAN(I)=LSMEAN(J) I/J	1	2	3
1988(1)	3288.04077	1	.	0.0001	0.0001
1988(2)	1337.14445	2	0.0001	.	0.7104
1989(1)	1364.67211	3	0.0001	0.7104	.

TEST PERIOD	TRT	CONE INDEX LSMEAN	LSMEAN NUMBER
1988(1)	CT	2841.00667	1
1988(1)	F	3788.15414	2
1988(1)	NT	3234.96149	3
1988(2)	CT	1411.70895	4
1988(2)	F	1260.32733	5
1988(2)	NT	1339.39708	6
1989(1)	CT	1683.18586	7
1989(1)	F	1195.61702	8
1989(1)	NT	1215.21344	9

PROB > |T| H0: LSMEAN(I) = LSMEAN(J)

I/J	1	2	3	4	5	6	7	8	9
1	.	0.0001	0.0040	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
2	0.0001	.	0.0005	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
3	0.0040	0.0005	.	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
4	0.0001	0.0001	0.0001	.	0.2394	0.5733	0.0379	0.0957	0.1412
5	0.0001	0.0001	0.0001	0.2394	.	0.5382	0.0014	0.6187	0.7323
6	0.0001	0.0001	0.0001	0.5733	0.5382	.	0.0089	0.2672	0.3506
7	0.0001	0.0001	0.0001	0.0379	0.0014	0.0089	.	0.0002	0.0010
8	0.0001	0.0001	0.0001	0.0957	0.6187	0.2672	0.0002	.	0.8871
9	0.0001	0.0001	0.0001	0.1412	0.7323	0.3506	0.0010	0.8871	.

Table 10. Statistical Test Results on Cone Index Data from the 20-25-cm Layer

TREATMENT	CONE INDEX LSMEAN	PROB > |T| H0: LSMEAN(I)=LSMEAN(J)			
		I/J	1	2	3
CT	2174.13762	1	.	0.1540	0.4250
F	2272.08933	2	0.1540	.	0.0297
NT	2125.54647	3	0.4250	0.0297	.

TEST PERIOD	CONE INDEX LSMEAN	PROB > |T| H0: LSMEAN(I)=LSMEAN(J)			
		I/J	1	2	3
1988(1)	3545.65386	1	.	0.0001	0.0001
1988(2)	1518.42575	2	0.0001	.	0.8597
1989(1)	1507.69380	3	0.0001	0.8597	.

TEST PERIOD	TRT	CONE INDEX LSMEAN	LSMEAN NUMBER
1988(1)	CT	3040.70408	1
1988(1)	F	4085.08851	2
1988(1)	NT	3511.16900	3
1988(2)	CT	1664.73078	4
1988(2)	F	1471.30198	5
1988(2)	NT	1419.24449	6
1989(1)	CT	1816.97800	7
1989(1)	F	1259.87749	8
1989(1)	NT	1446.22591	9

PROB > |T| H0: LSMEAN(I)=LSMEAN(J)

I/J	1	2	3	4	5	6	7	8	9
1	.	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
2	0.0001	.	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
3	0.0001	0.0001	.	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
4	0.0001	0.0001	0.0001	.	0.0671	0.0214	0.1530	0.0002	0.0413
5	0.0001	0.0001	0.0001	0.0671	.	0.6236	0.0013	0.0477	0.8138
6	0.0001	0.0001	0.0001	0.0214	0.6236	.	0.0002	0.1309	0.8052
7	0.0001	0.0001	0.0001	0.1530	0.0013	0.0002	.	0.0001	0.0009
8	0.0001	0.0001	0.0001	0.0002	0.0477	0.1309	0.0001	.	0.0908
9	0.0001	0.0001	0.0001	0.0413	0.8138	0.8052	0.0009	0.0908	.

Table 11. Moisture Variations Between Test Periods and Treatments

Test Period	Treatment	Depth (cm)				
		0-5	5-10	10-15	15-20	20-25
1988 (1)	CT	14.10	16.91	16.38	16.14	17.24
1988 (1)	F	6.33	6.12	5.72	6.98	9.55
1988 (1)	NT	12.76	13.97	13.43	13.17	13.96
1988 (2)	CT	27.09	25.29	22.16	20.40	21.04
1988 (2)	F	28.05	25.66	24.16	20.77	21.09
1988 (2)	NT	27.35	25.77	23.87	20.48	19.69
1989 (1)	CT	19.69	21.18	20.78	18.93	19.47
1989 (1)	F	26.25	23.56	22.81	19.35	19.54
1989 (1)	NT	30.83	28.22	26.32	22.87	22.80

cone index are to be evaluated, moisture variations should be eliminated by irrigating the plots prior to testing to bring the moisture contents to a standard level such as field capacity.

The test periods had significant influences on cone index data within all depth layers. In the surface layer, cone index data at the beginning of the 1988 season were significantly higher compared to other seasons while the cone index data at the end of the 1988 cropping season and at the beginning of the 1989 cropping season were similar. This relationship between test periods was similar in all depth layers. Again, these variations between test periods were caused by different moisture levels in those test periods. According to data presented in Tables 6 through 10, within each treatment, cone index increases with depth, which is related to the increases in bulk density with depth.

3.5 Conclusions

Based on the core sample analyses, the following conclusions were drawn:

1. Most of the structural changes due to tillage occurred in the topsoil layer.
2. Only in the 0-7.5-cm layer was there a significant increase in bulk density with time for each tillage treatment.
3. Significant differences in bulk density between tillage treatments did not appear within three cropping seasons.
4. In the topsoil layer there were significant fluctuations in both noncapillary porosity and capillary porosity between cropping seasons. At the end of each cropping season capillary porosity increased, but it was reduced after the winter months. The noncapillary porosity showed opposite changes. This soil loosening could be due to freeze/thaw and drying/wetting cycles.
5. There were no significant differences in void ratio below 20-cm depth.
6. The variations in bulk density, capillary porosity, noncapillary porosity, and void ratio within subsoil layers was probably due to volume changes resulting from fluctuating moisture contents.
7. Tillage treatments significantly influence the cone index values only within the 0-5-cm depth layer.

8. The least squares means of cone index values were influenced by soil moisture content.

9. The cone index increased with depth, down to 25-cm, in all tillage treatments.

10. Future research should evaluate the effect of tillage on cone index by eliminating moisture variations by conducting penetration tests after irrigating the plots to bring the soil moisture content to field capacity.

4.0 BULK DENSITY - CONE INDEX - MOISTURE CONTENT MODELS

4.1 Introduction

Soil bulk density provides direct information on the level of soil compaction even though air permeability, saturated hydraulic conductivity, and cone index data are also used for this purpose by some researchers. Collecting undisturbed soil samples to determine the soil bulk density using gravimetric procedures is very labor intensive when the data must be collected from deep soil profiles. The gamma-ray densitometer is an alternate method of estimating soil bulk density. In addition to health hazard potentials, the gamma-ray method often yields erroneous results because it is highly sensitive to the accuracy of field calibration. Gamma-ray densitometers have produced erroneous results when used within 10-cm from the surface, where most of the density changes due to tillage and traffic occurs. Therefore, the gamma-ray method is not suitable for studies on soil compaction due to different tillage and traffic treatments.

Some researchers have attempted to use cone index alone as a measure of soil compaction since this parameter is quickly determinable. There have been several attempts to convert cone index data to bulk density using other soil parameters (Wells and Baird, 1978;

Upadhyaya et al., 1982; Gameda et al., 1989; Ohu et al., 1988; and Ayers and Perumpral, 1982). Cone index models for predicting soil bulk density are not being adopted by many researchers because either they have not been tested in the field or they do not show advantages over the core sample method due to the use of additional soil parameters like soil organic matter content, determined through expensive laboratory analysis procedures.

It has been found that the cone index is highly influenced by bulk density and the moisture content of the soil, even though the relationship between these three parameters may vary depending on the soil type. Therefore, this study was aimed at the development of a model for predicting soil bulk density using cone index and moisture content data under field conditions in a Virginia soil.

4.2 Literature Review

Soil bulk density is defined as the dry weight of soil per unit volume, and can be determined through direct and indirect procedures. The soil core methods and excavation methods are direct methods while the radiation methods and cone index models are indirect methods.

4.2.1 Procedures Used for Determining Soil Bulk Density

To determine soil bulk density by the excavation method, a quantity of soil is excavated, oven dried and weighed. Measurement of the volume of excavated soil may be done using either the sand funnel, balloon, or high viscosity fluid method (Erbach, 1987). Although these methods give accurate results at the surface, they become less accurate when the data is taken from subsoil layers because of the difficulty in excavating an amount of soil and filling that exact volume.

The soil core method uses a cylindrical metal sampler that is pressed or driven into the soil to the desired depth and then carefully removed to preserve a known volume of soil as it existed in situ. Although the commercially available core samplers have various dimensions, the arrangement of the parts is similar to that illustrated in Figure 2. The procedure involves extracting a known volume of soil using the core sampler, determining the dry weight, and computing the bulk density using the following formula:

$$\text{Bulk Density} = \frac{\text{oven dry weight}}{\text{volume of the ring}} \qquad [4.1]$$

When soil samples are to be collected from the subsurface layers, a hole slightly larger in diameter than the size of the base plate of the core sampler is excavated down to the top of the subsurface layer. The soil samples are collected in the same manner as previously explained. In the event that two soil samples have to be collected at depth intervals less than the length of the cylinder, a second hole must be excavated near the first one.

This core procedure requires considerable amounts of time and labor, especially when subsurface soil samples are taken. Driving the core sampler into rocky or dry clay soils involves tedious work. This method of sample collection can not be performed in loose or soft soils because the soil column drops out when the core sampler is pulled from the soil.

The transmission of gamma radiation through soil or scattering within soil varies with soil properties, including bulk density. Soil density can be related to the change in attenuation of gamma radiation in the soil as compared with attenuation in the air (Revut and Rode, 1969). By suitable calibration, measurement of transmission or scattering of gamma radiation can be used to estimate bulk density.

The gamma-ray scattering method uses a source and a detector located in either a surface gauge or a single probe. The instrument records reflected gamma radiation (Rozhkov, 1970) and must be calibrated for the conditions to be measured. The volume of soil that influences the count rate varies with soil density and is roughly hemispherical with a diameter approximately equal to the distance between the source and the detector (Frietag, 1971). Vomocil (1954) reported that the single probe method measures the average density of a 20-25-cm layer of soil and should not be used closer than 15-20-cm below the surface.

According to Gameda et al. (1987a), the attenuation of gamma radiation passing through a soil can be expressed as follows:

$$\ln I = \ln I_0 - X(\mu_S\gamma + \mu_W\theta) \qquad [4.2]$$

where

$I =$ count rate through the soil,

I_0 = unattenuated count rate,

X = soil thickness (m),

μ_S = mass attenuation coefficient of soil (m^2/Mg),

μ_W = mass attenuation coefficient of water (m^2/Mg),

γ = soil bulk density (Mg/m^3), and

θ = volumetric soil moisture content (m^3/m^3).

Using the relationship

$$\theta = \gamma(mc) \qquad [4.3]$$

where

mc = gravimetric soil moisture content (g/g),

soil bulk density can be calculated as follows:

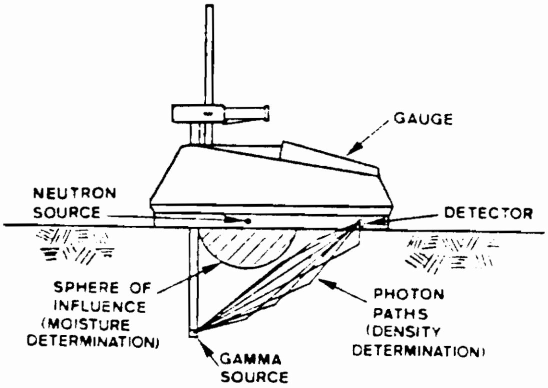
$$\gamma = \frac{\ln(I_0/I)}{X(\mu_S + \mu_W\,mc)} \qquad [4.4]$$

This relationship implies that the soil moisture content must be determined concurrently with readings for bulk density. In addition, μ_S is dependent on soil type; therefore, no universal relationship between count rate and bulk density can be established (Reginato and Van Bavel, 1964; Rawitz et al., 1982). As a result, it is important to conduct calibrations for the soil or range of soils to be investigated (Gameda et al., 1987a). Therefore, gamma-ray densitometers are not practical for use in layered soils because they must be calibrated for each layer.

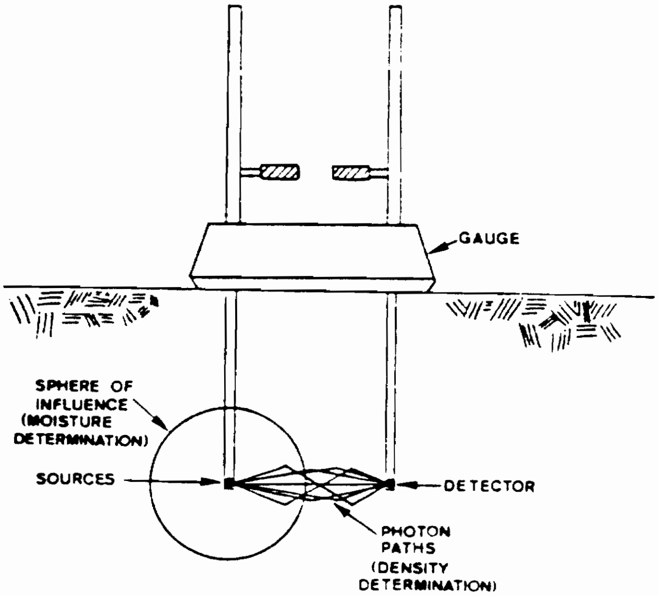
Densitometers that use the gamma-ray attenuation method may have single or dual probe configurations (Figure 8). In the single probe configuration, the gamma-ray source is mounted at the end of the probe while the detector is located at the bottom of the body. Readings represent average bulk density from the soil surface to the depth of source insertion. In the dual probe configuration, the source is in the tip of one probe and the detector is in the other. Gameda et al. (1987a) reported that both configurations of attenuation gamma-ray densitometers performed well in clay and sandy soils, but poorly in loamy soil due to the presence of large amounts of stones and pyrites which can change attenuation properties of the soil. The dual probe gauge yielded better results than the single probe gauge. However, the use of the single probe gauge was limited to a working depth of 0.3 m. Gameda et al. (1987a) observed that the readings with the single probe were reflective of soil layer density at the depth of probe insertion rather than average density from the surface to probe tip. Because of these problems and the potential health hazards, gamma-ray densitometers are limited for use in measuring soil density.

4.2.2 Bulk Density - Cone Index - Moisture Content Models

According to WES (1964), Melzer (1971), Turnage (1974), and Ayers and Perumpral (1982), moisture content also influences penetration resistance (cone index). Penetration resistance (cone index) increases with increasing bulk density and decreases with increasing moisture content. Studies conducted on fine-grained soils at or near saturated conditions have revealed



Schematic diagram of the single probe gauge.



Schematic diagram of the dual probe gauge.

Figure 8. Single and Dual Probe Configurations of the Gamma-Ray Densitometer (Gameda et al., 1987a)

that penetration resistance decreases as a logarithmic function of soil moisture level for different densities (WES, 1958; Knight, 1961; Smith, 1964; Turnage, 1970).

In order to predict soil bulk density using cone index and moisture content of a particular soil, it is important to investigate the inter-relationship of those parameters. However, only a limited number of studies of this type have been conducted in the past. Collins (1971) investigated 95 different sets of field data and developed the following equation to predict cone index (CI) using moisture content (MC) data:

$$\ln(CI) = a + b * \ln(MC) \qquad [4.5]$$

where a and b are constants determined by soil characteristics. He also observed that an increase in the finer fraction in the soil increased the moisture content needed to produce a specific cone index value. Conversely, an increase in the coarse fraction reduced the moisture content needed for a specific value of cone index.

In another study, Wells and Treesuwan (1977) measured cone index at three bulk densities and moisture contents ranging from 2 to 25 percent (dry basis) and found that, at a given bulk density, cone index increased when the moisture content increased from 2 to 15 percent but that a further increase in moisture content reduced the cone index value. They also found good agreement between the test data collected at and above the 15 percent moisture content and the values predicted using the equation developed by Collins (1971).

Hayes and Ligon (1977) conducted penetration tests on clay loam and loamy sand soils at different moisture contents and bulk densities. Using linear regression methods, they developed several equations to relate bulk density and moisture content at different depth layers. Based on their data, penetration resistance was most closely correlated with moisture content, bulk density, percent silt, and percent clay.

Using silty loam, silty clay loam, and loamy sand soils at 2 bulk densities and 4 moisture contents, Wells and Baird (1978) developed empirical equations to predict cone index and the slope of the penetration resistance curve. The equations to predict cone index (CI) and the slope of penetration resistance curve (PSL) are:

$$CI = K0 + K1(BD) + K2(PCL) + K3(POM) + K4(\log(MC))^2 + K5(\log(MC))^3 \qquad [4.6]$$

$$PSL = D0 + D1(BD) + D2(POM) + D3(\log(MC)) + D4(\log(MC))^2 + D5(\log(MC))^3 \qquad [4.7]$$

where

BD = bulk density (kg/m^3),

PCL = percent clay (%),

POM = percent organic matter (%),

MC = moisture content (% wet basis), and

K0, K1, K2, K3, K4, K5, D0, D1, D2, D3, D4 and D5 are constants.

Using dimensional analysis techniques, Upadhyaya et al. (1982) developed the following equation to predict cone index using soil bulk modulus, bulk density, and moisture content:

$$\alpha(CI/K) = a(\rho/\rho_s)^n e^{-b\theta} \qquad [4.8]$$

where

α = non-dimensional factor numerically equal to K,

CI = cone index,

K = bulk modulus,

ρ = dry bulk density (g/cm^3),

ρ_s = soil particle density (g/cm^3),

θ = soil moisture content (%), and

a, b, n = soil constants.

Using 4 moisture contents in the range 19 to 34.9 percent and 4 compression levels at 0, 100, 200 and 300 kPa, Gameda et al. (1989) predicted (K/CI) values for Ste. Rosalie soil using the following equation:

$$(K/CI) = A(\rho/\rho_s)^n e^{b\theta} \qquad [4.9]$$

where A is a constant and the rest of the symbols are defined as above. For each moisture content, the equation became:

$$(K/CI) = B(\rho/\rho_s)^n \qquad [4.10]$$

where $B = A \times e^{b\theta}$. The values for constants B and n have been computed for each moisture content. The penetration resistances were measured before and after compressing the soil cores in 100-mm diameter cylinders. The values of changes in void ratio were utilized to determine the constrained moduli. However, they observed the greatest statistical variabilities at the lowest and highest moisture contents. At the lowest moisture content, soil deformation was restricted by the friction between the soil and the cylinder wall. At the highest moisture content, which was above the optimum moisture content for maximum compaction, excess soil moisture resisted the deformation. When the data collected at the highest moisture content were excluded, the R^2 value improved from 53.2 % to 80.2 %.

Similarly, Ohu et al. (1988) developed the following equation for cone index prediction:

$$(CI/Pc) = A(Ts/Qp)^{n\theta} \qquad [4.11]$$

where

CI = cone index,
Pc = applied pressure,

Ts = shear strength,

Qp = overburden pressure ,

θ = soil moisture content, and

A, n = constants dependent on moisture content and soil texture.

Ayers and Perumpral (1982) prepared five artificial soil types by mixing different proportions of fire clay and zircon sand. Using soil samples compacted to 3 bulk densities at different moisture levels in the range of 0 to 20 percent, they developed the following model:

$$CI = (C1 \times DD^{C4})/[C2 + (MC - C3)^{C5}] \qquad [4.12]$$

where

CI = cone index (kPa),

DD = dry bulk density(g/cm^3),

MC = percent moisture content (db), and

C1, C2, C3, C4 and C5 are constants that depend on the soil type.

4.3 Objectives

If the soil bulk density can be predicted using only cone index and moisture content data, it will reduce time and labor requirements in future studies on soil compaction. As stated above, however, the predictive model proposed by Ayers and Perumpral (1982) has not been tested under field conditions while other models require more soil characteristics in addition to cone index and moisture content data. Therefore, the specific objectives of this study were:

1. Conduct laboratory tests to study the effect of soil bulk density and moisture content on cone index for a selected soil.
2. Using the information from objective 1, develop a mathematical model expressing the bulk density as a function of cone index and moisture content.
3. Experimentally verify the model developed, under field conditions.

4.4 Methodology

4.4.1 Sample Preparation

Two bulk soil samples were collected from the top and subsoil layers at two random locations in the experimental area described in the previous chapter. These samples were air dried and roots and plant residue were removed from the soil samples. These samples were then crushed into individual particles using a cement mixer. Since the subsoil sample could not be pulverized using this process, the clods in the sample were broken with a 2-kg hammer. The soil particles were separated using a Number 40 (42 mm opening size) sieve.

After sieving, each soil sample was brought to the desired moisture content by spraying small quantities of water over time, while mixing thoroughly. These moistened samples were left covered for more than 24 hours to allow moisture to spread evenly within the samples.

Test samples were prepared in the molds (Figure 9) using the procedure described by Ayers

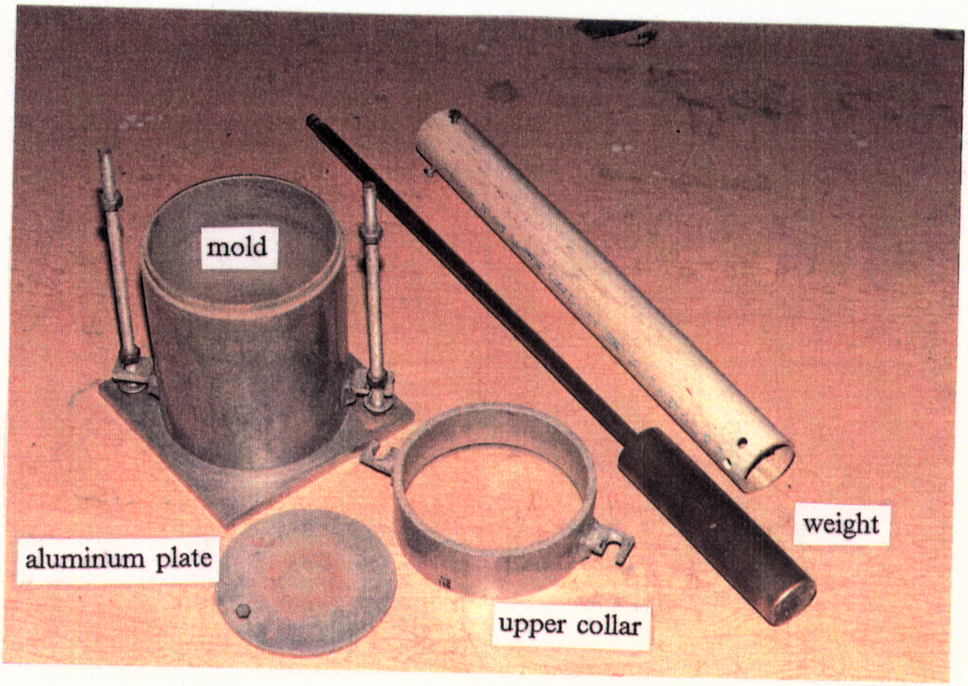


Figure 9. Equipment Used in the Laboratory to Prepare Soil Samples

and Perumpral (1982). The samples were prepared in a 15-cm (6-in.) diameter mold which consisted of two sections. The bottom section was 20-cm (8-in.) high and the upper 6-cm (2.5-in.) section was removable.

The soil sample was prepared by placing the soil in 5 equal layers. After placing each loose soil layer in the mold, an aluminum plate 3.2-mm (0.125-in.) thick was placed over the soil and a 9.5-kg weight was dropped onto the plate from a height of 31.5-cm (12-in.) for a predetermined number of times. After the five layers of soil had been placed in the mold and were compacted, the upper collar of the mold was removed and excess soil was shaved off to bring the sample surface flush with the top of the mold. The mold was then weighed to determine the average bulk density of the soil. Four different compaction levels were obtained using 3, 6, 12, and 18 blows. Each level was replicated three times.

The penetration test on the prepared sample was then conducted using the same penetrometer assembly used during the field study. In the laboratory, the penetrometer assembly was powered by a hydraulic pump on a Sperry-Vickers Fluid Power Trainer (Model 83137). The penetrometer probe was pushed into the soil at the rate of 3 cm/s (72 in./min) up to 16.5-cm (6.5-in.) depth while the penetration resistance data were recorded at 1.27-cm (0.5-in.) intervals.

The soil was then removed from the mold and the clods were crushed by hand. The same soil sample was compacted in the mold again as described above and the penetration resistance was again measured. After this procedure was repeated three times, the number of blows per layer was increased to the next level and test was repeated three more times. This procedure was continued for all the compaction efforts. After all tests at one moisture level were completed, additional water was added to the soil sample to increase the moisture content to the next level, the soil was allowed to equilibrate for another 24-h period, and the test was repeated.

Two moisture samples each were collected at the beginning and at the end of the tests at each moisture level. The average moisture content of these two samples was used in further calculations. Knowing the moisture content, the total weight of the soil in the mold, and the volume of the mold, the dry bulk density of each sample was calculated using the following equation:

$$BD = \frac{(\text{Wt. of mold with soil} - \text{Wt. of empty mold}) \times 100}{(100 + MC) \times (\text{Volume of the mold})} \qquad [4.13]$$

where

BD = the average bulk density of the sample (g/cm^3), and

MC = the average moisture content of the subsample (% dry basis).

When the penetration resistance was recorded at the 16.5-cm depth, the cone tip was very close to the bottom of the mold. To avoid any boundary-effects, the resistance data at 16.5-cm depth were not used in determining the average penetration resistance. Using the data collected, a regression analysis was conducted to develop a model which would express the bulk density of soil as a function of penetration resistance and moisture content. The models considered in this study are listed in Appendix E.

The exponential models were converted to linear models using a log transformation technique. The linear regression procedure (GLM) in the SAS program (SAS, 1985) was used to fit these linear models to the data sets collected for topsoil and subsoil samples. The nonlinear model (model number 14) with different coefficients for C5 was fitted to these data sets using the Marquardt method in the nonlinear regression procedure (NONLIN) of the SAS program.

The coefficient of determination (**R**^{2}) represents the proportion of the total variability among the cone index values that is accounted for by the independent variables bulk density and moisture content of the soil. For the linear models, the **R**^{2} values were computed using the following equation:

For linear models

$$\mathbf{R}^2 = \frac{SS_{\text{Regression}}}{SS_{\text{Total}}} \qquad [4.14]$$

Since the linear model equation gives a very crude estimate of **R**^{2} for nonlinear models, the following equation for nonlinear relationships was used.

$$\mathbf{R}^2 = 1 - \frac{SS_{\text{Residual}}}{SS_{\text{Corrected Total}}} \qquad [4.15]$$

The **R**^{2} values computed for all the models in the topsoil and subsoil samples are summarized in Appendix E.

The levels of bulk density and moisture content used in the laboratory tests fall into a narrow range compared to the actual values expected under field conditions. Therefore, the behavior of these models outside the bulk density and moisture content ranges used in the laboratory tests should be studied further for accurate expression of the relationship between cone index, bulk density, and moisture content under actual field conditions. In addition to the **R**^{2} value, the surface of prediction of each model was evaluated before a particular model was selected. In order to evaluate the surface of prediction, sets of cone index values were generated for each model listed in Appendix E using bulk density values in the range of 1 to 2 g/cm^3 and moisture content values from 6 to 30 percent. If the soil bulk density corresponding to a given cone index value was unreasonably low or high at extreme moisture conditions, the model was rejected even though it contained the highest **R^2** and, instead, the model that contained the next highest **R^2** was evaluated for conservative performance. This procedure was repeated until an appropriate model was found for each soil sample.

4.4.2 Model Validation

After a model was selected that would express the relationship between cone index, bulk density, and moisture content data under field conditions, it was necessary to verify the performance of that model using actual field data. As described in the previous chapter and illustrated in Figure 1, soil bulk density in each plot was determined using core samples collected from four layers, close to the middle of the second vertical section used for the penetration tests. The cone index data were collected for 15 penetration tests per vertical section, at 1.27-cm (0.5-in.) depth intervals. The average soil moisture content for each 5-cm (2-in.) layer was determined for each vertical section up to 25-cm (10-in.) depth. Thus, these bulk density, cone index and moisture content data were used for the model validation.

Because the soil core samples were collected from each plot close to the middle of the second vertical section consisting of 15 penetration tests, the data from three penetration tests closest to the center line of that section (seventh, eighth and ninth tests) were extracted from that section of each plot. Since the soil core samples that represented the topsoil layer were collected from the 0-7.5-cm (0-3-in.) depth range, the first 7 cone index values from each field penetration test were selected to represent the topsoil. These cone index values with the corresponding moisture contents were then used in the model selected for the topsoil, and the average of all predicted bulk density values within this depth in each plot was determined.

This procedure was repeated for all test seasons except the 1987 season which contained a majority of incomplete penetrations caused by very low soil moisture levels. These predicted bulk density averages were plotted against the actual soil bulk density values determined from soil core samples.

The validation tests for the models selected for the subsoil were similar to those conducted for the topsoil layer. In this case, however, bulk density and cone index data collected within the 25-32.5-cm (10-13-in.) layer were used. Although soil moisture data had been collected only down to the 25-cm (10-in.) depth, it was assumed that the moisture content at this depth does not vary much, and the moisture data from the 20-25-cm (8-10-in.) depth layer were used in the model.

4.5 Results and Discussion

The average bulk density, the soil moisture content, and the average of 13 penetration resistance values at the 1.27-cm depth interval from each mold tested were used for analysis. The relationship between penetration resistance and soil bulk density under different soil moisture contents are presented in Figures 10 and 11. According to these results, cone index increased at an increasing rate when the soil bulk density increased at each moisture level. However, the rate of increase in cone index increased with increasing moisture content at low moisture levels, and reduced when the soil moisture content was increased further. This behavior of cone index was observed for both topsoil and subsoil samples.

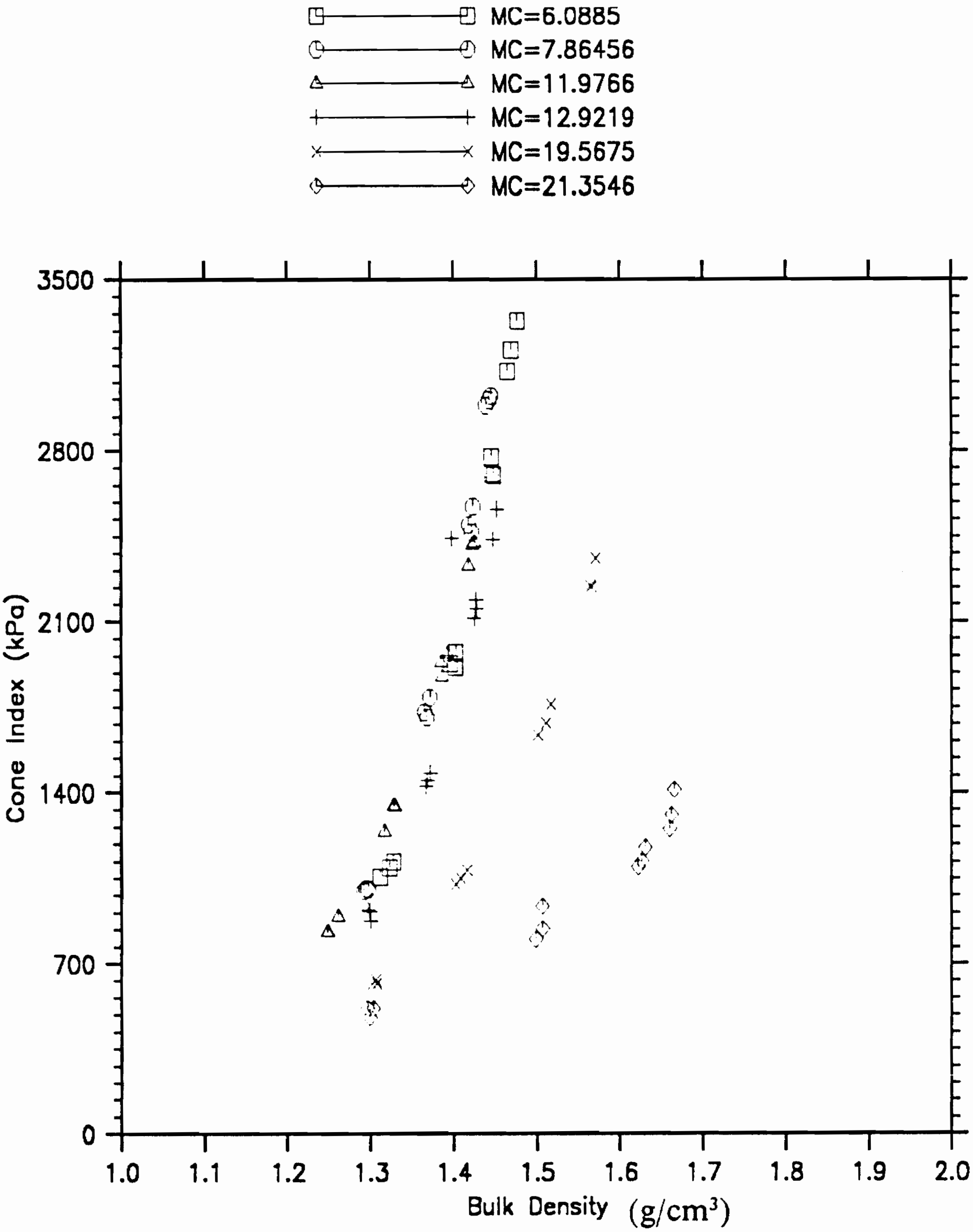


Figure 10. Laboratory Data for Moisture Content, Bulk Density, and Cone Index Interactions of Topsoil

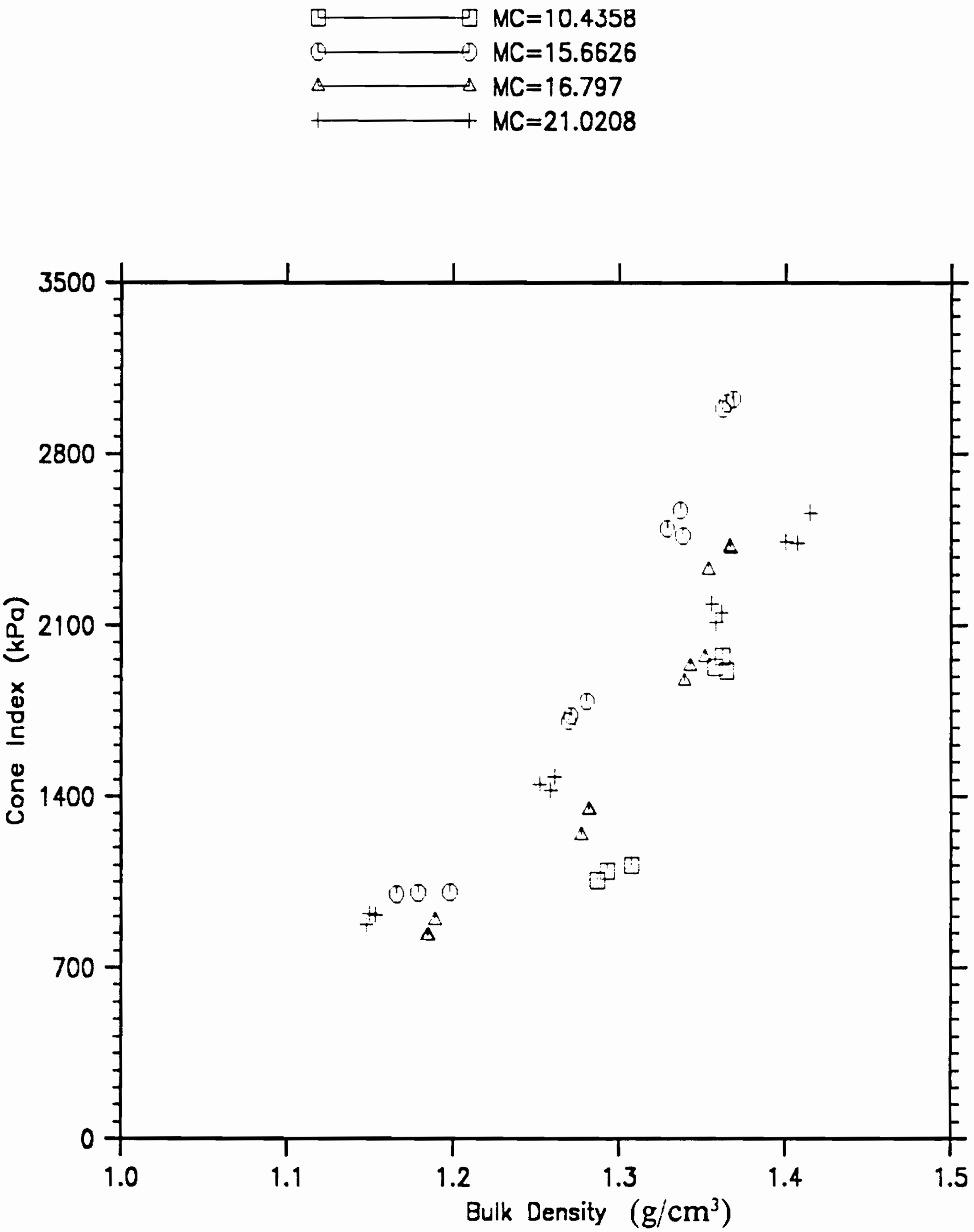


Figure 11. Laboratory Data for Moisture Content, Bulk Density, and Cone Index Interactions of Subsoil

4.5.1 Bulk Density-Cone Index-Moisture Models

4.5.1.1 Topsoil Sample

Model number 14 listed in Appendix E, originally suggested by Ayers and Perumpral (1982), with the coefficient C5 = 8 fitted the data set with the highest **R²** value (**R²** = 0.9492295) among all the models tested for the topsoil. When this model was used with the cone index values and corresponding soil moisture contents, the predicted soil bulk densities in dry soils (MC < 20%) were very close to the actual values determined from the soil core samples. Data predicted for wet soil conditions (MC > 22%) were about 50-60% higher than the actual values. The prediction surface of this model (Figure 12) reveals that the cone index corresponding to a given bulk density approaches zero at moisture contents higher than 22%. Therefore, it predicted higher bulk densities than actual values when the field soil moisture content exceeded 22%.

If this model is to be used for predicting soil bulk density using cone index and moisture content data, the soil moisture content in the topsoil layer should be below 20% for accurate results. However, in a field study it is not always possible to wait until the soil moisture content decreases below this level. If the moisture content in this top layer is very low, then the penetrometer probe can not be driven past the plowpan in many cases because of the high soil impedance in the subsoil layer. At the beginning of the cropping season and after the harvest, soil moisture content is usually above 20% because of rain during these periods. During the middle part of the cropping season, it is difficult to collect data without damaging the crop, even though the soil moisture content is within the acceptable range for this model. Damaging the crop may destroy the validity of other data collected in combined studies. In this study, soil moisture content in many test plots exceeded this 20% limit, especially in the

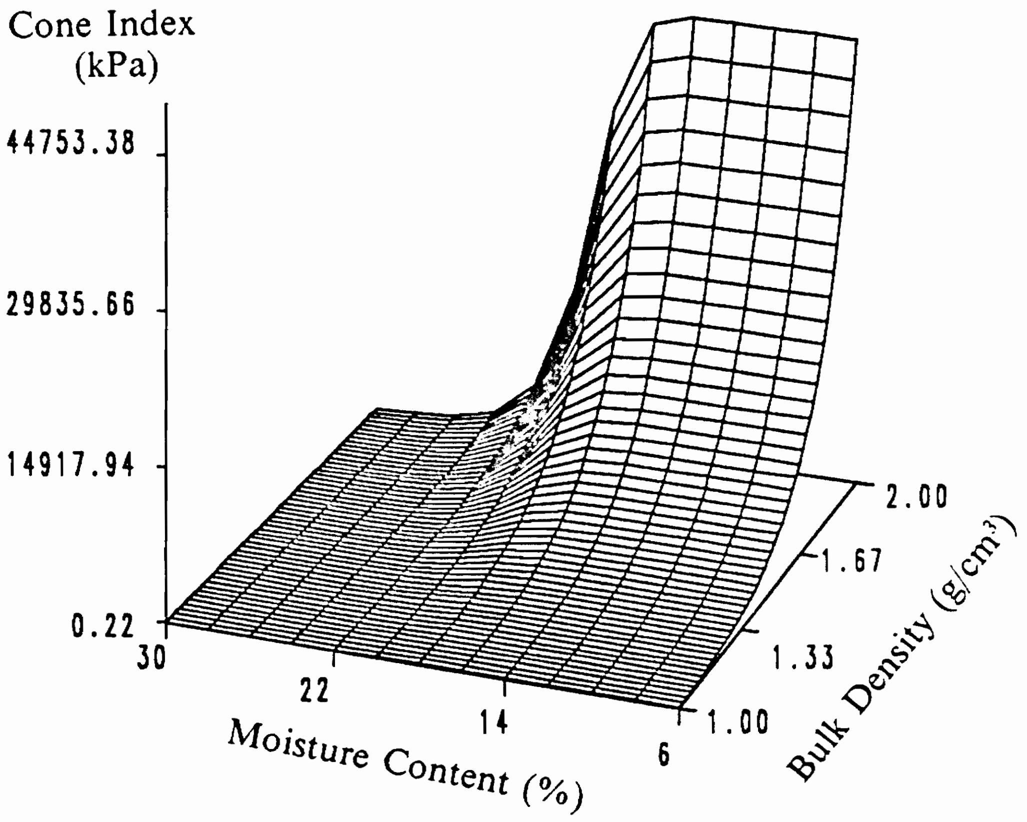


Figure 12. Surface of Prediction of the Model number 14 (C5 = 8) for Topsoil

last two test periods. In order to reduce error in predicting soil bulk density in those test periods, this model was not used.

Model number 14 with the coefficient C5=4 was also considered (**R**^{2} = 0.898897). The surface of this model is illustrated in Figure 13. It was also rejected because its behavior is similar to the previous model at higher moisture contents although the degree of over estimation was reduced.

Model number 11, listed in Appendix E (**R**^{2} = 0.895627), was considered next. This model under-predicted the dry bulk density at higher moisture levels and over-predicted at low moisture levels because the cone index increased exponentially with increasing moisture contents for a given dry bulk density (Figure 14). Therefore, this model was also rejected.

Model 14 with the coefficient C5=2 had the next best **R**^{2} value (**R**^{2} = 0.848784). The model surface, given in Figure 15, illustrates that the cone indices corresponding to higher moisture contents were large. Therefore, it predicted bulk density values close to the actual values even at higher moisture contents. Thus, this model was selected for further evaluation even though it did not have the highest **R**^{2} value. Thus, the model selected for the topsoil layer was:

$$\mathbf{CI} = \frac{9931.86909 \times \mathbf{BD}^{7.150479}}{[45.064824 + (\mathbf{MC} - 9.119457)^2]}$$

where

BD = Bulk Density(g/cm^3),

MC = Average Moisture Content (%), and

CI = Cone Index (Penetration Resistance) (kPa).

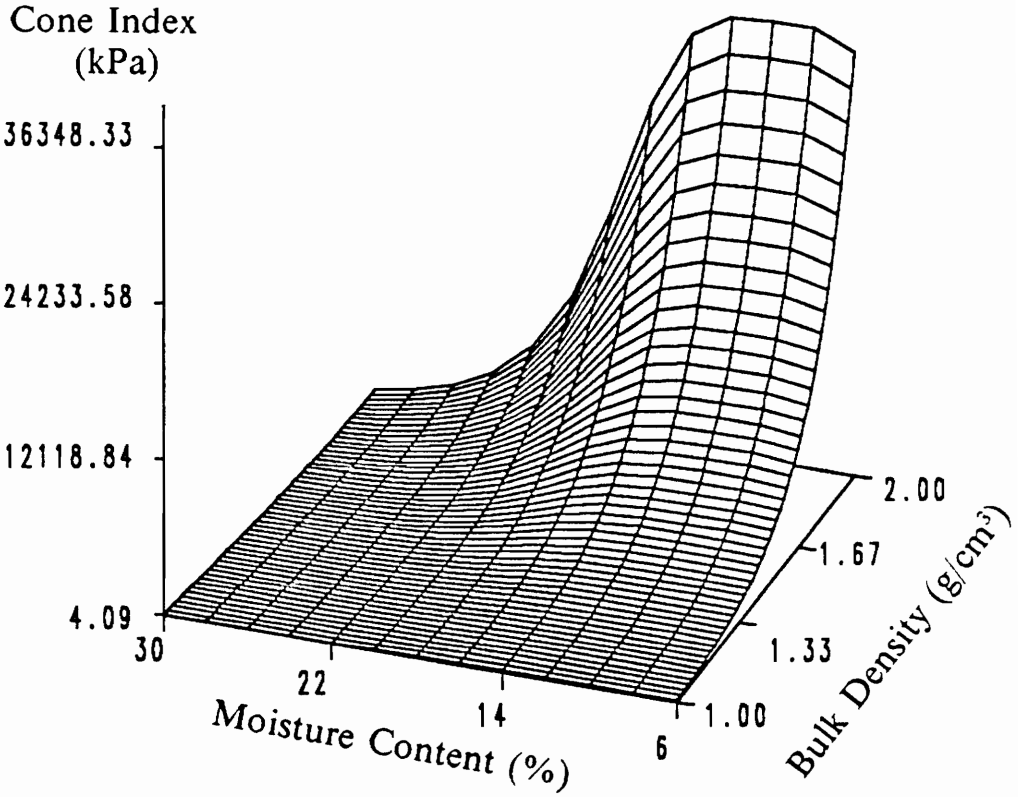


Figure 13. Surface of Prediction of the Model Number 14 (C5 = 4) for Topsoil

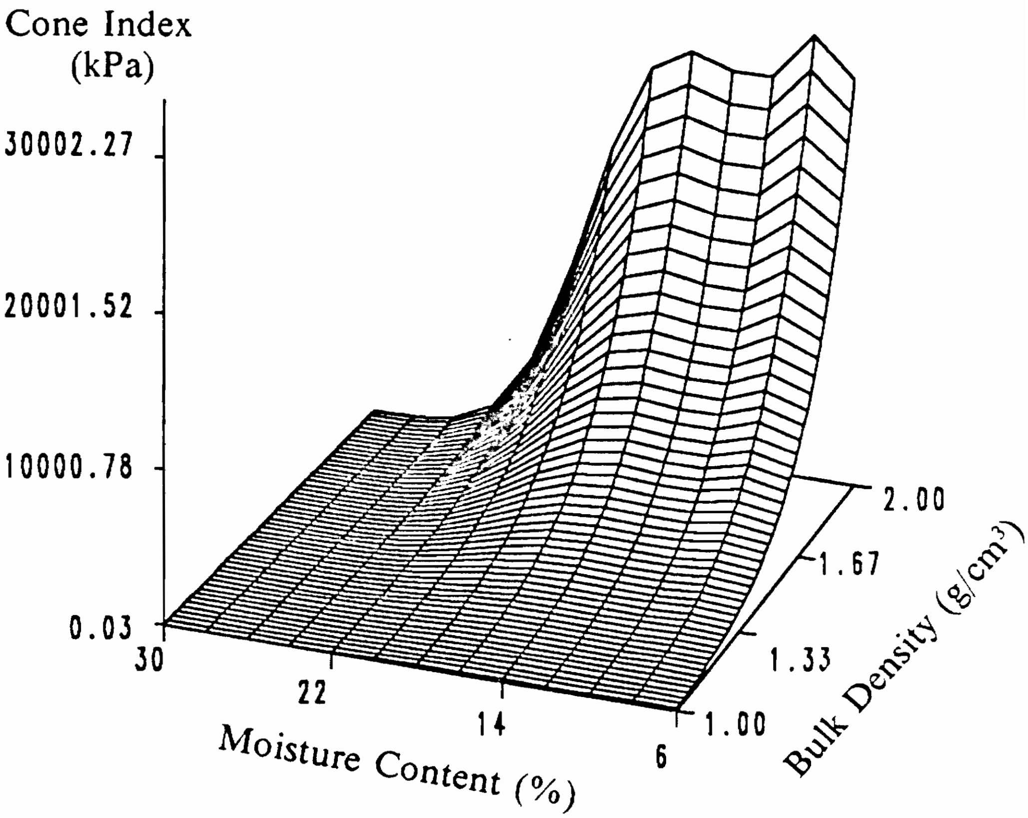


Figure 14. Surface of Prediction of the Model Number 11 for Topsoil

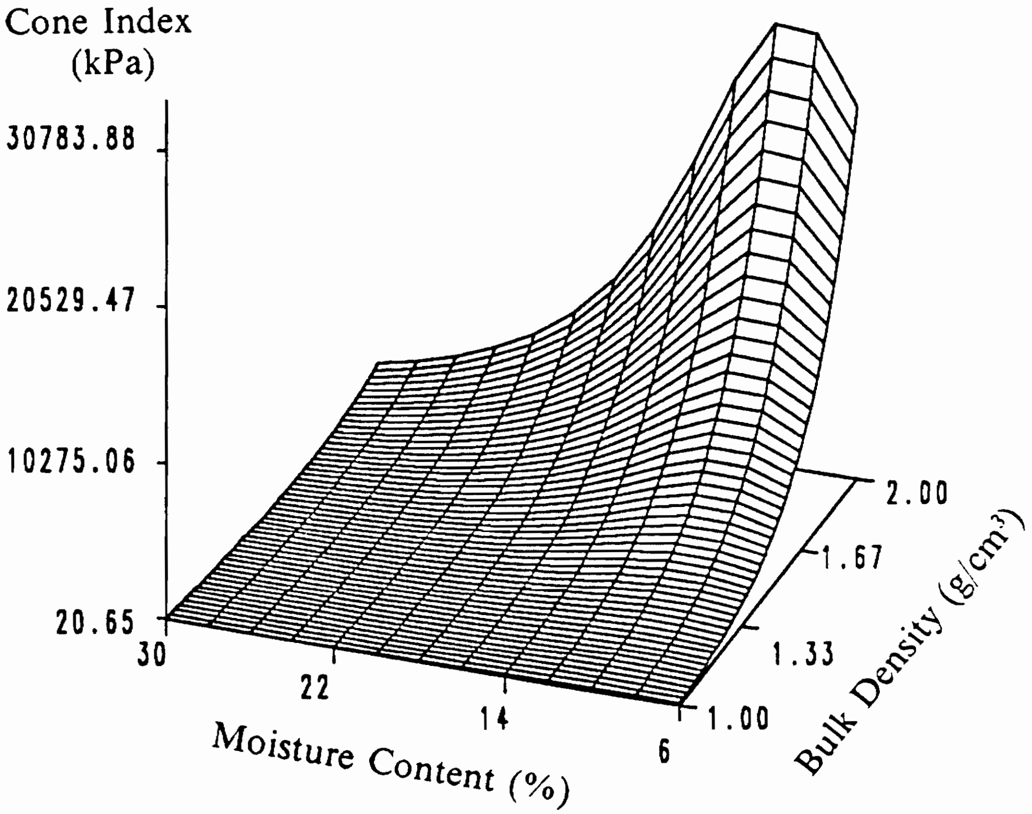


Figure 15. Surface of Prediction of the Model Number 14 (C5 = 2) for Topsoil

4.5.1.2 Subsoil Sample

For the subsoil, model number 8 (Appendix E) had the highest **R²** value (**R²** = 0.941673). The surface of prediction of this model is given in Figure 16. For model number 8, the cone index also increased with increasing moisture content for a given bulk density. Thus, this model predicted very low bulk density values at higher moisture contents, and was not acceptable.

Model number 14 (C5 = 6) was examined since it had the next best **R²** value (**R²** = 0.86397). As illustrated by the prediction surface of this model in Figure 17, the bulk densities predicted by this model at high moisture contents appear to be higher than the actual values. Therefore, the model number 14 (C5 = 4) (**R²** = 0.863958) was considered. The surface of this model, illustrated in Figure 18, indicated that the model was acceptable. Hence, the model selected for the subsoil layer was :

$$\mathbf{CI} = \frac{956617.1324 \times \mathbf{BD}^{6.5533}}{[2873.0359 + (\mathbf{MC} - 16.2706)^4]}$$

where

BD = Bulk Density(g/cm³),

MC = Average Moisture Content (%), and

CI = Cone Index (Penetration Resistance) (kPa).

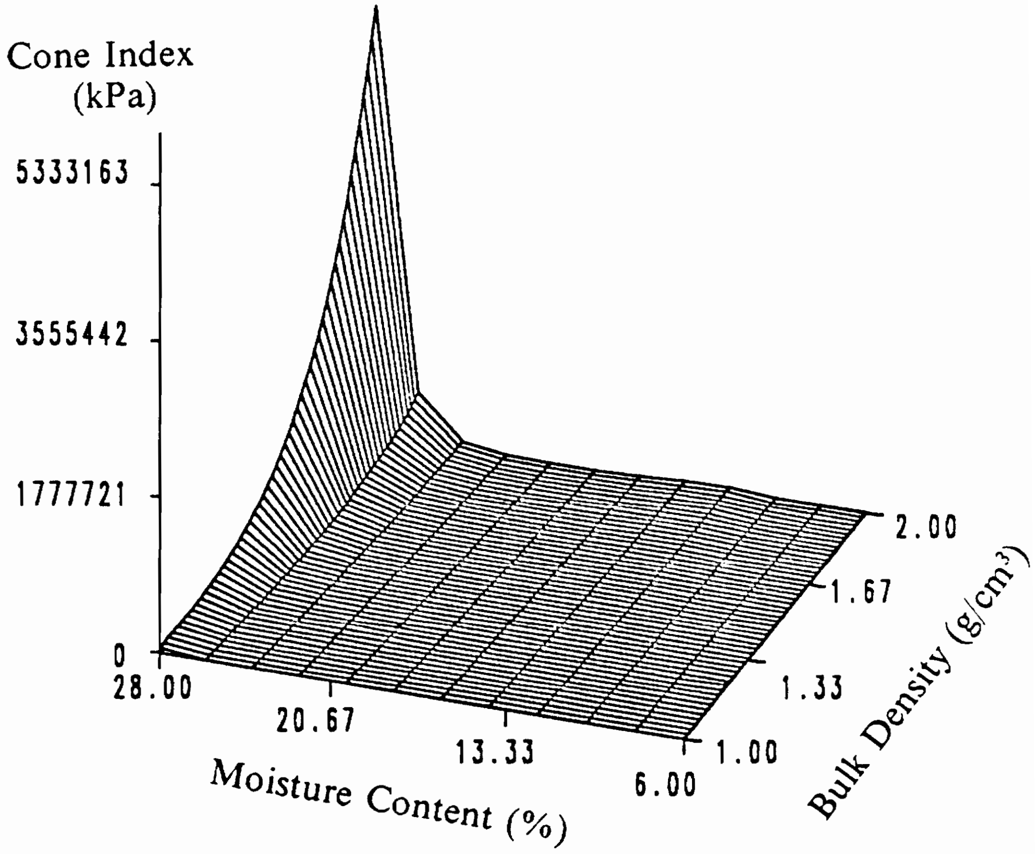


Figure 16. Surface of Prediction of the Model Number 8 for Subsoil

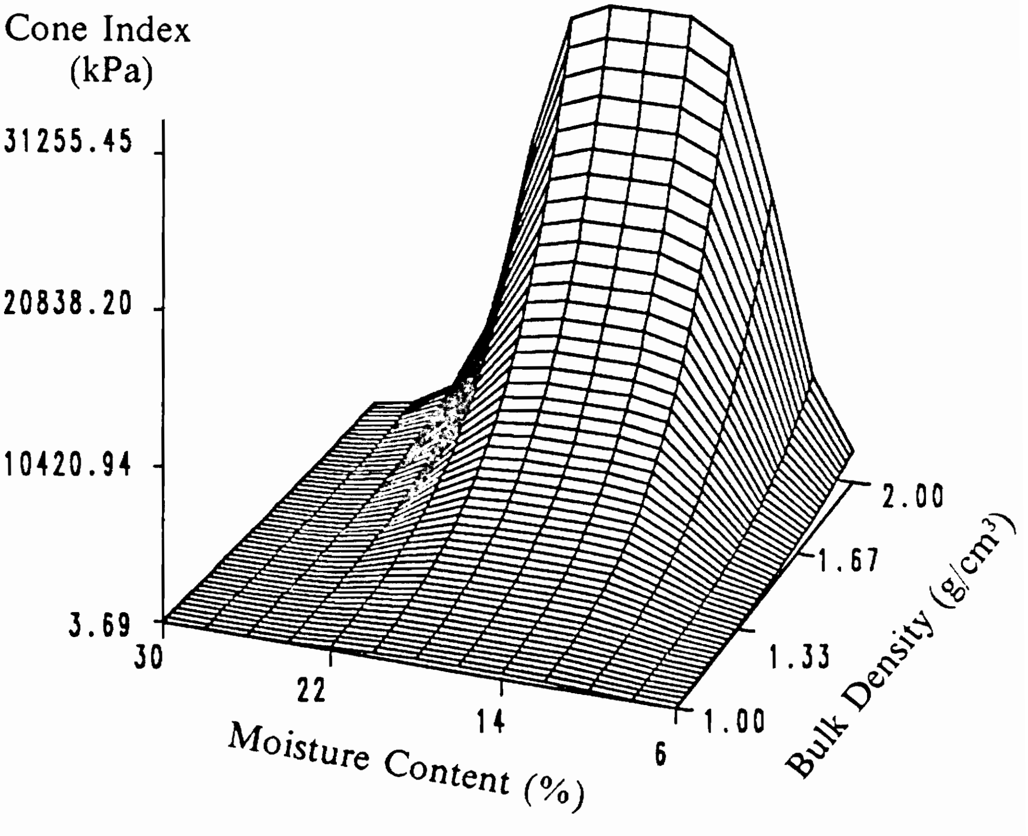


Figure 17. Surface of Prediction of the Model Number 14 (C5 = 6) for Subsoil

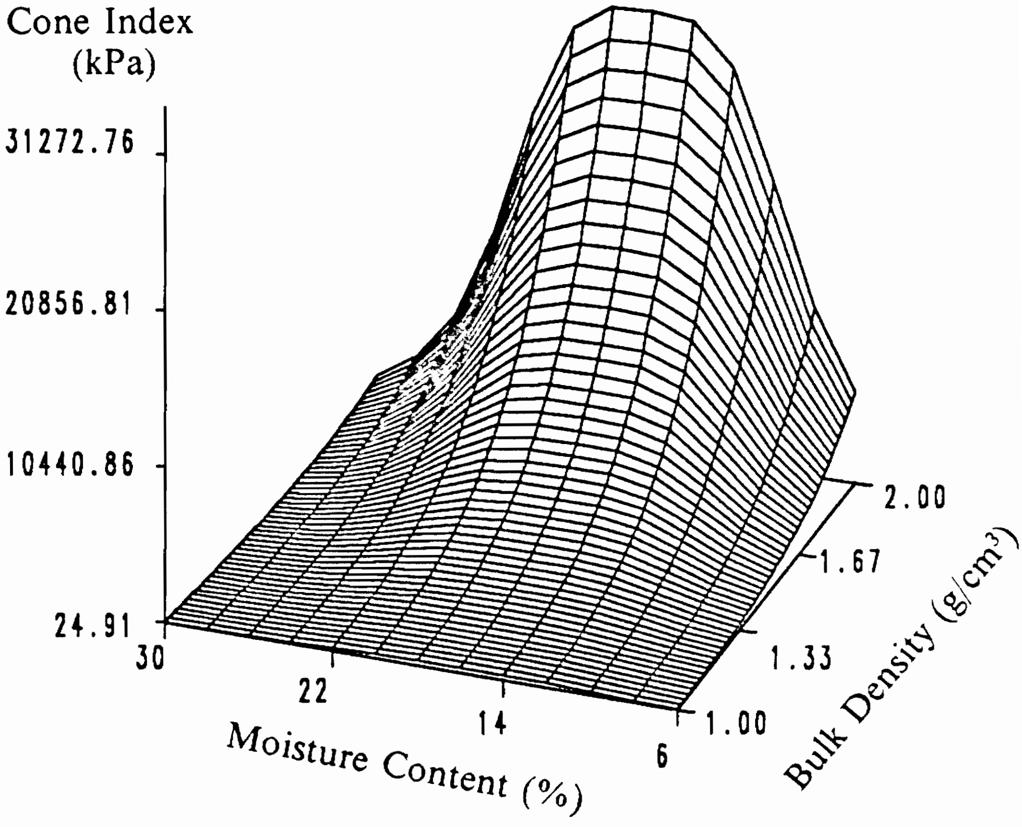


Figure 18. Surface of Prediction of the Model Number 14 (C5 = 4) for Subsoil

4.5.2 Model Validation

4.5.2.1 Topsoil Sample

The bulk density values predicted by the selected model were plotted versus the actual values determined from the soil core samples and are illustrated in Figures 19 through 24. These figures indicate that the predicted values are scattered in small regions instead of falling on a straight line as desired. However, these results are acceptable since the soil samples used in the laboratory tests were free of particles larger than 0.42-mm (0.0165-in.) due to the use of the number 40 sieve for sample preparation. When the cone head of the penetrometer encounters larger particles, it senses higher penetration resistances and falsely predicts higher bulk density values than actual.

According to Figure 19, the predicted bulk density in the CT plots falls very close to the 1:1 line at the beginning of the 1988 and 1989 cropping seasons while the data for the end of the 1988 season indicate a small over-prediction. The NT and F plots also indicate small over-predictions for all test periods, according to the Figures 20 and 21.

Figures 22 and 24 illustrate that the model selected for the topsoil layer is capable of predicting bulk density accurately in the recently disturbed soils. The over-prediction in the NT and F plots could be due to soil strengthening through an ageing effect. The extreme over-predictions in bulk density in the four NT plots in Figure 24 were caused by extremely high moisture levels (up to 40%). Assuming that the penetration tests will not be conducted under extremely high moisture conditions, those four data points may be discarded. In Figure 23, the error of over-prediction was similar in all treatments at the end of the 1988

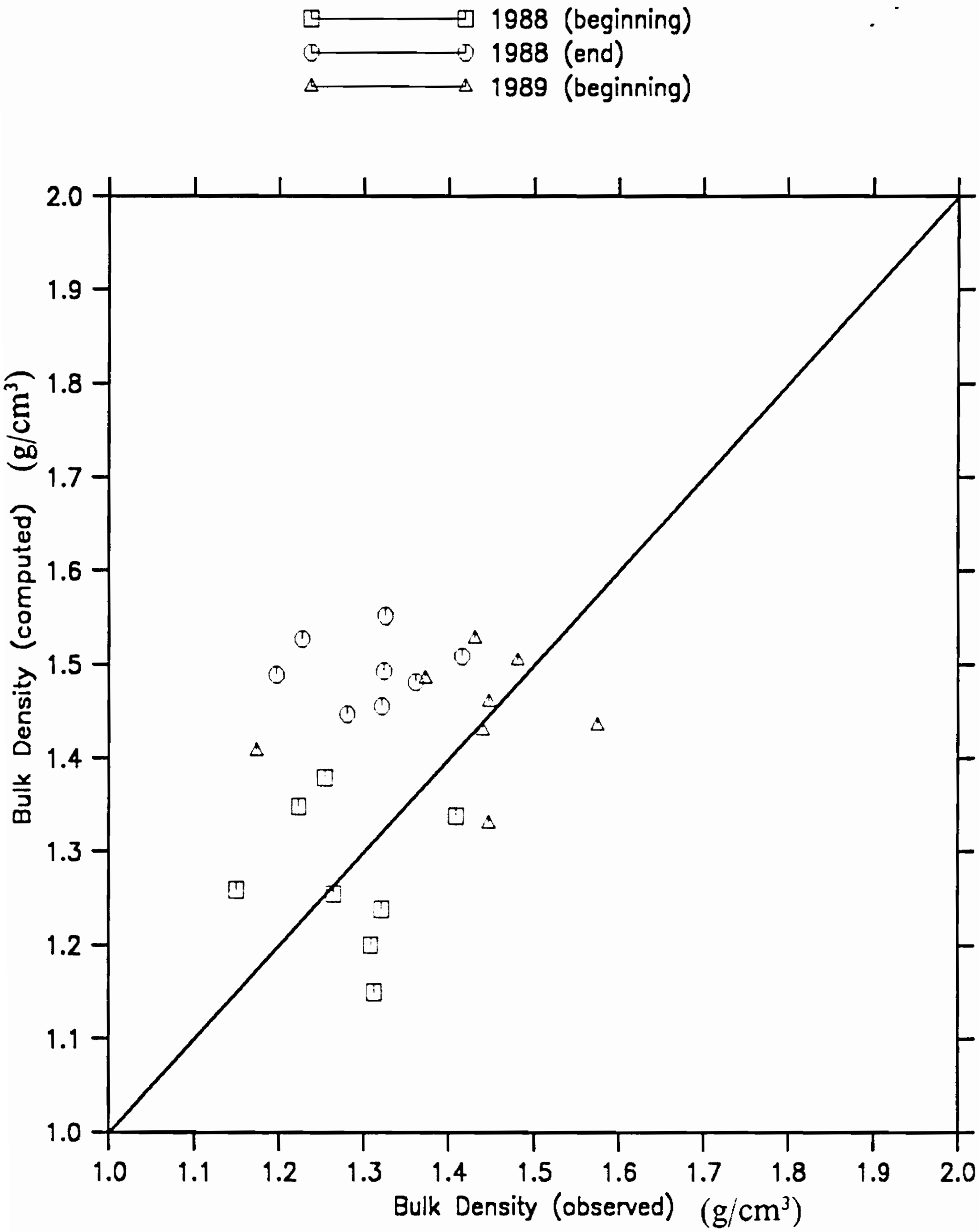


Figure 19. Performance of the Selected Model in the Topsoil of CT Plots

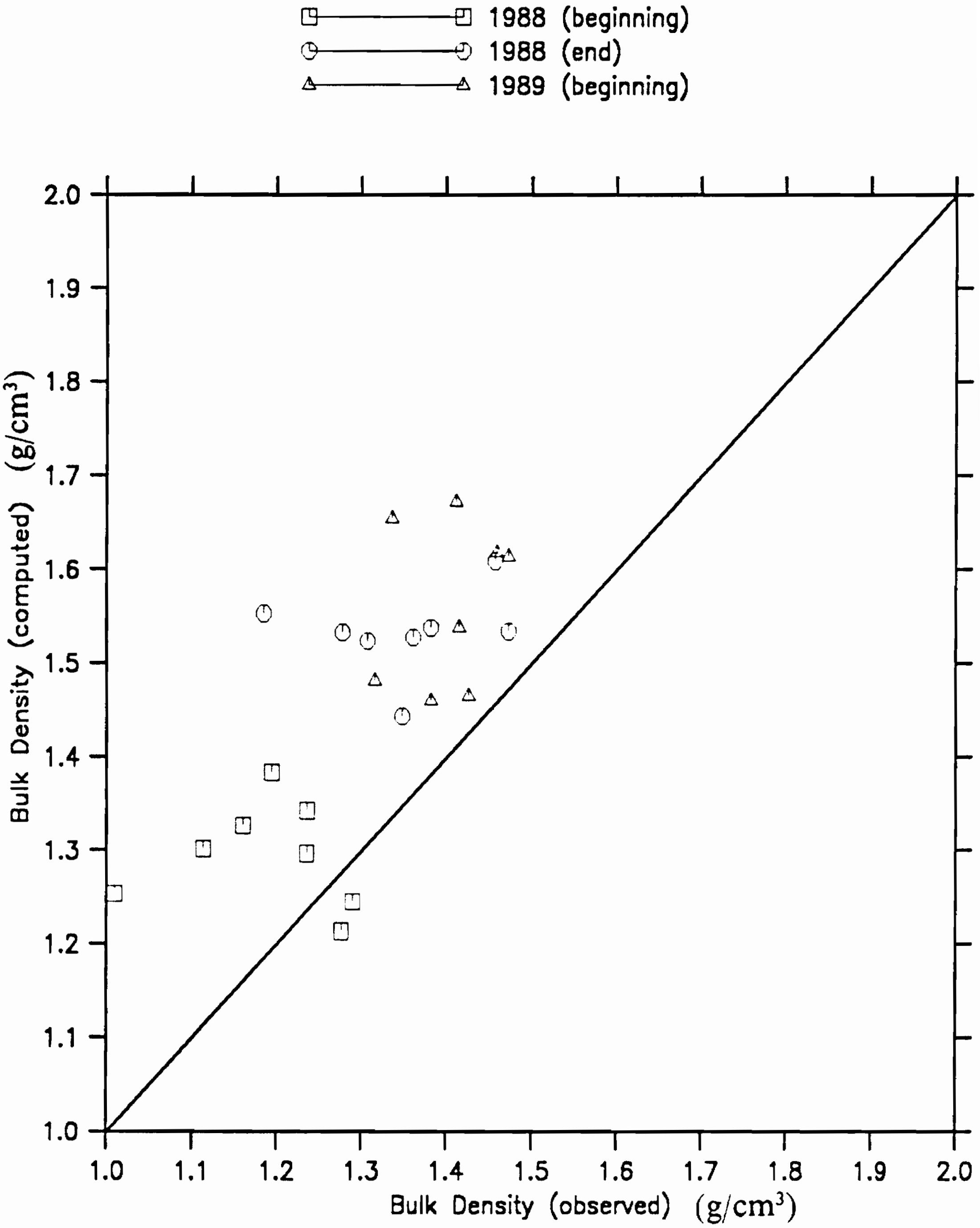


Figure 20. Performance of the Selected Model in the Topsoil of NT Plots

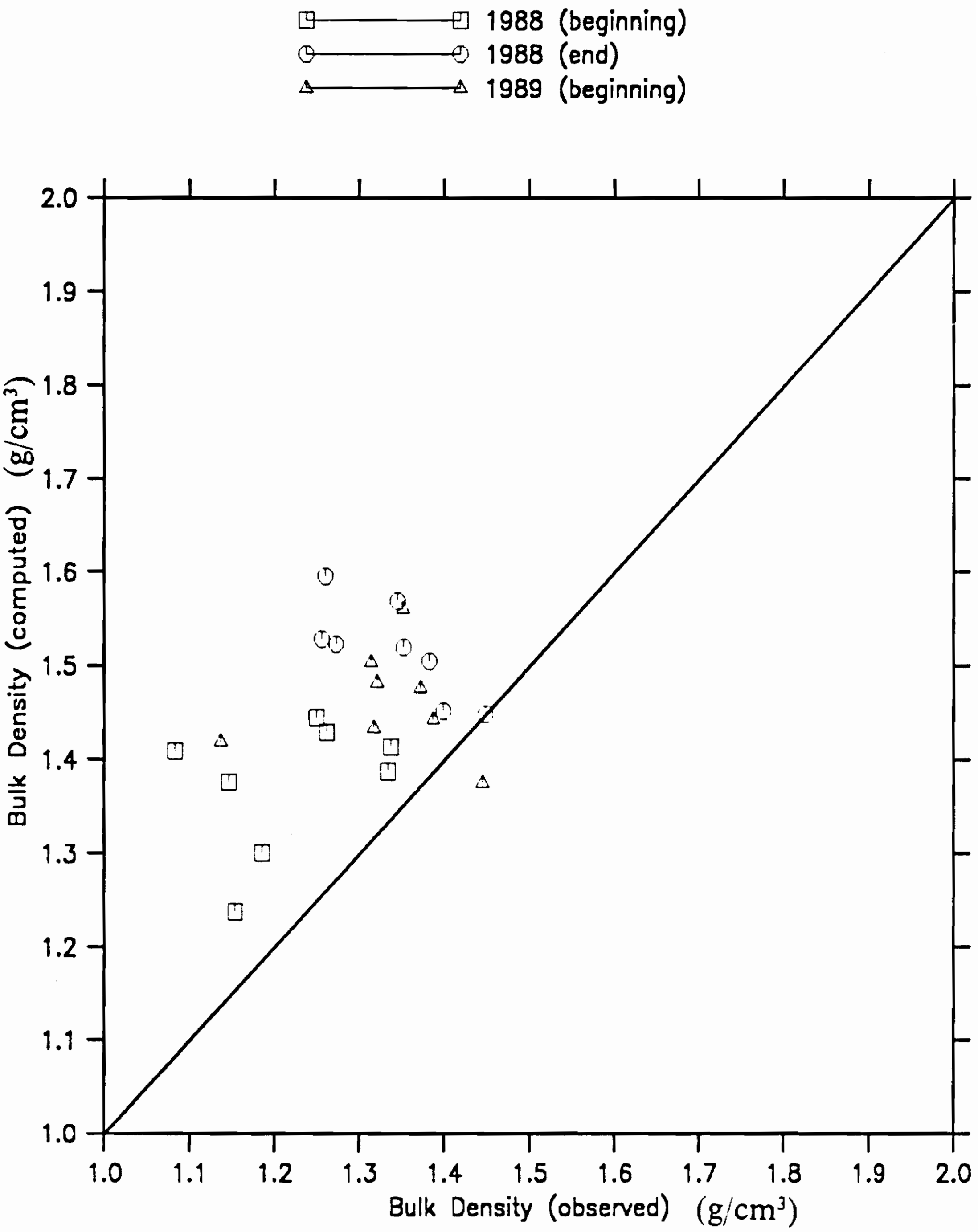


Figure 21. Performance of the Selected Model in the Topsoil of F Plots

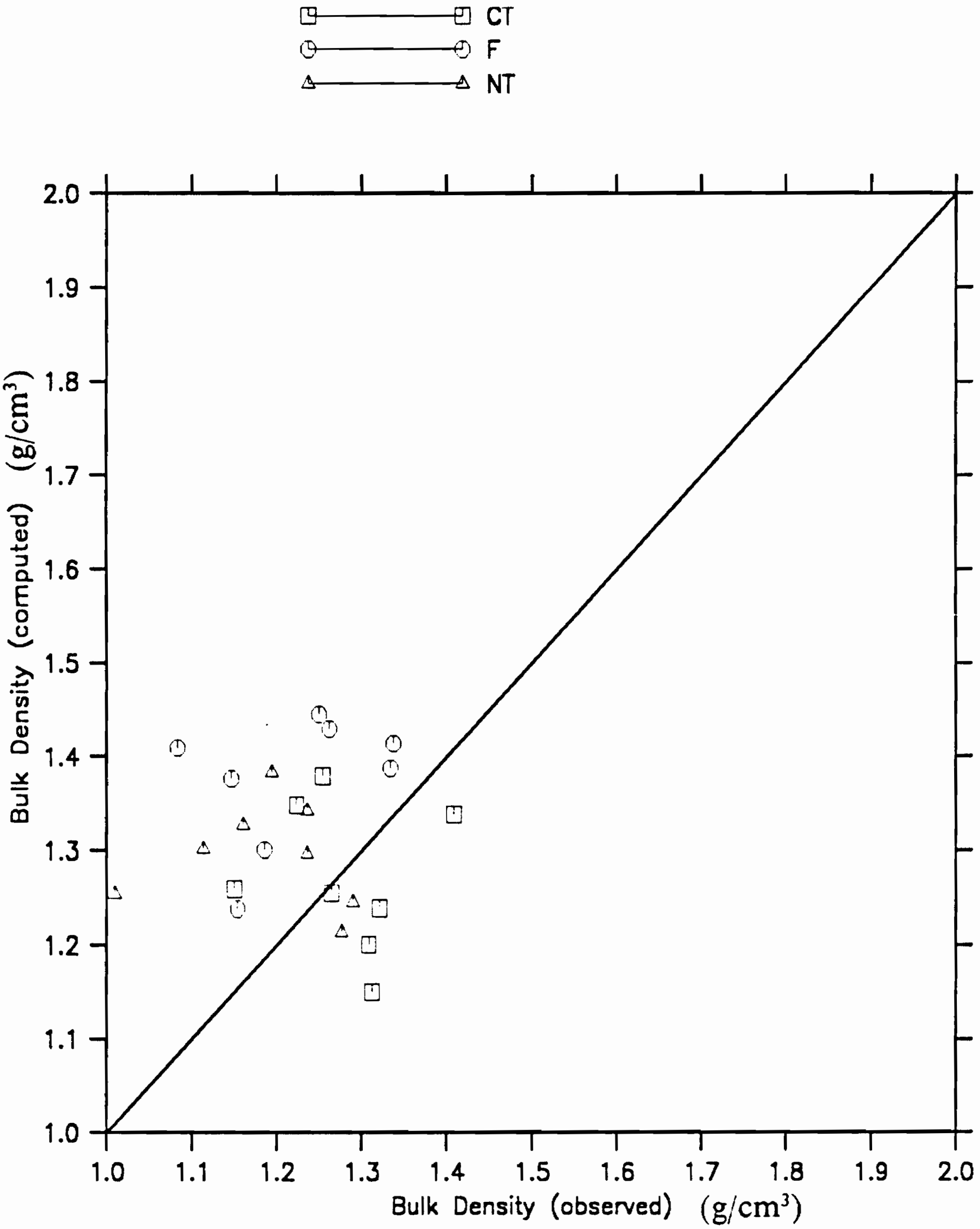


Figure 22. Performance of the Selected Model for the Topsoil at the Beginning of the 1988 Season

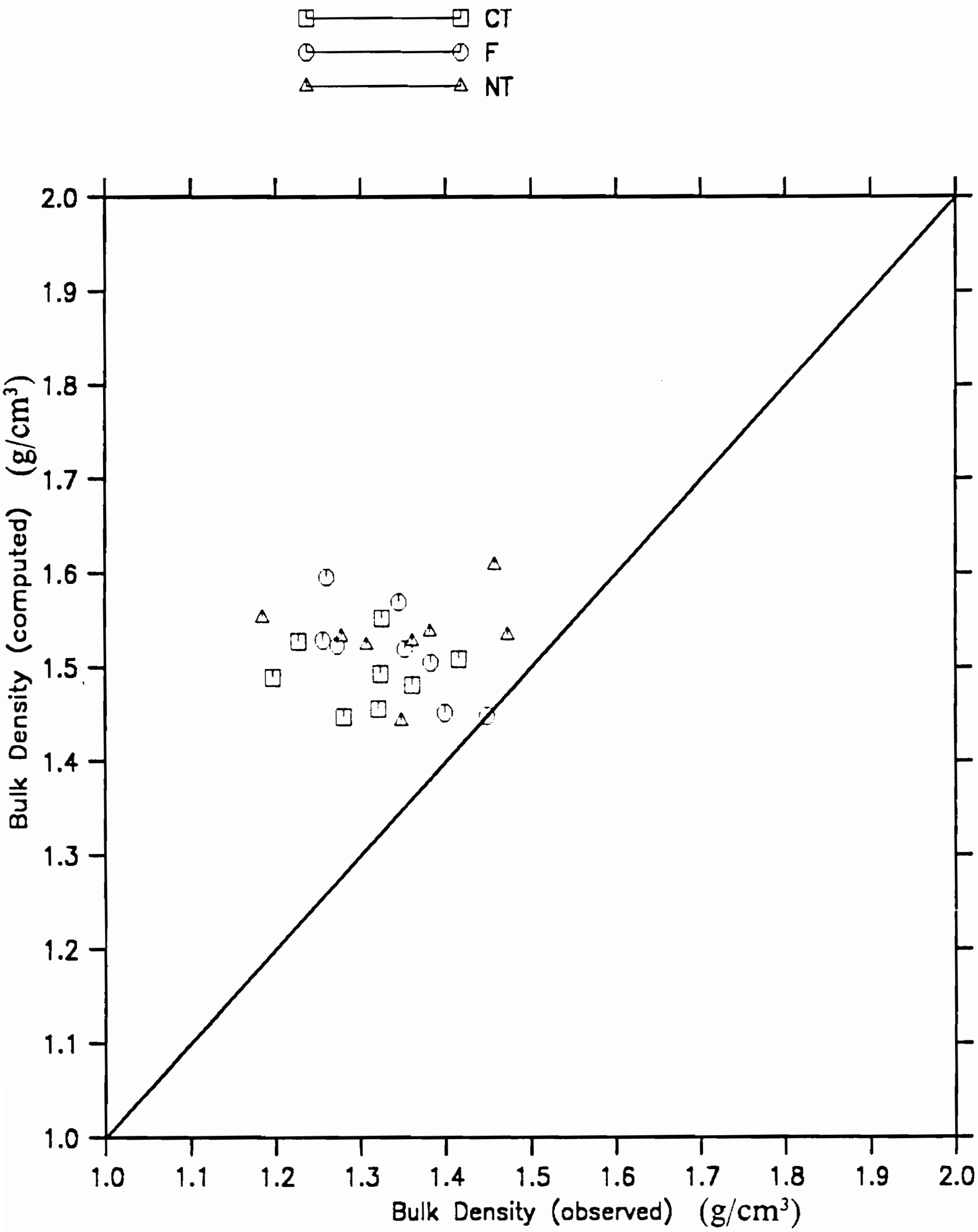


Figure 23. Performance of the Selected Model for the Topsoil at the End of the 1988 Season

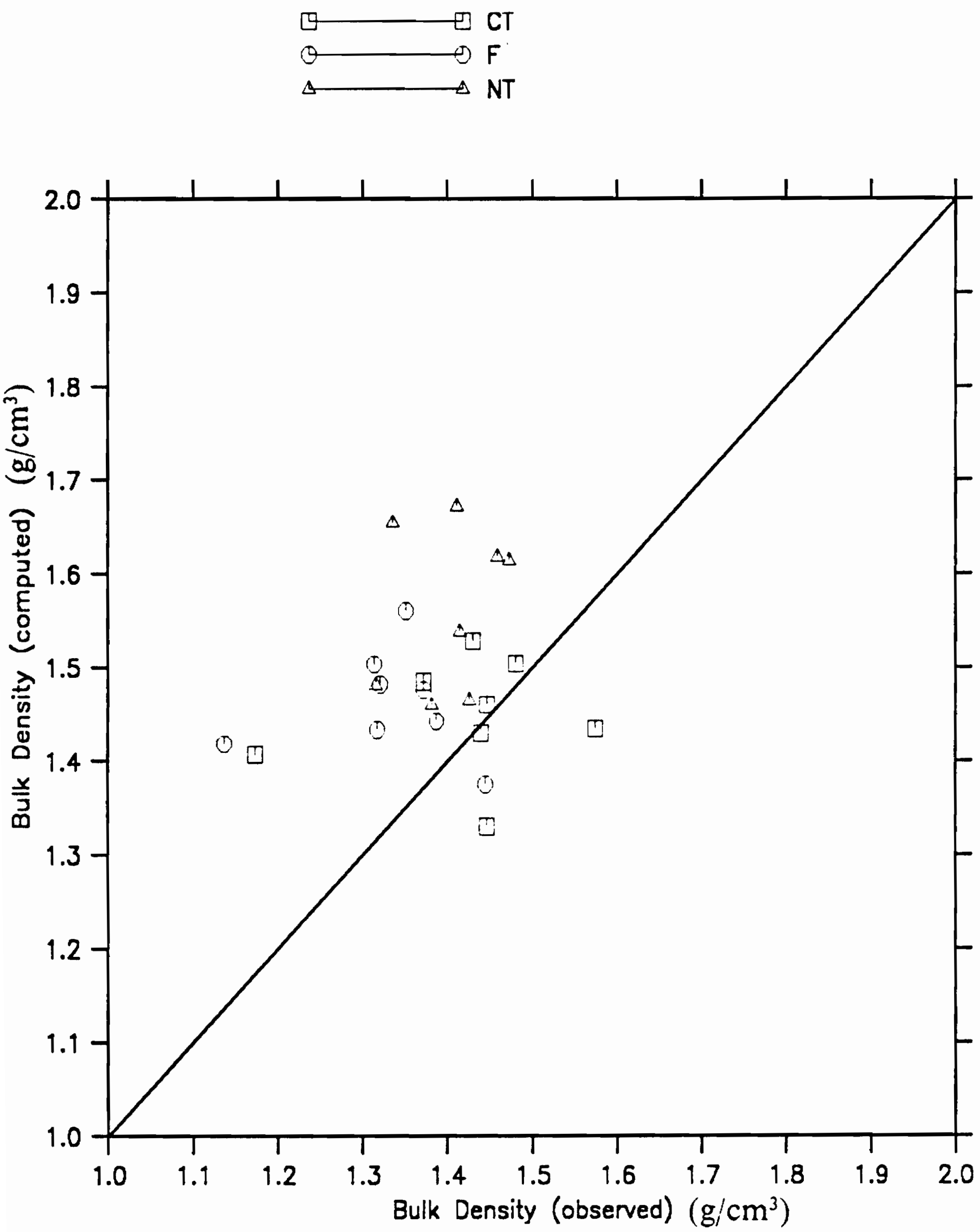


Figure 24. Performance of the Selected Model for the Topsoil at the Beginning of the 1989 Season

cropping season, and indicated that soil strengthening due to the ageing effect begins in the soil within one cropping season.

4.5.2.2 Subsoil Sample

As seen in Figures 25 through 30, the model selected under-predicted bulk density. The predicted bulk density values were about 10% lower than the actual values determined from soil core samples at the beginning of the 1988 cropping season for all treatments. Figure 29 shows that, at the end of the 1988 cropping season, the error of prediction had been reduced in the CT plots compared to other plots. The error of prediction at the end of the 1988 cropping season ranged from 0% to about 25% in CT plots. The bulk density values predicted in NT plots in that season were 10% to 30% lower than actual values, although most of the values were 25% to 30% lower. The under-prediction in F plots ranged from 0% to about 25%, while many values were about 25% under-predicted. The same trend was seen in the data collected at the beginning of the 1989 cropping season (Figure 30).

Even though the model performed better for CT plots, tillage did not contribute directly to the differences between treatments since the soil at this depth was not disturbed during land preparations. Therefore, soil moisture contents must have influenced the results. At the beginning of the 1988 cropping season, the soil was dry. Hamblin (1984), Lal (1985), Derpsch et al. (1986), Ike (1986), Grevers et al. (1986), Ojeniyi (1986) and Al-Darby et al. (1987) stated that CT plots store less moisture in the soil than do NT plots. Therefore, the improved performance of the subsoil model at the beginning of the 1988 cropping season in all treatments, and in CT plots during the other two test periods, could be due to the effect of the low moisture content of the soil. When the soil moisture content was high in the NT and

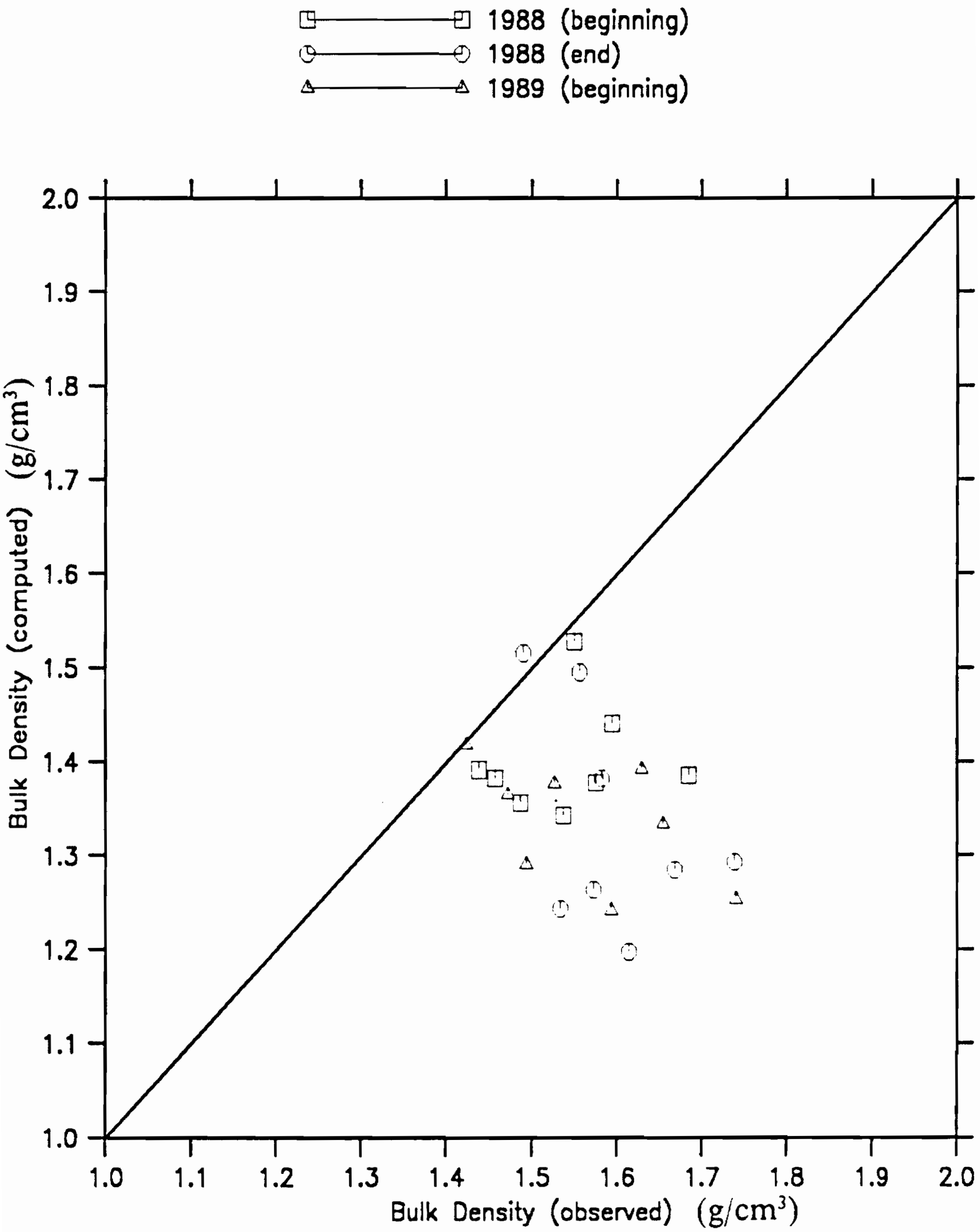


Figure 25. Performance of the Selected Model in the Subsoil of CT Plots

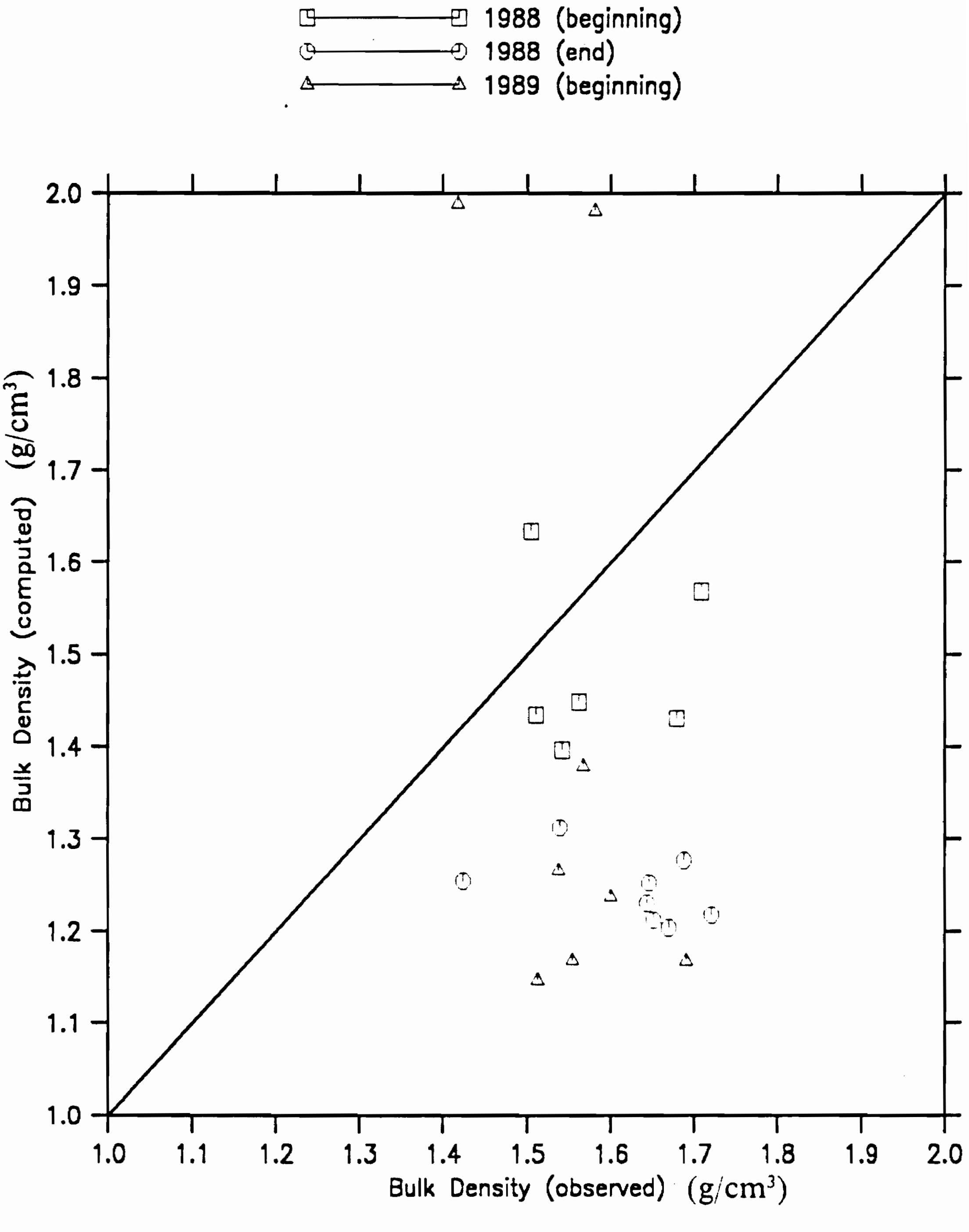


Figure 26. Performance of the Selected Model in the subsoil of NT Plots

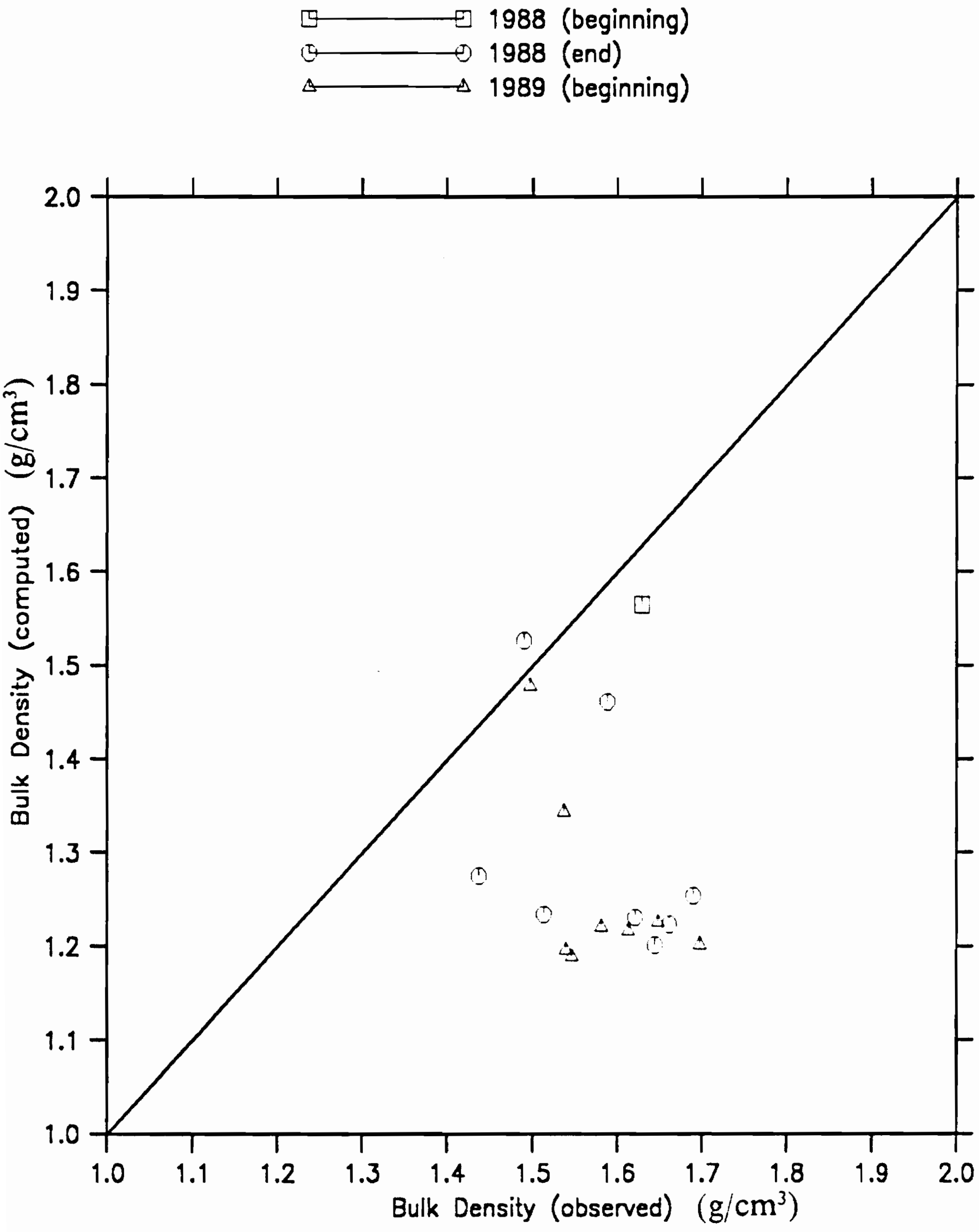


Figure 27. Performance of the Selected Model in the Subsoil of F Plots

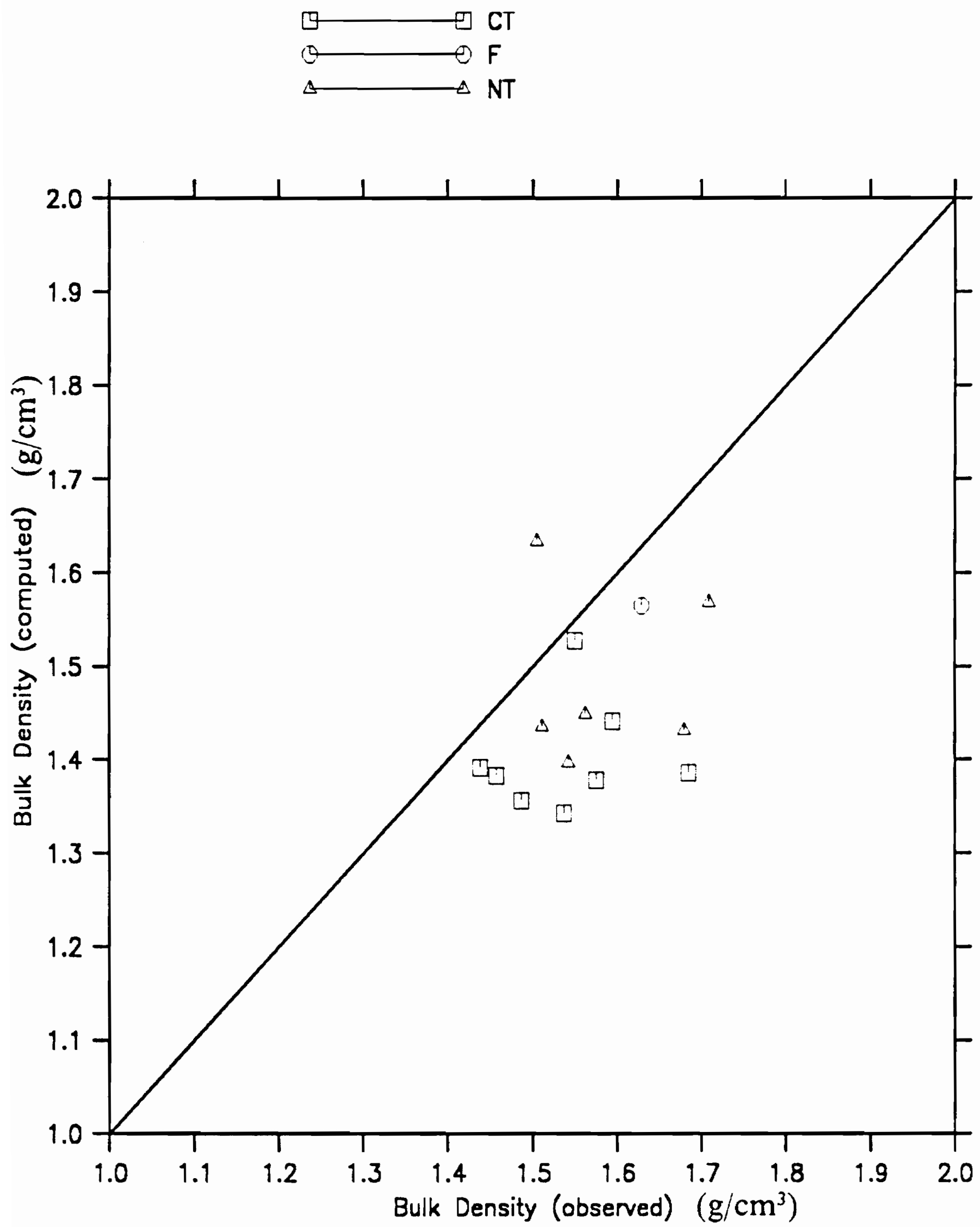


Figure 28. Performance of the Selected Model for the Subsoil at the Beginning of the 1988 Season

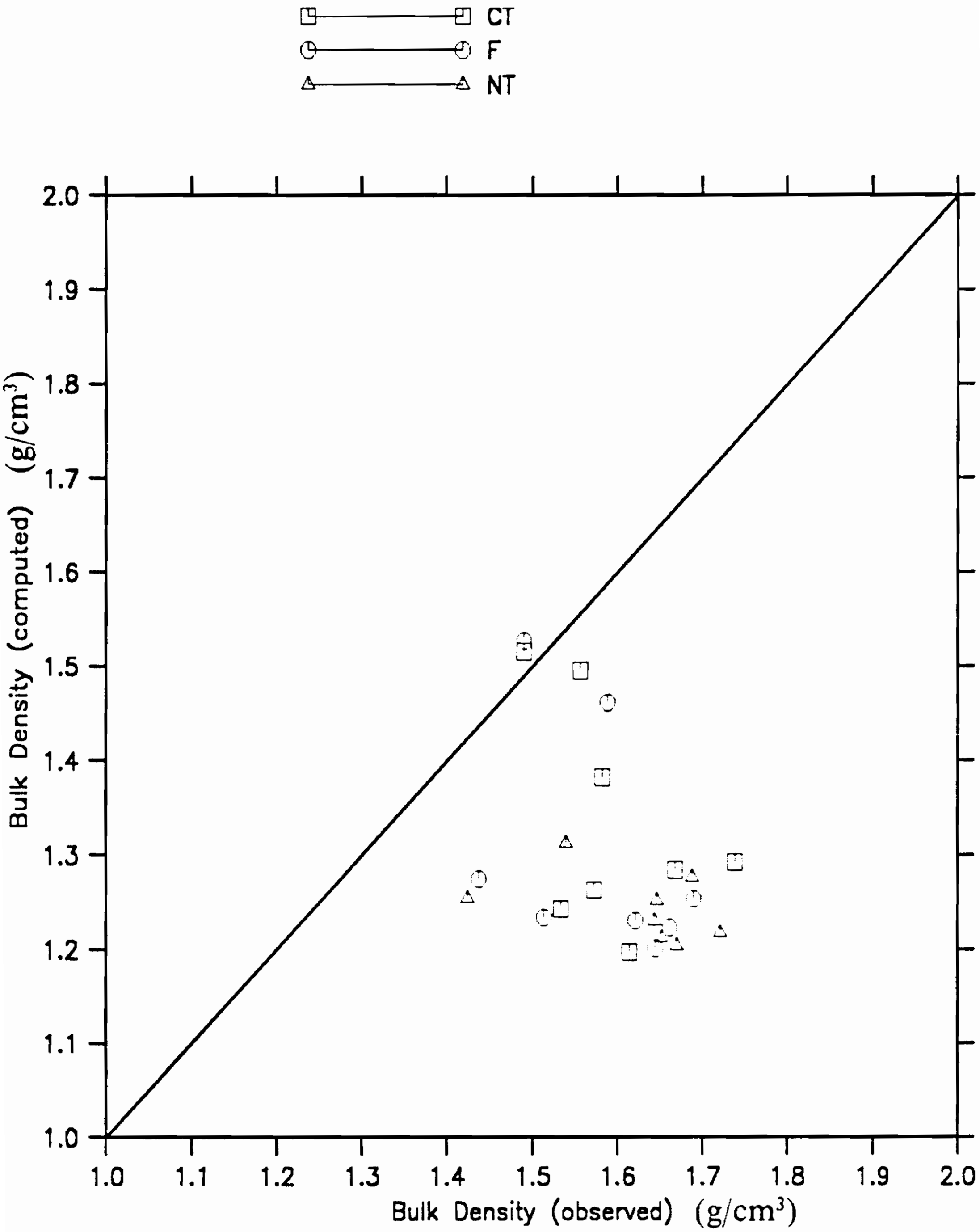


Figure 29. **Performance of the Selected Model for the Subsoil at the End of the 1988 Season**

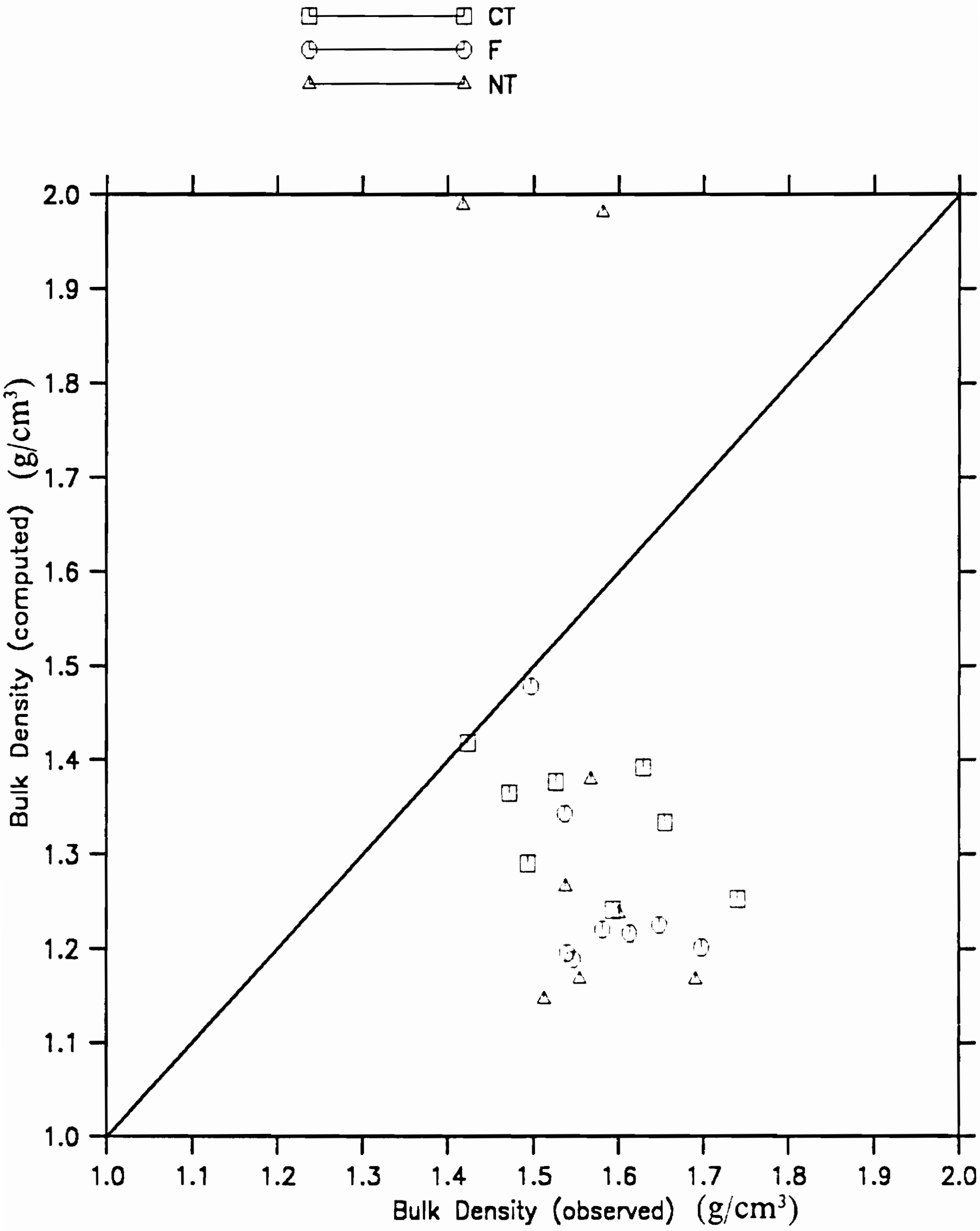


Figure 30. Performance of the Selected Model for the Subsoil at the Beginning of the 1989 Season

the F plots at the end of the 1988 and the beginning of the 1989 cropping seasons, the error increased.

One possibility for poor performance of the model selected for the subsoil layer is that the moisture data was obtained from the 20-25-cm depth layer and the cone index data was obtained from 25-32.5-cm layer. During a short dry season, the upper soil layers contain less moisture due to evapo-transpiration losses. However, after a prolonged dry period, the moisture content may not vary significantly between subsoil layers. Soon after a rainy period, however, the upper layers may contain more moisture, depending on the amount of moisture absorbed into the soil and on the rate of evapo-transpiration losses. Based on the soil moisture data presented in Appendix F, the wetting front had not reached the 20-25-cm depth layer at the end of the 1988 or at the beginning of the 1989 cropping season in most of the test plots, even when the data collections were made only a short period after rain showers. Therefore, it is likely that in those two wet seasons, the actual moisture contents at the points where cone indices were determined were higher than those used in the model validation procedure. According to the surface of prediction of the model selected for the subsoil layer, the predicted bulk density for a given cone index value increases with increasing moisture contents. Therefore, if the actual moisture contents at the depths of cone indices were used, the model should have predicted more accurate bulk density values in those two wet seasons. On the other hand, the moisture contents used for mold preparation from subsoil sample were in a very narrow range due to practical limitations, and this narrow range also could have caused the model to perform poorly when used at higher moisture contents.

4.6 Conclusions

The model selected for the topsoil layer was:

$$\mathbf{CI} = \frac{9931.86909\times\mathbf{BD}^{7.150479}}{[45.064824 + (\mathbf{MC} - 9.119457)^2]}$$

where

BD = Bulk Density(g/cm^3),

MC = Average Moisture Content (%), and

CI = Cone Index (kPa).

The following conclusions regarding the performance of this model were drawn from this study:

1. The model can be used to predict soil bulk density accurately in the topsoil layer of recently disturbed Virginia soils.

2. About 15 to 20% over-prediction can occur due to the ageing effect at the end of the cropping season and thereafter.

3. Extreme moisture levels above 35% should be avoided for reasonably accurate results.

4. One cropping season after plowing the soil, the predicted bulk density in the disturbed layer should be reduced by 15% to cancel the effect of soil strengthening from the ageing effect. This 15% reduction in predicted bulk density should be made only in undisturbed topsoil layers.

The model selected for the subsoil layer was:

$$\mathbf{CI} = \frac{956617.1324\times\mathbf{BD}^{6.5533}}{[2873.0359 + (\mathbf{MC} - 16.2706)^{4}]}$$

where

BD = Bulk Density(g/cm^3),

MC = Average Moisture Content (%), and

CI = Cone Index (kPa).

The following conclusions regarding the performance of the model selected for the subsoil layer were drawn:

1. The model predicted bulk density data using cone index and moisture content data accurately under dry soil conditions.
2. The amount of under-prediction increases with increasing soil moisture content.
3. The model would produce better results in wet seasons if the moisture contents from the same depths where the cone index data were collected were used in the model.
4. The bulk density values predicted by this model should be increased by about 15% to improve accuracy.

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APPENDIX A. DESIGN DETAILS AND OPERATION OF THE PENETROMETER

The tractor-mounted, hydraulically-operated recording penetrometer developed by Jayatissa (1986) was modified for collecting penetration resistance data in this study. The penetrometer consisted of two major systems:

1. The penetrometer assembly, and
2. The data acquisition system.

A.1 Penetrometer Assembly

The penetrometer assembly consisted of a frame to facilitate lateral movement of the penetrometer, a penetrometer carriage, and a hydraulic system for controlling the rate of penetration.

A rectangular frame 3-m long, 0.5-m wide was constructed using 5-by-5 cm box beams. This rectangular frame was supported by two 3.75-by-3.75 cm angle iron legs in the front and two

2.5-by-2.5 cm angle iron legs in the rear. The 97.5-cm long legs were welded to the frame at the corners. A 5-by-5 cm box beam was located between the front legs, approximately 60 cm below the upper rectangular frame, to mount the connectors for the 3-point linkage. Additional braces, as shown in Figure 31, were provided for reinforcement. The entire frame was mounted on two 75-by-20-by-2.5 cm wooden boards for stability as well as for distributing the load over a larger area.

The penetrometer carriage illustrated in Figure 32 included a rectangular steel plate, a frame to guide the penetrometer probe, and wheels to support and guide the carriage during lateral movement. On each corner of the 52.5-by-45-by-0.625 cm rectangular steel plate, approximately 4.5 cm from the edges in the long direction, four 20-cm posts constructed of 5-by-5 cm box beams were mounted. Two-cm wide vertical slots were made through each set of posts mounted along the longest dimension of the rectangular plate. After attaching the steel plate to the rectangular frame from the bottom, two 1.9-cm diameter 50-cm long shafts were inserted into the slots made in the vertical posts such that the axes of the shafts were perpendicular to the longest dimension of the frame. Then, 5-cm wide and 5-cm diameter steel rollers (press wheels) were mounted at the ends of these two shafts directly above the box beams. The four press wheels riding on the box beam supported the entire penetrometer carriage. The shafts with wheels were spring-loaded, with four springs located vertically inside each vertical post. The force on these springs pressing on the shafts could be increased by turning the bolt provided on the top plate of the post clockwise and then pushing against a flat washer located on the top of the springs. In order to prevent rotation of the penetrometer carriage and to guide it along the box beams of the rectangular frame, 4 wheels with flanges 5 cm wide and 7.5 cm in diameter were mounted directly beneath the press wheels so that the box beams were sandwiched between four sets of wheels. The wheels with flanges were mounted on the rectangular plate from underneath and through the slots provided on the plate. The wheels were pressed against the beam.

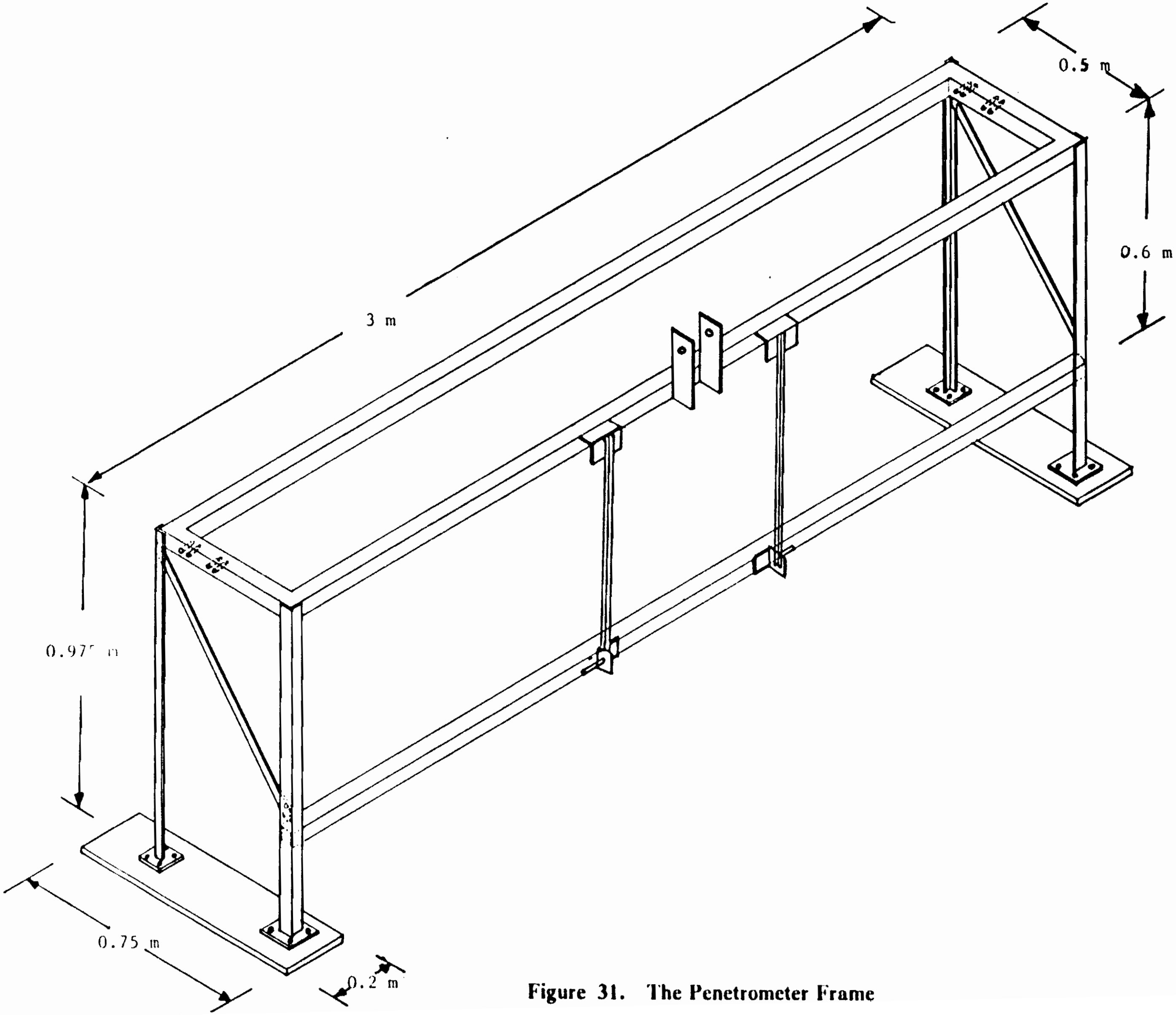


Figure 31. The Penetrometer Frame

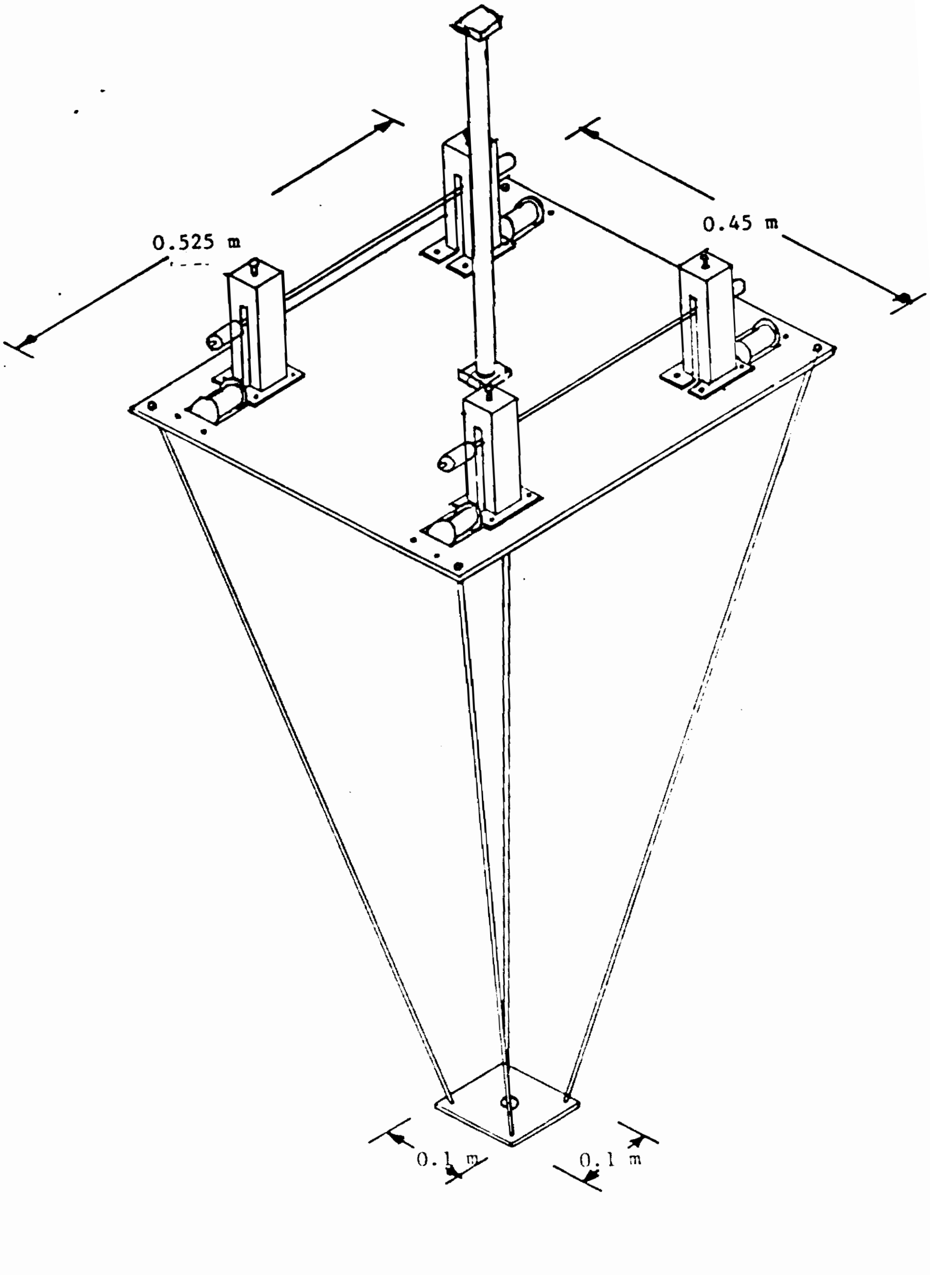


Figure 32. The Penetrometer Carriage

In order to guide the penetrometer straight into the soil, a square steel plate (10-by-10-by-0.625 cm) with a 2-cm hole in the center was located 85-cm below the larger plate described earlier. This plate was attached to the larger plate with the help of four 1.3 cm threaded rods. The two plates were located in such a fashion that the centers of both plates were on the same vertical line.

The lateral movement of the penetrometer carriage on the rectangular frame was facilitated with a hand-cranking mechanism. As Illustrated in Figure 33, it consisted of a crank, four sprockets, and two roller chains. On either side of the rectangular frame, two sets of sprockets were mounted. A hand-crank went through the sprockets on the right, which were the driving sprockets. Two roller chains were looped around all four sprockets, and the ends of the chains were attached to the penetrometer carriage. A retractable 3.3-m metal tape was mounted on the same end of the rectangular frame with a hand-crank. The tape end was attached to the penetrometer carriage, and it extended as the carriage moved to the left. This simple arrangement helped the lateral placement of the penetrometer assembly at predetermined intervals.

The simple hydraulic circuit illustrated in Figure 34 was used to control the rate of penetration and to limit the maximum force on the penetrometer during penetration into the soil. The components of the circuit included a hydraulic cylinder, pressure relief valve, directional control valve, and flow control valve.

The hydraulic cylinder with a 3.75-cm bore and 70-cm stroke, was mounted on the large rectangular steel plate with the rod extending downward through a 2.6-cm hole provided at the center of that plate. The pressure relief valve shown in Figure 34 was in addition to the relief valve available with the tractor hydraulic system and was provided to limit the maximum force on the penetrometer. The pressure and temperature compensated flow

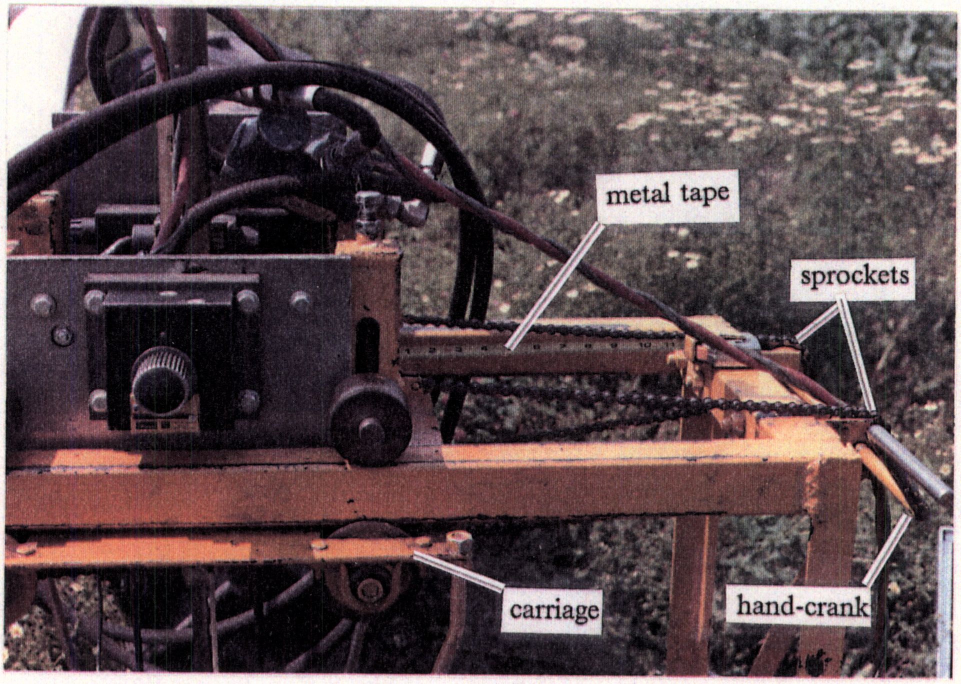


Figure 33. Hand-cranking Mechanism for Lateral Movement of the Penetrometer Carriage

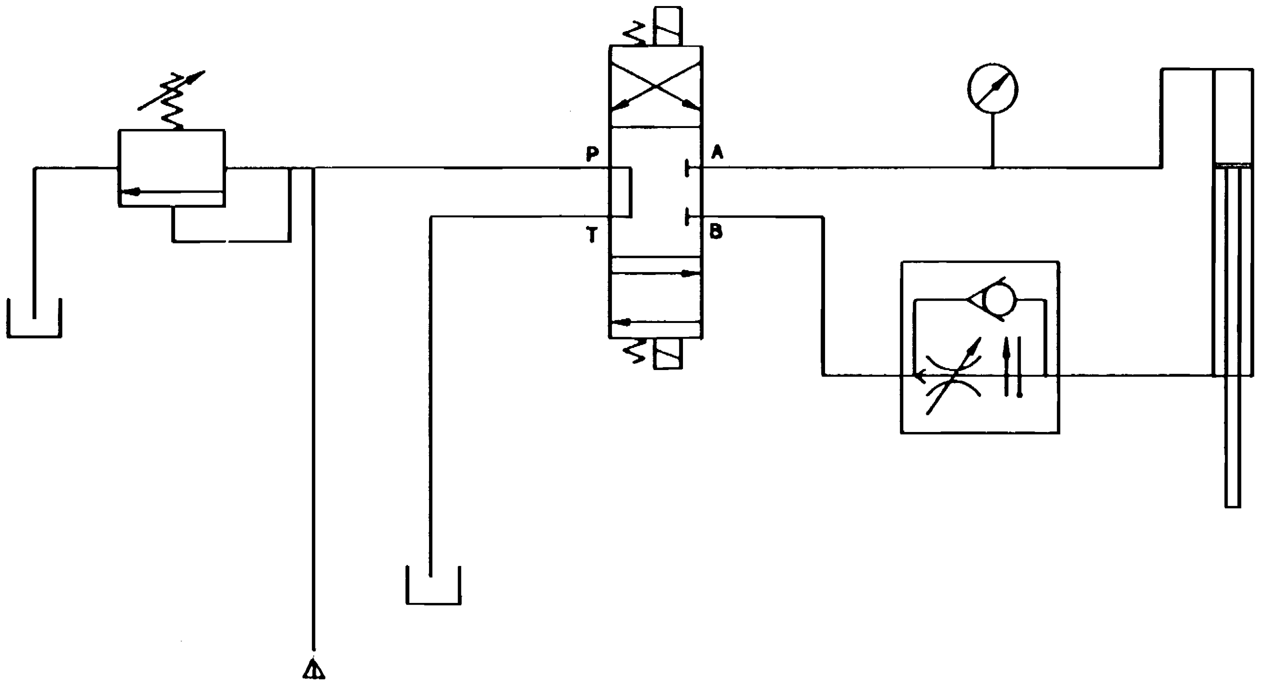


Figure 34. The Schematic of the Hydraulic System Added to Control the Penetration Rate and Maximum Force on the Penetrometer

control valve was located on the rod end of the cylinder to regulate the flow rate from the cylinder and thereby control the penetration at 3 cm/s rate. The solenoid-operated, three-position, tandem-center, 4-way directional control valve was used to extend or retract the cylinder. The directional control valve could be activated using the power from the tractor ignition system. These components of the hydraulic circuit were mounted on aluminum plates and were secured on the penetrometer carriage.

A.2 Data Acquisition System

The penetrometer data acquisition system included the following major components:

1. Standard cone head mounted on a 71-cm long steel shaft
2. Force transducer
3. Amplifier to condition the transducer output
4. Analog-to-digital (A/D) converter
5. Depth transducer to trigger the A/D conversion
6. Microcomputer for data collection and recording on micro diskettes
7. DC/DC converter to condition the power input to other components in the data acquisition system

The 5V DC excitation voltage for the 2224-N capacity, sheer-type strain gage load cell (GSE model 5353) was obtained from the tractor ignition system through a DC/DC converter (PACKAGED POWER ES12T15). This DC/DC converter also produced + 15V and -15V DC supplies for the custom made A/D converter and the signal conditioner based on the INTEL SB30J amplifier. The 12V DC tractor battery supplied power to the DC/DC converter.

Circuit diagrams for the data logging system are given at the end of Appendix A. The load cell was mounted at the end of the hydraulic cylinder rod using an adapter made of aluminum. A limit switch moving over a grooved bar triggered the conversion of the analog signal from the load cell to a digital signal by the A/D converter at 1.27-cm depth intervals (Figure 35), and the signal was then transmitted to the microcomputer as the probe was penetrating the soil. The grooves in the bar were cut 0.7-cm wide and 0.3-cm deep, across a 90-cm long, 2.5-cm by 0.6-cm steel bar at 1.27-cm intervals. This bar with grooves was used in a frame that consisted of another bar having the same dimensions but without grooves and two, 10-cm by 10-cm square plates having 2.6-cm diameter holes at the center. This frame was hung on the hydraulic cylinder rod above the load cell. The penetrometer probe could extend through the hole at the center of the bottom plate. The limit switch was mounted on a block that surrounded the grooved bar. This block was loosely connected to a metal disk mounted on the aluminum adapter above the load cell. Using this setup, both the frame and the limit switch moved down with the penetrometer, until the frame touched the ground. The connector between the block and the metal disk was adjusted to position the block such that the limit switch started triggering the A/D converter just before the penetrometer cone touched the ground and continued to do so at each 1.27-cm (0.5-in.) penetration of the cone tip. In the event that the soil resistance force exceeded the total weight of the penetrometer setup, the frame of the penetrometer would lift up from the surface. In such instances, the frame with the grooved bar and the limit switch remained stationary and prevented the collection of inaccurate data after the tip advancement had stopped.

The circuit boards with the amplifier, the DC/DC converter, and the A/D converter were housed in an aluminum rack. Thirty-two pin connectors and multi-wire ribbon cables were used to make connections between boards. The A/D converter was connected to the serial port of an IBM Convertible microcomputer that collected A/D converter output data and stored the data on micro diskettes. The rack with the circuit boards and the microcomputer were kept in an aluminum case for transportation and for protection in field conditions. A 37-pin quick coupler was mounted on the case for the external connections between the transducers and the data logger. Another 16-pin quick coupler was fitted to the case to supply power from the tractor battery.

The data acquisition program listed in Appendix B was used to collect A/D converter output data and to store them on the micro diskettes. The data collected from all penetration tests in one vertical section were stored in one file. This data acquisition program had three major sections. The first section was used to record the background information about the plots. The second section was used for the data collection and was initiated by pressing any key on the key pad. The program collected the first data point just before the cone touched the soil surface and discarded the next two data points received before the cone was fully inserted into the soil. The fourth data point was assumed to be collected when the base of the cone was flushed with the soil surface and from that point, the program collected all the data received from the A/D converter. If the base of the cone was flush with the surface after collecting the fourth data point, the operator included a comment in the third section of the program to be stored with the A/D output data and removed those extra data points collected before the cone was fully inserted into the soil. After the penetrometer was fully extended or, in case of an emergency such as the frame lifting off the ground if the penetrometer ran into a rock,

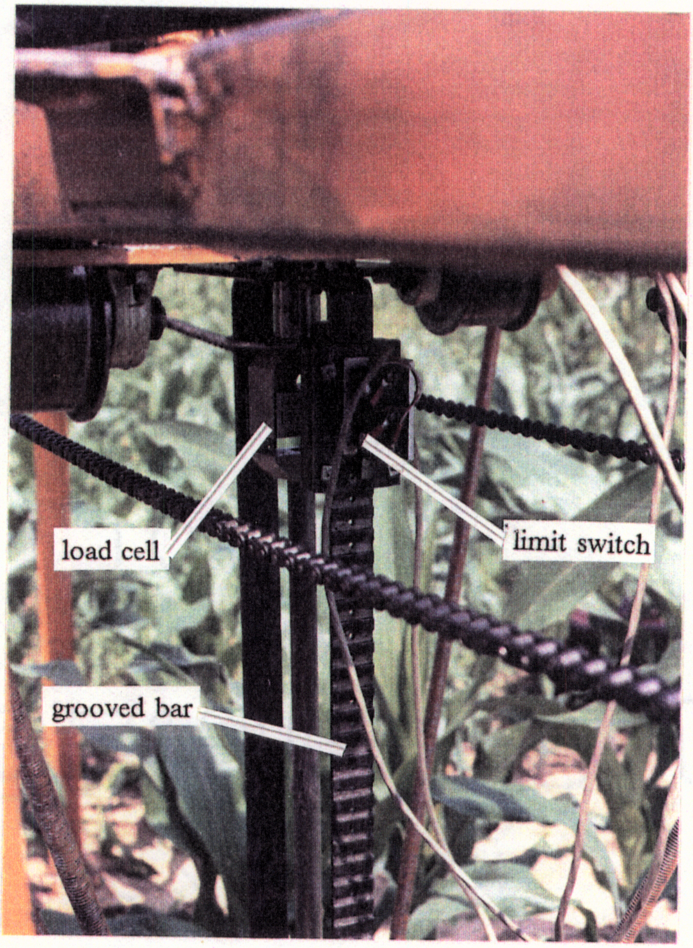


Figure 35. Arrangement of Components in the Depth Sensing Mechanism.

the data collection was stopped by pressing the function key F1. Before entering the comments in the third section of the program, the operator was given an opportunity to discard the data collected if an error occurred during the penetration test just completed and then to run another test. After comments were entered, the program recorded data and comments on a diskette and then looped back to the second section for collection of another set of data. After collecting data from all the penetration tests in the vertical section, the data file was closed and another file was opened for the set of data from the next vertical section. Therefore, a file-naming convention was followed to identify the plots and the vertical sections from which these data sets were collected.

A.3 Operating the Penetrometer in the Field

After the tractor had been driven backwards into the test plot, the penetrometer was positioned over the vertical section from which the data were to be collected. The wire connections between the penetrometer and the data logger, the hydraulic lines between the penetrometer and the tractor, and the power connection between the data logger and the tractor battery were made. After the power was applied to the data logger, 30-45 minutes were allowed for warm-up. The penetrometer carriage was then moved using the hand-cranking mechanism to position the penetrometer over the point where the penetrometer test was to be conducted. Next, the data acquisition program listed in Appendix B was run on the computer and the information about the test was entered. When the computer was waiting for data from the A/D converter, the hydraulic cylinder was activated by flipping the toggle switch that controlled the solenoid-operated directional-control valve, to push the penetrometer into the soil. At the end of penetration, data acquisition was stopped by pressing the function key F1, and the penetrometer was withdrawn from the soil by flipping the toggle switch to the opposite direction. After the comments were entered, the penetrometer carriage was moved to the next test location, using the tape measure as a guide, and the data collection was repeated as before. At the end of data collection from one vertical section, the tractor was driven back to the next vertical section. While moving the tractor within the test area, the data logger was kept on the frame of the penetrometer with the power on.

A.4 Converting A/D Output to Cone Index

After the penetration tests were completed, the data files containing A/D converter output were transferred to the MicroVAX computer for storage and for fast conversion to cone index data. Unnecessary data were removed from those files using a file editing program. After the data files were transferred, a second copy of these files was made using the files stored in the MicroVax computer, and the first copy was then discarded. This step was included to remove the 'end of file' (CNTL-Z) characters used in IBM machines, which leads to erroneous results due to incompatibility. The names of the input data files were listed in the file named 'DIR.DAT' to be used by the data conversion program listed in Appendix C. When this data conversion program was run, it first asked the operator to enter the file extension used for input files and for the output files. It then asked for the coefficients in the linear calibration equation developed for the penetrometer data logger. Next, it selected the data files with the given extension from the file list stored in the 'DIR.DAT' file and started data conversion. The first data point in each penetration test was considered as the no-load output of the A/D converter. This no-load output was subtracted from subsequent values in each penetration test and, using the calibration equation, the remainder was converted to cone index data. These output data were stored in a file with the same name as the input file but with the file extension provided by the operator. When the output file was sent to the printer or copied onto a floppy diskette, the cone index data were seen in a tabulated form.

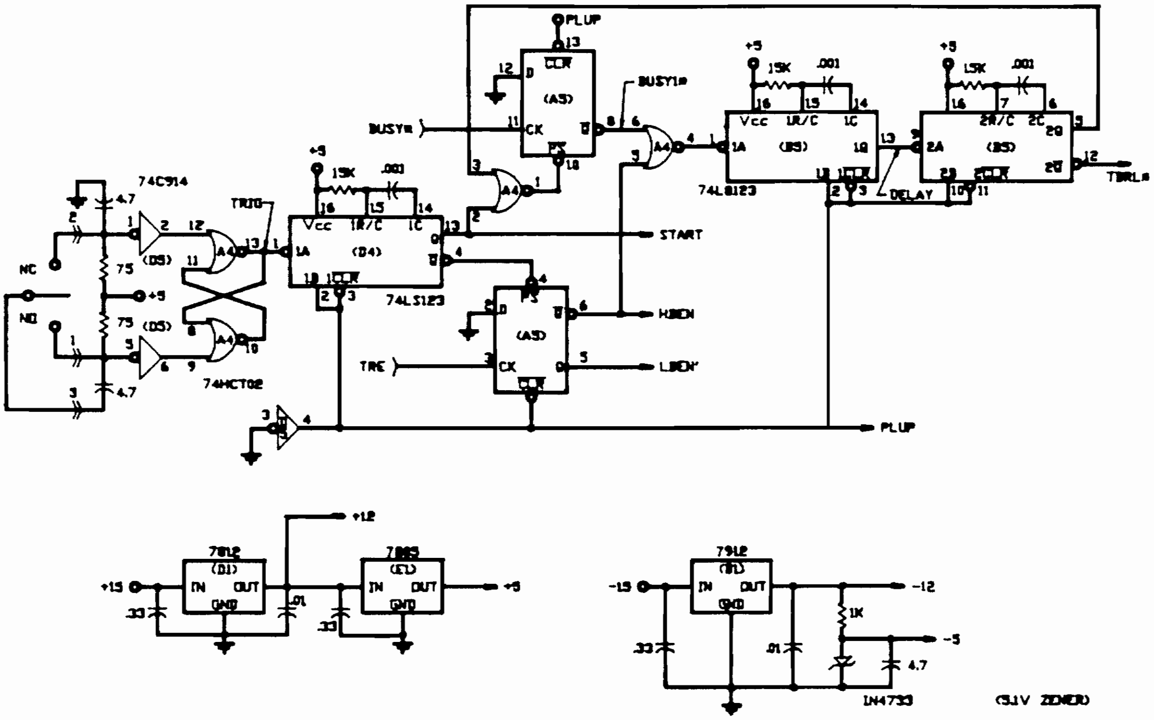


Figure 36. Circuit Diagram of the A/D Converter (Part 1)

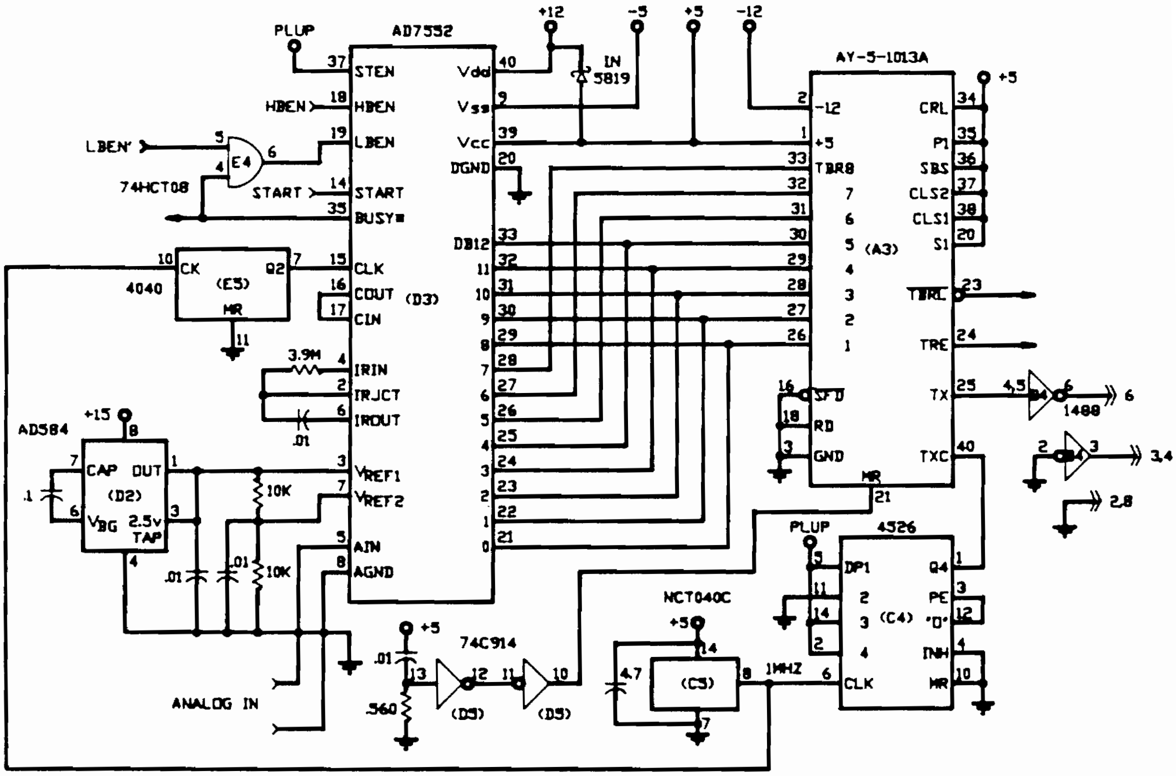


Figure 37. Circuit Diagram of the A/D Converter (Part 2)

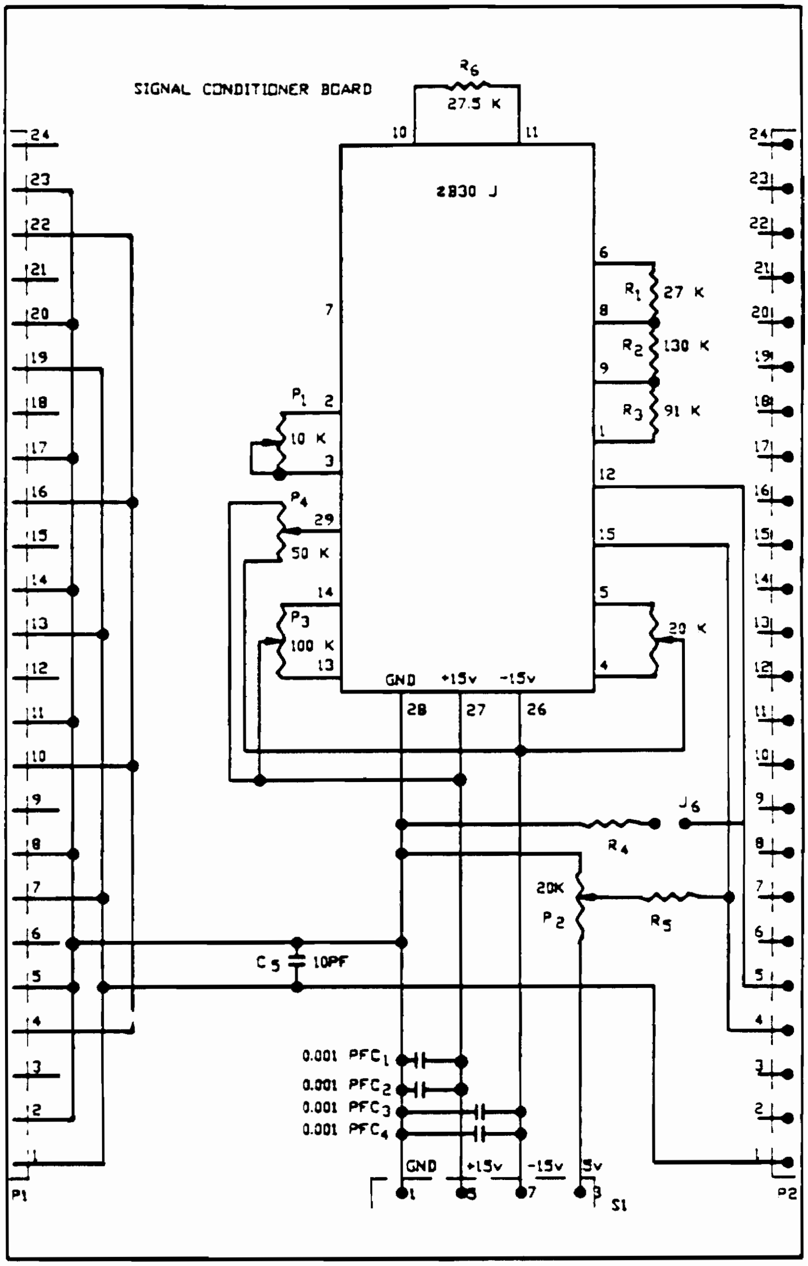


Figure 38. Circuit Diagram of the Amplifier

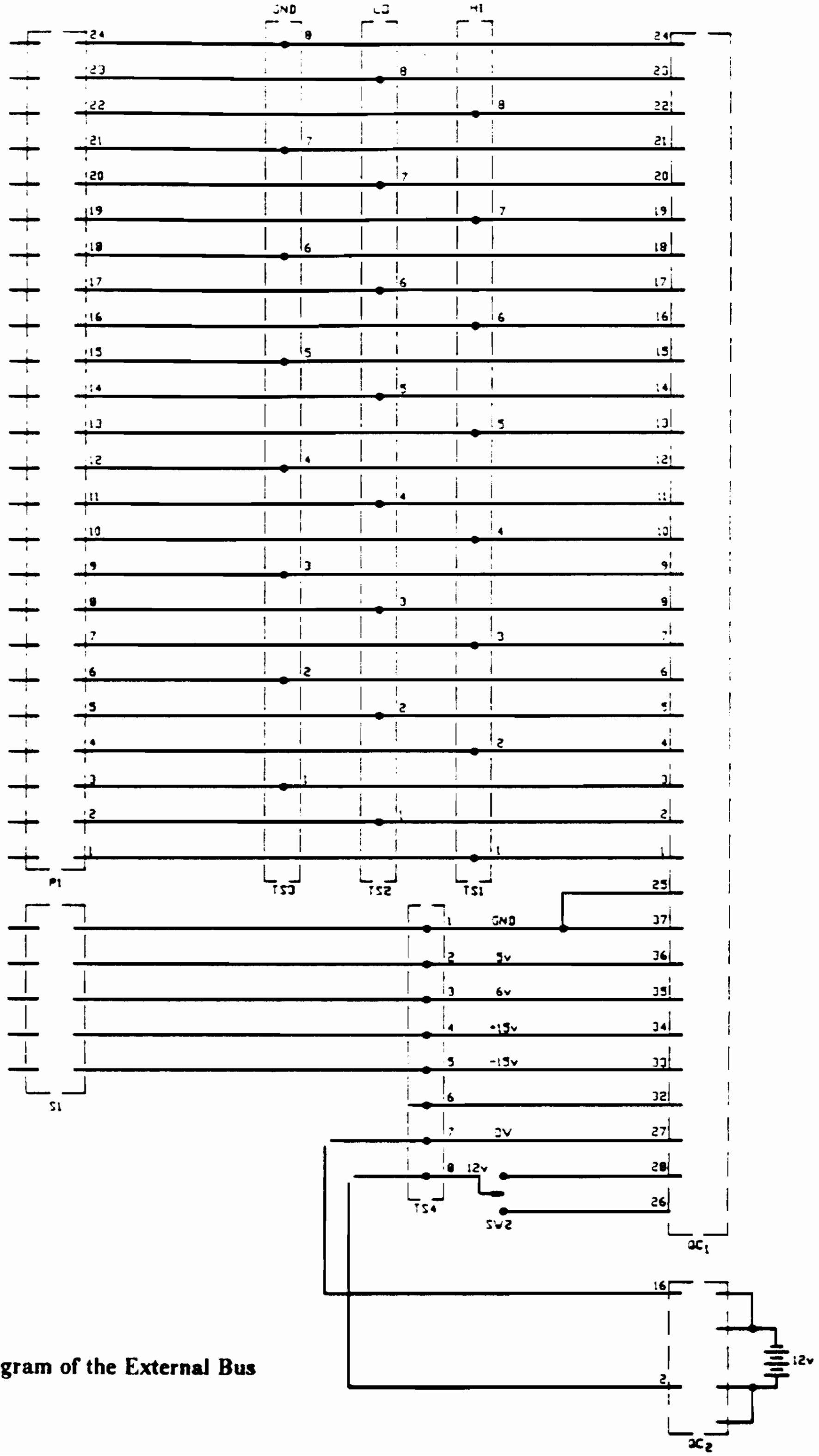


Figure 39. Circuit Diagram of the External Bus

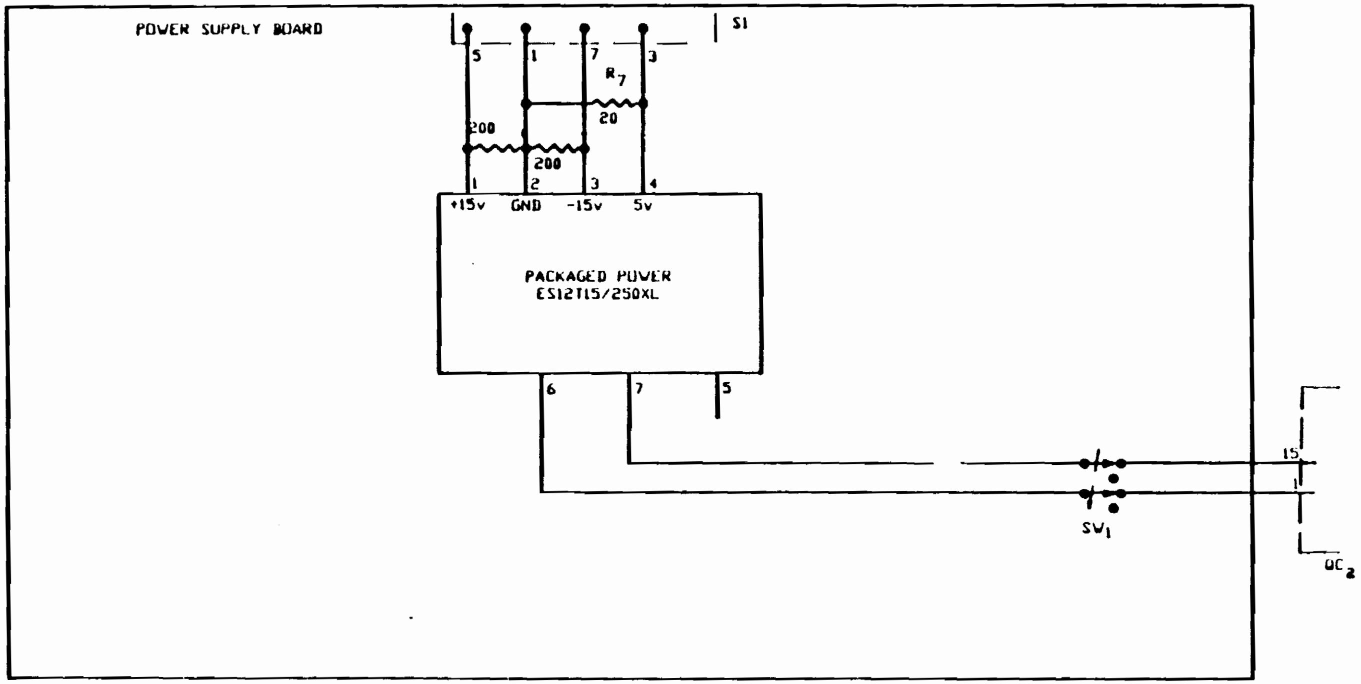


Figure 40. Circuit Diagram of the Power Supply

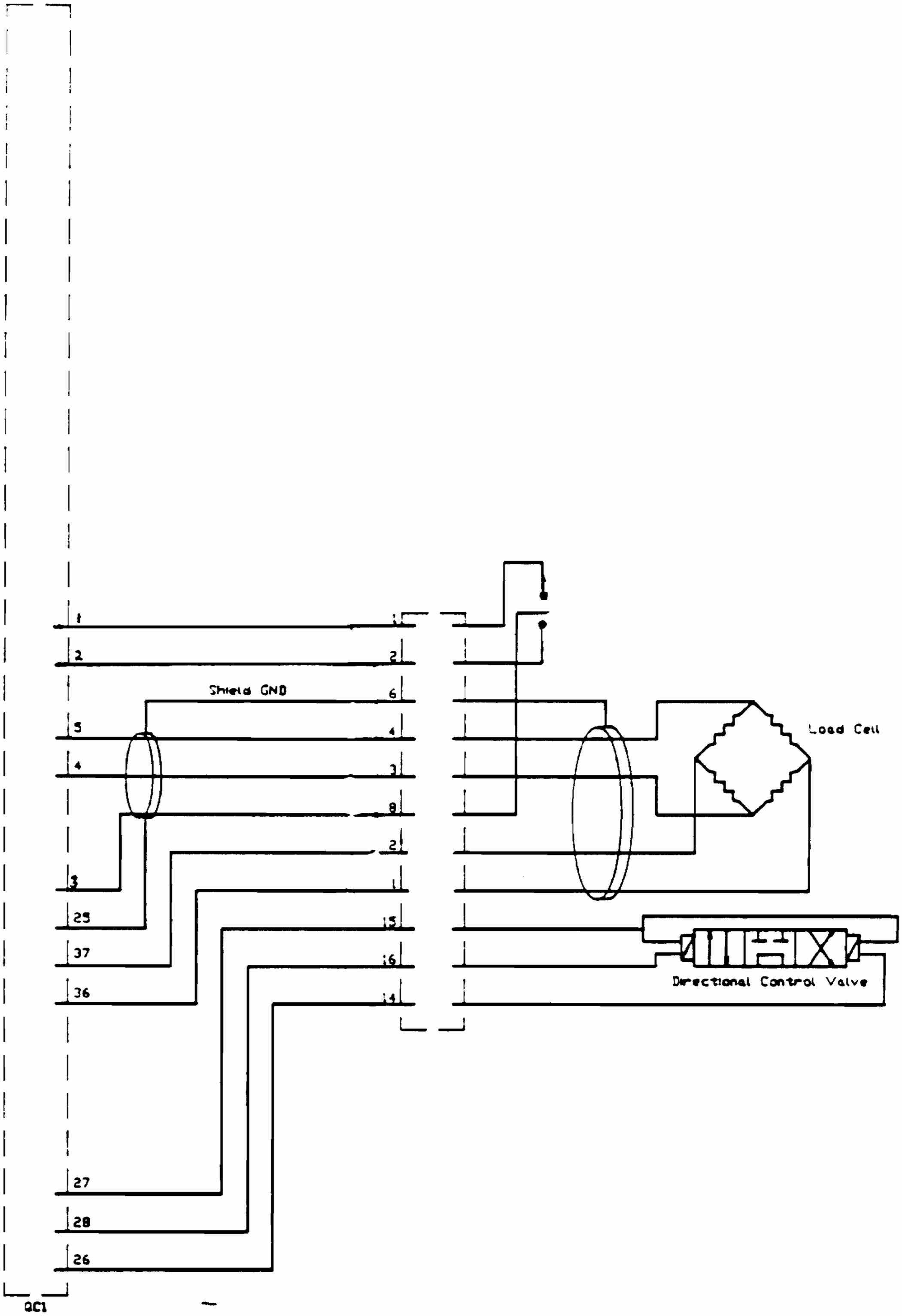
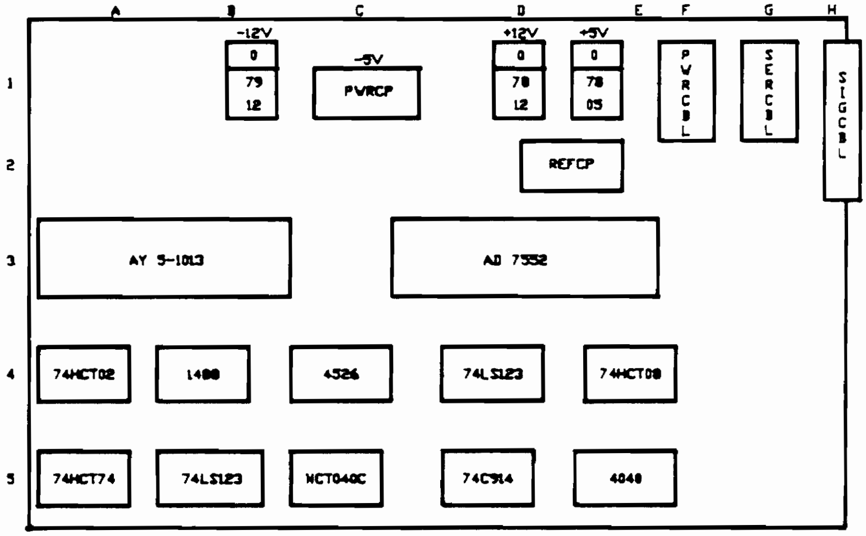
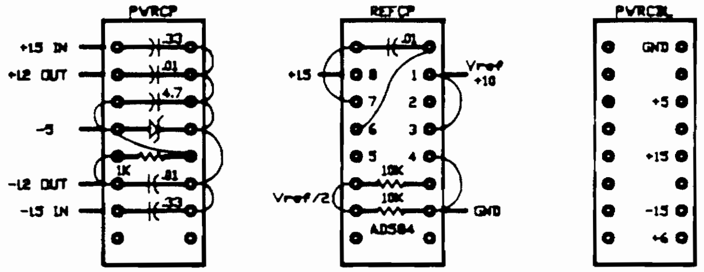


Figure 41. Circuit Diagram of the Load Cell and the Depth Sensor



Circuit Board, Component Side



Component Platforms, Wire Wrap Side

Figure 42. Layout of Components on A/D Converter Board

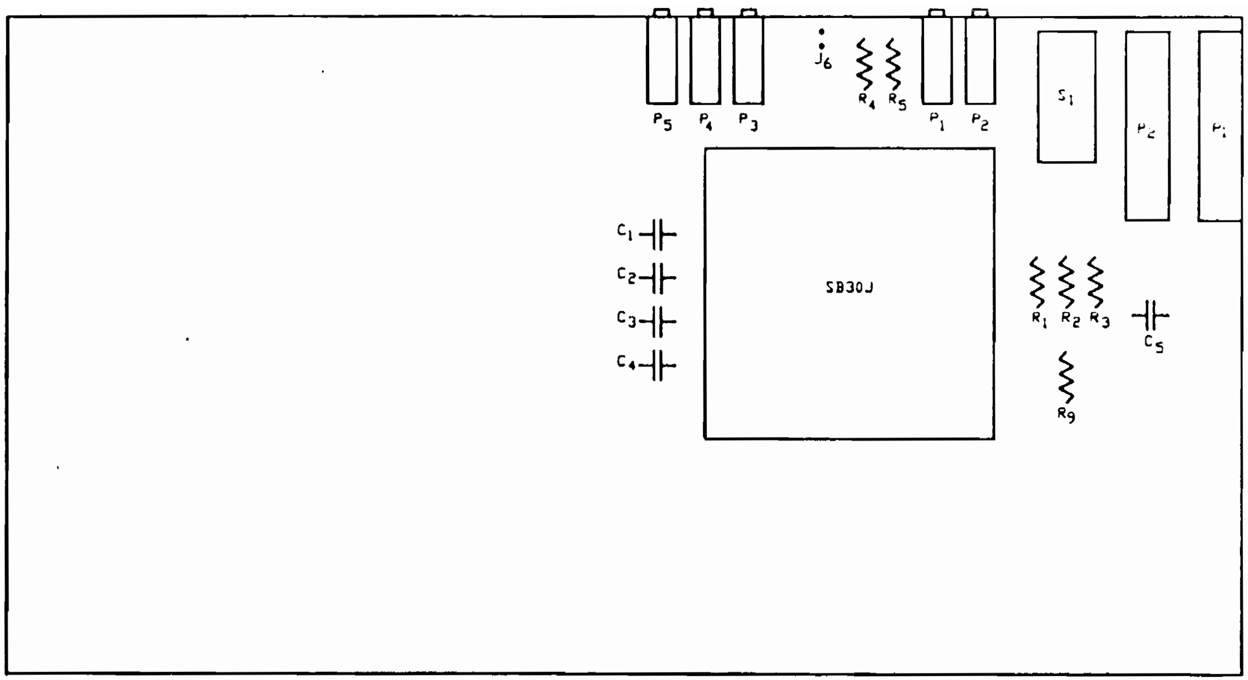


Figure 43. Layout of Components on the Amplifier Board

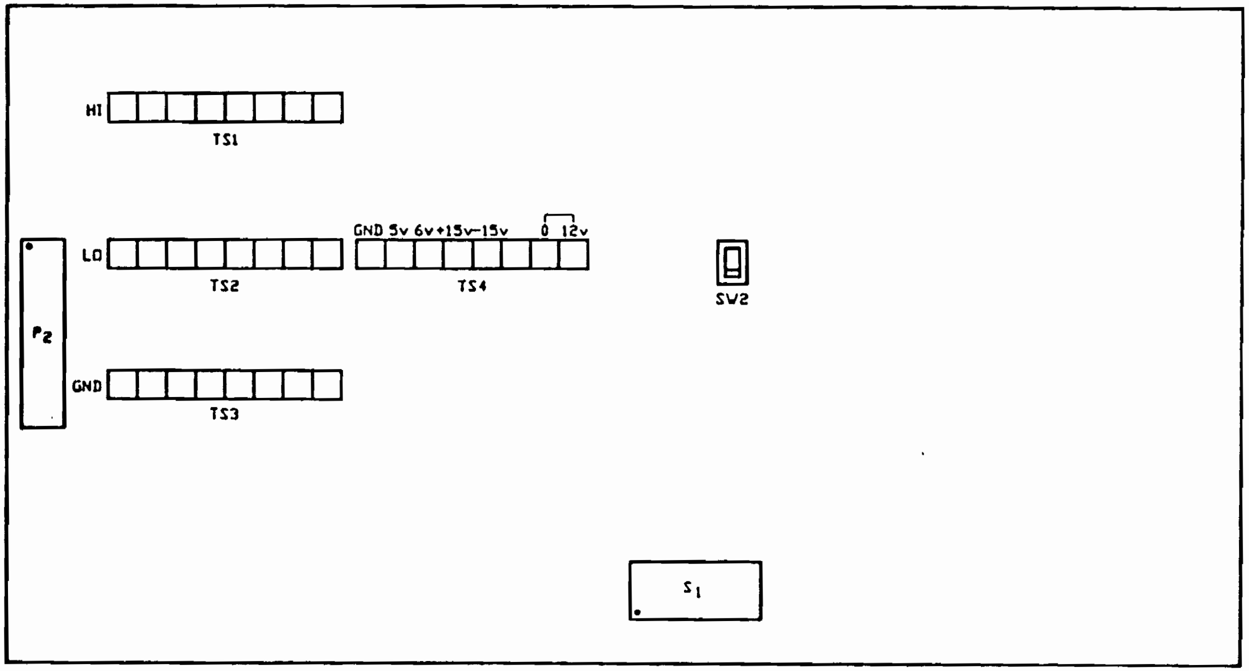


Figure 44. Layout of Components on the External Bus Board

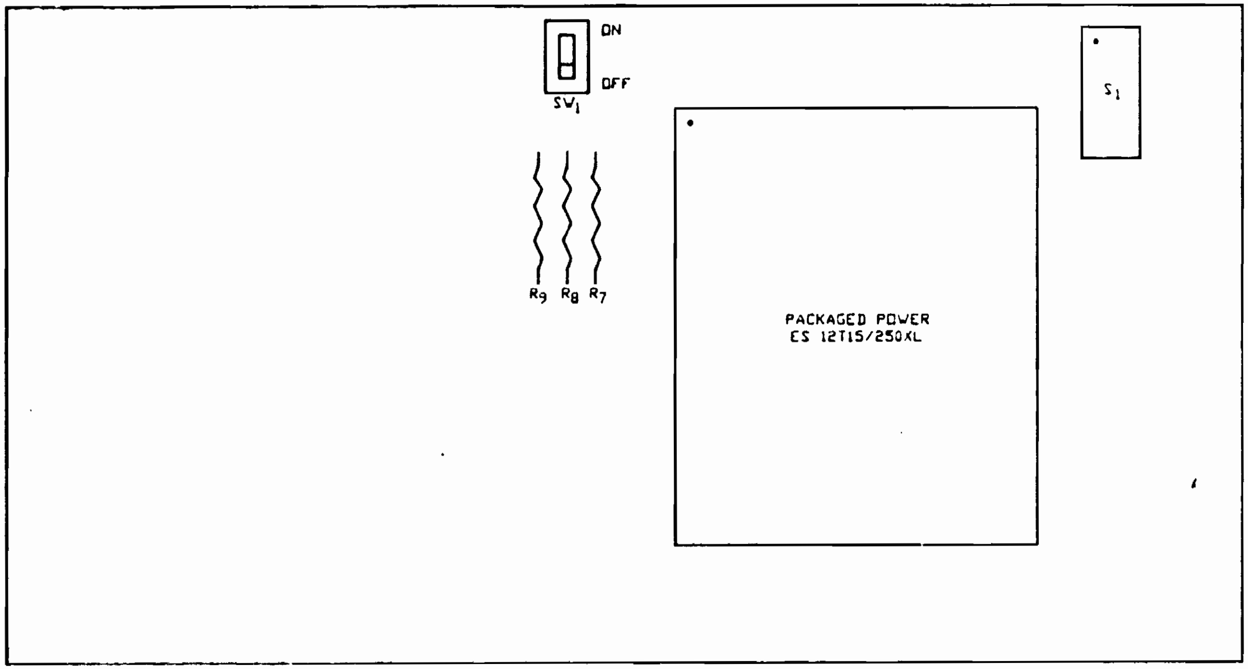


Figure 45. Layout of Components on the DC/DC Converter Board

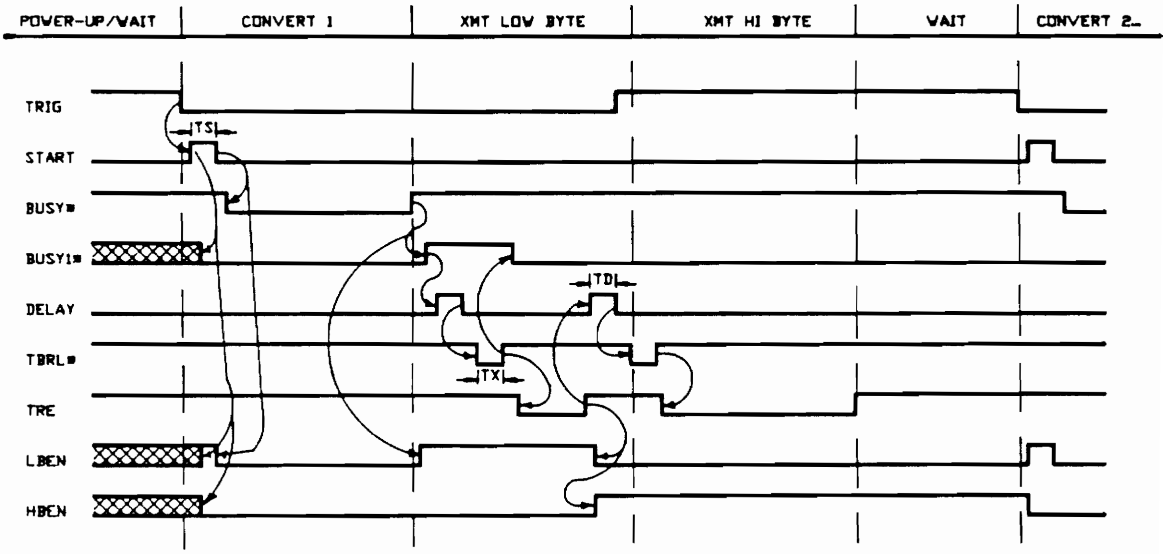


Figure 46. Timing Diagram of the A/D Converter

APPENDIX B. DATA ACQUISITION PROGRAM

```
0   '************************************************************************
10  '*
20  '*   This program is written by D. N. JAYATISSA to collect penetration
30  '*  resistance data using the tractor-mounted hydraulically-operated
35  '*  penetrometer.
40  '*  Data would be collected at 0.5 inch depth intervals and be stored
50  '*  on diskette for further analysis.
60  '*
70  '************************************************************************
80  CLS
90  CLEAR,65500!,40000!
100 ON ERROR GOTO 2000
110  DIM  HB$(100) , LB$(100)
120  PRINT "" : PRINT "" : PRINT "": PRINT ""
130  PRINT "                    DATA ACQUISITION PROGRAM"
140  PRINT "" : PRINT ""
150  PRINT "                         Written By"
160  PRINT "" : PRINT ""
170  PRINT "                       D. N. Jayatissa"
180  PRINT "" : PRINT "" : PRINT "" : PRINT "" : PRINT ""
190  PRINT " Press Any Key To Continue ............"
200  A$ = INKEY$ : IF A$ = "" THEN 200
210  CLS : PRINT "" : PRINT ""
220  PRINT " Please ENTER following information : - "
230  INPUT " What is the disk drive for data storage (A/B) "; DD$
231  FF$ = DD$ + ": *.*"
233  FILES FF$
240  PRINT "" : PRINT " Enter the name for the output file"
250  INPUT " The extension '.DAT' would be added automatically "; NA$
260  DF$ = DD$ + ":" + NA$ + ".dat"
270  CLS
280  PRINT "" : PRINT " Enter date if it is not - > " DATE$
290  INPUT D$ : IF D$ = "" THEN D$ = DATE$
300  PRINT : INPUT " What is the treatment ";TR$
310  PRINT : INPUT " What is the horizontal spacing ";SP
320  PRINT : INPUT " What is your name "; NA$
330  PRINT : INPUT " Do you want to change  informations above (y/n)" ;A$
340  IF A$ = "y" OR A$ = "Y" THEN 280
350  OPEN DF$ FOR OUTPUT AS #1
360  PRINT#1,"  Date : " D$
370  PRINT#1,"  Treatment : " TR$
380  PRINT#1,"  horizontal spacing : " SP "in."
390  PRINT#1,"  Vertical depth increment : 0.5 in."
400  PRINT#1,"  Data collected by : " NA$
410  '
420  PRINT#1," ***************************"
430  SOUND 2000,10
```

```
440  CLS : PRINT " " : PRINT " your last test # was " TN
450  INPUT " What is the test number "; TN
460  LO = (TN-1) * SP
470  PRINT " Enter location if it is not -> " LO
480  INPUT C$ : IF C$ = "" THEN C$ = STR$(LO)
490  CLS
500 '
510 ' Start data collection
520 '
530  NO = 0
540  PRINT "" : PRINT "" : PRINT "" : PRINT "" : PRINT ""
550  PRINT "                    Press any key to start scanning !"
560  A$ = INKEY$ : IF A$ = "" THEN 560 ELSE SOUND 600,10
570  PRINT "" : PRINT "" : PRINT "" : PRINT "" : PRINT ""
580  PRINT "                  SCANNING !!! "
590  ST$ = TIME$ ' starting time
600  '
610  OPEN "com1:4800,N,8,2" AS # 2
620  PRINT "" : PRINT " PRESS F1 to STOP SCANNING !!!!!"
630  FIELD #2,1 AS SL$, 1 AS SH$
640  ON COM(1) GOSUB 670
650  IF 1 < > 2 THEN : KEY(1) ON : ON KEY(1) GOSUB 700 : COM(1) ON :
    GOTO 650
660 '
670  GET#2,2 : NO = NO + 1
680  LB$(NO) = SL$ : HB$(NO) = SH$ : PRINT (NO-4)*.5,SL$,SH$ : SOUND 3000,1
690  GOTO 650
700 '
710  CLOSE #2
720  SOUND 500,30
730  INPUT " Do you want to save these data (y/n)"; Y$
740  IF Y$ = "n" OR Y$ = "N" THEN 750 ELSE 760
750  PRINT"" : PRINT "  RUN another test !!!!" : GOTO 470
760  INPUT " Any comments ?  If it is OK press ENTER ";CO$
780  IF CO$ = "" THEN CO$ = "OK"
800  PRINT#1,"  Test : " TN
810  PRINT#1,"  Position : " C$
820  PRINT#1," DEPTH \ OUTPUT --------> "
830  'Pent. resist. at -1.0 depth is the no-load output of the load cell.
     Fourth data point is taken when the base of the cone is flushed
     with surface.
840  I = 1
850  GOSUB 1000
860  PRINT#1,"-1.0",C
865  PRINT"-1.0",C
870  FOR I = 4 TO NO
880  GOSUB 1000
890  PRINT#1,(I-4)*.5,C
895  PRINT C ":";
900  NEXT I
910  PRINT#1,"  COMMENTS : " CO$
920  INPUT " Another test ?";A$
930  IF A$ = "n" OR A$ = "N" THEN CLOSE : END ELSE 410
1000 '
1010 A = ASC(LB$(I)):B = ASC(HB$(I))AND 31
1020 C =  A + B*256
1030 IF C > = 4096 THEN C = C-8192
1040 RETURN
2000 IF ERR = 53 THEN RESUME NEXT 'no files on the diskette
```

APPENDIX C. DATA REDUCTION PROGRAM

```
C ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
C
C       This program uses the list of files stored in DIR.TXT file with
C       the given extension and converts the A/D output collected using
C       the data acquisition program listed in Appendix B, to cone
C       index using the linear calibration equation.
C
C ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
      DIMENSION IENTRY(55,15),ENTRY(55,15)
      CHARACTER ENTRY*5,FILENM*11,OFILENM*11,FILE*7,EXT*3,
     / EXT1*3,EXT2*3,SP*2,CMNT*10,COMMENT*5,LINE*80
      INTEGER D,RESIST,IFLAG,IENTRY,IROW,MAXD,MAXL
      REAL DD,DEPTH
      DOUBLE PRECISION SLOPE, AINTRCP
C
C
      LN=4
      WRITE(6,10)
 10    FORMAT(' PRESS ANY KEY TO CONTINUE')
      READ(5,11)A
 11    FORMAT(A1)
      WRITE(6,12)
 12    FORMAT(' WHAT IS THE FILE EXTENSION FOR INPUT FILES ?',$)
      READ(5,14) EXT1
      WRITE(6,13)
 13    FORMAT(' WHAT IS THE FILE EXTENSION FOR OUTPUT FILES ? ',$)
      READ(5,14) EXT2
 14    FORMAT(A3)
      WRITE(*,*)' ENTER THE VALUES FOR THE CALIBRATION EQUATION'
      WRITE(6,15)
 15    FORMAT(1X,' SLOPE  ',$)
      READ(5,20)SLOPE
      WRITE(6,16)
 16    FORMAT(1X,' INTERCEPT  ',$)
      READ(5,20)AINTRCP
 20    FORMAT(F10.6)
C
      OPEN(UNIT=1,FILE='DIR.TXT',STATUS='OLD')
C
 25    READ(1,30,END=600)FILENM,COLON
 30    FORMAT(A11,A1)
       IF(COLON.EQ.';') THEN
        BACKSPACE 1
        READ(1,32)FILE,EXT
 32    FORMAT(A7,1X,A3)
       ELSE
        BACKSPACE 1
        READ(1,31,END=600)FILENM
 31    FORMAT(A10)
        BACKSPACE 1
        READ(1,33)FILE,EXT
 33    FORMAT(A6,1X,A3)
       END IF
      IF(EXT.NE.EXT1) GOTO 25
      OFILENM=FILE//'.'//EXT2
C
      MAXD=0
      IROW=0
C
```

```
      OPEN(UNIT=2,FILE=FILENM,STATUS='OLD')
      OPEN(UNIT=3,FILE=OFILENM,STATUS='NEW')
C
       WRITE(3,*)' FROM FILE : ',FILENM
       WRITE(3,*)' '
C
      DO 50  I=1,55
       DO 50 J=1,15
        ENTRY(I,J)='     '
        IENTRY(I,J)=0
 50    CONTINUE
      WRITE(*,*)'FROM ',FILENM,' TO -> ',OFILENM

 100   READ(2,110,END=150)LINE
      DO 105 I = 1,20
         IF(LINE(I:I).EQ.CHAR(9))LINE(I:I) = ' '
 105   CONTINUE
 110   FORMAT(A)
      READ(LINE,'(5X,A2)')SP
      IF(SP.NE.'  ')THEN
       IFLAG=0
       READ(LINE,112)CMNT,COMMENT
 112     FORMAT(A10,2X,A5)
         IF(CMNT.EQ.'  COMMENTS') THEN
          D=D+1
          ENTRY(D,IROW)=COMMENT
         END IF
       GOTO 100
      ELSE
C        BACKSPACE 2
       READ(LINE,111)DEPTH,RESIST
 111     FORMAT(BN,F8.0,I12)
        DD=DEPTH*2.+1.
        D=DD
      END IF
       PR=6.894*(RESIST*SLOPE+AINTRCP)
      IF(IFLAG.EQ.0) THEN
       PZERO=PR
       IFLAG=1
       IROW=IROW+1
       GOTO 100
      END IF
      IF(D.GE.MAXD) MAXD=D
      IENTRY(D,IROW)=PR-PZERO
      GOTO 100
C
 150   CONTINUE
       WRITE(3,200)(I,I=1,15)
 200   FORMAT(1X,'     ',15(1X,I3,1X)/)
        MAXL=MAXD+1
       DO 250 D=1,MAXL
        IX=0
        DO 225 IROW=1,15
         IF(IENTRY(D,IROW).NE.0) IX=IX+1
         IF(ENTRY(D,IROW).NE.'     ') IX=IX+1
 225     CONTINUE
        IF(IX.EQ.0) GOTO 250
         WRITE(3,226)D
 226       FORMAT(1X,I4,$)
         DO 231 IROW=1,15
          IF(IENTRY(D,IROW).NE.0) THEN
           GO TO 230
          ELSE
           GO TO 235
          END IF
 231      CONTINUE
       GO TO 250
```

```
230     WRITE(3,240) IENTRY(D,IROW)
240      FORMAT('+',I5,$)
       GO TO 231
235     WRITE(3,245) ENTRY(D,IROW)
       GO TO 231
245      FORMAT('+',A5,$)
250    CONTINUE
C
     CLOSE (UNIT=2)
     CLOSE (UNIT=3)
      MAXD=0
      MAXL=0
     GO TO 25
600   CLOSE (UNIT=1)
      STOP
      END
```

APPENDIX D. DATA FROM CORE SAMPLE ANALYSES

Beginning of 1987 Cropping Season

Plot#	Depth	Bulk Density	Total Porosity	Micro Porosity	Macro Porosity	Void Ratio
1	1	1.135388	57.15516	31.35388	25.80127	1.334004
2	1	1.159867	56.23143	30.29616	25.93527	1.284745
3	1	1.403596	47.0341	34.7537	12.2804	0.888008
4	1	1.18971	55.10529	34.7537	20.35159	1.227434
5	1	1.25408	52.67623	31.58054	21.0957	1.113103
6	1	1.077365	59.34473	33.77153	25.57319	1.459705
7	1	1.211242	54.29275	30.59837	23.69438	1.187837
8	1	1.10751	58.20718	30.59837	27.60881	1.392755
9	1	1.170898	55.81519	32.56271	23.25248	1.26322
10	1	1.108945	58.15301	30.29616	27.85685	1.389659
11	1	1.168102	55.92067	30.37171	25.54896	1.268637
12	1	1.221593	53.90217	29.6162	24.28597	1.169299
13	1	1.363403	48.55084	33.09157	15.45927	0.943666
14	1	1.115141	57.91923	31.35388	26.56534	1.376381
15	1	1.113176	57.99335	30.82502	27.16833	1.380576
16	1	1.119825	57.74246	41.10003	16.64243	1.366441
17	1	1.265941	52.22863	33.01602	19.21261	1.093305
18	1	.	. * damaged sample ! *			
19	1	1.372242	48.21727	35.05591	13.16136	0.931146
20	1	1.303415	50.81453	31.42943	19.3851	1.033121
21	1	1.19515	54.90002	31.50499	23.39503	1.217295
22	1	1.276821	51.81808	35.43367	16.38442	1.075467
23	1	1.332956	49.69979	32.48716	17.21263	0.988063
24	1	1.213962	54.19012	28.33182	25.85829	1.182935
1	2	1.475446	44.3228	35.35811	8.964688	0.796067
2	2	1.058326	60.06318	30.59837	29.46481	1.503954
3	2	1.154352	56.43956	31.73164	24.70791	1.29566
4	2	1.380855	47.89225	33.54488	14.34738	0.919101
5	2	1.417724	46.50097	31.9583	14.54267	0.869193
6	2	1.447945	45.36057	34.37594	10.98462	0.83018
7	2	1.464642	44.73049	33.84708	10.88341	0.809316
8	2	1.497053	43.50742	33.99819	9.509229	0.770144
9	2	1.512239	42.93436	33.84708	9.087281	0.752369
10	2	1.454896	45.09827	31.58054	13.51774	0.821436
11	2	1.323361	50.06187	31.80719	18.25467	1.002477
12	2	1.317921	50.26714	31.88274	18.38439	1.010743
13	2	1.663342	37.23236	28.86068	8.371679	0.593178
14	2	1.460033	44.90441	31.80719	13.09721	0.815027
15	2	1.39249	47.4532	30.82502	16.62818	0.903066
16	2	1.500831	43.36487	31.12723	12.23764	0.765688
17	2	1.527727	42.34991	31.80719	10.54272	0.734603
18	2	1.535434	42.05911	31.27833	10.78078	0.725896
19	2	1.374509	48.13174	32.18495	15.94679	0.927961
20	2	1.558401	41.1924	31.27833	9.914071	0.700461
21	2	1.454594	45.10968	30.29616	14.81352	0.821814
22	2	1.491009	43.7355	32.48716	11.24834	0.77732

23	2	1.529994	42.26438	26.74524	15.51914	0.732033
24	2	1.386371	47.68413	31.58054	16.10359	0.911465
1	3	1.53566	42.05055	33.69598	8.354573	0.725642
2	3	1.598897	39.66427	31.20278	8.461486	0.657393
3	3	1.661151	37.31504	30.82502	6.490019	0.595279
4	3	1.636975	38.22736	29.16289	9.064473	0.61884
5	3	1.64589	37.89094	27.50076	10.39019	0.610071
6	3	1.517981	42.71769	30.14506	12.57263	0.74574
7	3	1.424977	46.22727	41.85555	4.371725	0.859679
8	3	1.535811	42.04485	37.85131	4.193537	0.725473
9	3	1.447869	45.36342	39.36235	6.001072	0.830276
10	3	1.51375	42.87734	34.22484	8.652503	0.750619
11	3	1.526594	42.39267	32.03385	10.35883	0.73589
12	3	.	. * damaged sample ! *			
13	3	1.611212	39.19955	35.88697	3.312578	0.644725
14	3	1.587262	40.10332	31.35388	8.749437	0.669542
15	3	1.598519	39.67852	28.33182	11.3467	0.657784
16	3	1.65065	37.71133	31.27833	6.432999	0.605428
17	3	1.630402	38.4754	27.19855	11.27685	0.625366
18	3	1.585751	40.16034	32.78936	7.370978	0.671132
19	3	1.647325	37.83677	31.35388	6.482891	0.608669
20	3	1.478619	44.20306	37.2469	6.956157	0.792213
21	3	1.614763	39.06556	34.7537	4.311854	0.641108
22	3	1.588849	40.04345	34.37594	5.667505	0.667874
23	3	1.578498	40.43404	29.08734	11.3467	0.678811
24	3	1.803188	31.95516	29.16289	2.79227	0.469619
1	4	1.523572	42.50671	28.93623	13.57048	0.739334
2	4	1.527199	42.36987	33.84708	8.522782	0.735203
3	4	1.530447	42.24727	37.39801	4.849268	0.73152
4	4	1.642264	38.02779	31.50499	6.522805	0.613626
5	4	1.636446	38.24732	31.35388	6.893435	0.619363
6	4	1.618238	38.93441	29.08734	9.847072	0.637584
7	4	1.200136	54.71185	48.12632	6.585527	1.208083
8	4	1.235645	53.37188	40.19341	13.17847	1.144629
9	4	1.309686	50.5779	46.31309	4.264812	1.023386
10	4	1.466002	44.67918	40.94893	3.73025	0.807637
11	4	1.447794	45.36627	37.17135	8.194917	0.830371
12	4	1.549033	41.54593	36.18918	5.356746	0.710745
13	4	1.397779	47.25363	44.5754	2.67823	0.895865
14	4	1.393623	47.41044	39.51345	7.896988	0.901519
15	4	1.506951	43.13393	31.50499	11.62895	0.758518
16	4	1.468571	44.58224	34.90481	9.677438	0.804475
17	4	1.663645	37.22096	32.33605	4.884905	0.592888
18	4	1.26987	52.08038	46.9175	5.162878	1.086828
19	4	1.454216	45.12393	41.9311	3.192836	0.822288
20	4	1.278861	51.74111	44.27319	7.467912	1.072156
21	4	1.420595	46.39263	43.21547	3.177155	0.865416
22	4	1.446585	45.41188	37.92687	7.485018	0.831901
23	4	1.46706	44.63926	37.2469	7.39236	0.806334
24	4	1.788758	32.4997	30.74947	1.75023	0.481475

Beginning of 1988 Cropping Season

Plot#	Depth	Bulk Density	Total Porosity	Micro Porosity	Macro Porosity	Void Ratio
1	1	1.193714	54.95418	33.62043	21.33376	1.219962
2	1	1.333787	49.66843	33.16712	16.50131	0.986824
3	1	1.31165	50.50377	35.66032	14.84345	1.020356
4	1	1.223028	53.848	35.73587	18.11212	1.166753
5	1	1.14589	56.75887	29.16289	27.59598	1.312613
6	1	1.235192	53.38898	31.12723	22.26176	1.145415
7	1	1.153596	56.46807	26.66969	29.79838	1.297165
8	1	1.32049	50.1702	34.82925	15.34095	1.006831
9	1	1.112874	58.00476	34.22484	23.77991	1.381222
10	1	1.082578	59.14801	28.86068	30.28732	1.447861
11	1	1.253702	52.69049	39.96676	12.72373	1.11374
12	1	1.235419	53.38043	30.90057	22.47986	1.145021
13	1	1.308099	50.63777	35.81142	14.82635	1.025841
14	1	1.185403	55.26779	40.34451	14.92328	1.235527
15	1	1.27599	51.84944	28.40737	23.44207	1.076819
16	1	1.009066	61.92203	26.14083	35.7812	1.626191
17	1	1.408356	46.85449	31.05168	15.80281	0.881627
18	1	1.261786	52.38543	30.44727	21.93817	1.100198
19	1	1.160094	56.22288	31.42943	24.79344	1.284298
20	1	1.150045	56.60206	42.68661	13.91545	1.304258
21	1	1.249698	52.84159	30.06951	22.77209	1.120512
22	1	1.337489	49.52873	31.73164	17.79709	0.981325
23	1	1.289513	51.33912	29.69175	21.64737	1.055039
24	1	1.26443	52.28565	32.71381	19.57184	1.095806
1	2	1.449834	45.28929	33.77153	11.51776	0.827795
2	2	1.214642	54.16446	29.9184	24.24605	1.181713
3	2	1.300468	50.92572	33.46933	17.45639	1.037728
4	2	1.411151	46.749	29.4651	17.28391	0.8779
5	2	1.428679	46.08757	33.84708	12.24049	0.85486
6	2	1.396343	47.3078	30.52282	16.78498	0.897815
7	2	1.136446	57.11524	30.44727	26.66798	1.331831
8	2	1.446661	45.40903	32.48716	12.92188	0.831804
9	2	1.360456	48.66203	31.27833	17.38369	0.947876
10	2	1.191825	55.02546	28.78513	26.24033	1.223481
11	2	1.492596	43.67562	32.86491	10.81071	0.77543
12	2	1.375793	48.08327	34.82925	13.25402	0.926162
13	2	1.548277	41.57444	31.65609	9.918347	0.71158
14	2	1.360985	48.64207	34.82925	13.81281	0.947119
15	2	1.504533	43.22517	25.68752	17.53765	0.761344
16	2	1.413342	46.66632	27.123	19.54333	0.874989
17	2	1.61854	38.92301	27.80296	11.12004	0.637278
18	2	1.381384	47.8723	29.01179	18.86051	0.918366
19	2	1.500529	43.37627	31.35388	12.02239	0.766044
20	2	1.516848	42.76045	31.73164	11.02881	0.747044
21	2	1.285811	51.47881	29.23844	22.24037	1.060956
22	2	1.488818	43.81817	30.29616	13.52201	0.779935

23	2	1.458296	44.96998	28.78513	16.18485	0.817189
24	2	1.284149	51.54154	31.50499	20.03655	1.063623
1	3	1.561877	41.06126	32.18495	8.876306	0.696676
2	3	1.505062	43.20521	29.69175	13.51346	0.760725
3	3	1.437594	45.75115	29.23844	16.51271	0.843358
4	3	1.594364	39.83533	30.06951	9.765819	0.662105
5	3	1.488063	43.84668	29.16289	14.6838	0.780839
6	3	1.501813	43.3278	26.21638	17.11142	0.764534
7	3	1.436386	45.79677	32.33605	13.46072	0.844908
8	3	1.486552	43.9037	34.90481	8.9989	0.782649
9	3	1.542007	41.81107	30.90057	10.9105	0.71854
10	3	1.629042	38.52672	12.84376	25.68296	0.626723
11	3	1.537171	41.99353	34.07374	7.919796	0.723946
12	3	1.510804	42.98853	31.88274	11.10579	0.754033
13	3	1.456936	45.0213	35.96253	9.058771	0.818886
14	3	1.697189	35.95511	29.08734	6.867776	0.561405
15	3	1.504382	43.23087	29.6162	13.61467	0.761521
16	3	1.597386	39.72129	27.57631	12.14498	0.65896
17	3	1.68427	36.44264	28.10517	8.337467	0.573382
18	3	1.656316	37.49751	28.70958	8.787925	0.599936
19	3	1.67951	36.62225	29.9184	6.703844	0.577841
20	3	1.574569	40.58229	32.71381	7.868478	0.683
21	3	1.519719	42.65212	33.69598	8.956134	0.743743
22	3	1.651179	37.69137	29.31399	8.377381	0.604914
23	3	1.708673	35.52176	28.33182	7.189939	0.550911
24	3	1.550166	41.50316	28.70958	12.79358	0.709494
1	4	1.555984	41.28363	31.27833	10.0053	0.703102
2	4	1.496978	43.51027	30.14506	13.36521	0.770233
3	4	1.58424	40.21736	32.78936	7.427998	0.672726
4	4	1.513977	42.86879	30.52282	12.34597	0.750357
5	4	1.487534	43.86664	28.93623	14.93041	0.781472
6	4	1.573361	40.6279	33.84708	6.780821	0.684292
7	4	1.361816	48.61071	40.79782	7.812883	0.945931
8	4	1.322605	50.09038	45.48202	4.608358	1.003622
9	4	1.481717	44.08617	34.30039	9.785776	0.788466
10	4	1.339982	49.43465	38.07797	11.35668	0.977639
11	4	1.426186	46.18165	38.98459	7.197067	0.858103
12	4	1.511408	42.96573	32.2605	10.70522	0.753332
13	4	1.294953	51.13384	43.81989	7.313958	1.046406
14	4	1.462753	44.80177	35.73587	9.065898	0.811652
15	4	1.437217	45.76541	37.62466	8.140748	0.843841
16	4	1.613781	39.10262	28.70958	10.39304	0.642106
17	4	1.629722	38.50106	29.38954	9.111514	0.626044
18	4	1.559383	41.15534	34.30039	6.854947	0.69939
19	4	1.63146	38.43548	31.58054	6.854947	0.624312
20	4	1.400196	47.1624	37.39801	9.764393	0.892592
21	4	1.334467	49.64277	37.17135	12.47142	0.985812
22	4	1.559308	41.15819	34.30039	6.857798	0.699472
23	4	1.645134	37.91945	31.50499	6.414467	0.610811
24	4	1.633651	38.35281	27.95406	10.39874	0.622133

End of 1988 Cropping Season

Plot#	Depth	Bulk Density	Total Porosity	Micro Porosity	Macro Porosity	Void Ratio
1	1	1.381309	47.87515	36.49139	11.38376	0.91847
2	1	1.448625	45.33491	36.34028	8.994623	0.829321
3	1	1.280296	51.68694	36.86914	14.81779	1.069834
4	1	1.360381	48.66488	38.68238	9.982495	0.947984
5	1	1.344893	49.24933	34.52705	14.72228	0.970417
6	1	1.276972	51.81238	38.07797	13.73441	1.075222
7	1	1.382517	47.82953	38.60683	9.222703	0.916794
8	1	1.41508	46.60075	36.34028	10.26047	0.872686
9	1	1.360532	48.65917	38.53128	10.1279	0.947767
10	1	1.255969	52.60496	38.98459	13.62037	1.109925
11	1	1.226957	53.69974	35.28256	18.41718	1.159815
12	1	1.184346	55.30771	38.15352	17.15419	1.237522
13	1	1.196661	54.843	33.39377	21.44922	1.214495
14	1	1.260124	52.44815	37.0958	15.35236	1.102968
15	1	1.457087	45.01559	36.26473	8.750862	0.818697
16	1	1.472424	44.43684	36.9447	7.492145	0.799753
17	1	1.325023	49.99914	35.73587	14.26327	0.999965
18	1	1.351843	48.98704	37.62466	11.36238	0.960287
19	1	1.306437	50.70049	35.28256	15.41793	1.028418
20	1	1.323436	50.05902	31.42943	18.62958	1.002364
21	1	1.272514	51.98059	33.54488	18.43571	1.082492
22	1	1.398761	47.21657	36.34028	10.87628	0.894534
23	1	1.347613	49.1467	32.94047	16.20623	0.96644
24	1	1.321018	50.15025	36.79359	13.35665	1.006029
1	2	1.174373	55.68404	33.16712	22.51692	1.256523
2	2	1.307797	50.64917	33.92264	16.72654	1.026308
3	2	1.384708	47.74685	33.24267	14.50418	0.913761
4	2	1.527199	42.36987	31.20278	11.16709	0.735203
5	2	1.380553	47.90366	37.2469	10.65676	0.919521
6	2	1.444319	45.49741	31.80719	13.69022	0.834775
7	2	1.369523	48.31991	33.01602	15.30389	0.93498
8	2	1.27735	51.79813	33.09157	18.70656	1.074608
9	2	1.424448	46.24723	35.28256	10.96466	0.86037
10	2	1.394001	47.39618	34.30039	13.09579	0.901003
11	2	1.541327	41.83673	33.39377	8.442954	0.719298
12	2	1.615594	39.03419	32.2605	6.773693	0.640264
13	2	1.393775	47.40473	31.80719	15.59754	0.901311
14	2	1.545104	41.69418	32.4116	9.282574	0.715095
15	2	1.570414	40.73909	33.84708	6.89201	0.687453
16	2	1.483605	44.01489	32.94047	11.07443	0.78619
17	2	1.560366	41.11828	29.99396	11.12432	0.698319
18	2	1.495769	43.55588	32.2605	11.29538	0.771664
19	2	1.631309	38.44119	33.39377	5.047412	0.624462
20	2	1.557268	41.23517	32.4116	8.823563	0.701698
21	2	1.554019	41.35776	29.31399	12.04377	0.705256
22	2	1.481641	44.08902	34.7537	9.335318	0.788557

23	2	1.442128	45.58009	38.83348	6.746609	0.837562
24	2	1.535056	42.07336	31.12723	10.94613	0.726321
1	3	1.687368	36.32574	30.14506	6.180685	0.570493
2	3	1.513297	42.89445	32.03385	10.8606	0.751143
3	3	1.572756	40.65071	30.74947	9.901241	0.68494
4	3	1.667649	37.06986	31.50499	5.564869	0.589063
5	3	1.689105	36.26017	30.44727	5.812906	0.568878
6	3	1.720686	35.06845	29.7673	5.301151	0.540083
7	3	1.489801	43.78111	33.16712	10.61399	0.778761
8	3	1.490103	43.76971	39.66455	4.105156	0.778401
9	3	1.423693	46.27574	38.53128	7.744459	0.861356
10	3	1.587564	40.09192	33.84708	6.244833	0.669224
11	3	1.581747	40.31144	34.7537	5.557741	0.675363
12	3	1.53906	41.92226	33.77153	8.150727	0.72183
13	3	1.533167	42.14464	34.22484	7.919796	0.728448
14	3	1.620958	38.83177	30.29616	8.535612	0.634836
15	3	1.669462	37.00143	30.14506	6.856372	0.587338
16	3	1.643321	37.98788	29.38954	8.598334	0.612588
17	3	1.614309	39.08266	28.48293	10.59974	0.641569
18	3	1.661303	37.30934	28.55848	8.750862	0.595133
19	3	1.646192	37.87954	30.06951	7.810032	0.609776
20	3	1.556059	41.28078	38.38018	2.900608	0.70302
21	3	1.436914	45.77681	38.38018	7.396637	0.84423
22	3	1.644152	37.95652	30.74947	7.207045	0.611773
23	3	1.651405	37.68282	29.08734	8.595483	0.604694
24	3	1.737912	34.41842	29.38954	5.028881	0.524818
1	4	1.464717	44.72764	31.20278	13.52486	0.809223
2	4	1.562934	41.02134	33.77153	7.24981	0.695529
3	4	1.492445	43.68133	35.13146	8.549867	0.77561
4	4	1.514657	42.84313	36.86914	5.973987	0.749571
5	4	1.577365	40.4768	36.71804	3.75876	0.680017
6	4	1.592475	39.9066	34.30039	5.606208	0.664076
7	4	1.366727	48.42539	40.64672	7.778671	0.938939
8	4	1.262315	52.36548	46.76639	5.599081	1.099318
9	4	1.369447	48.32276	42.91327	5.409489	0.935088
10	4	1.351617	48.99559	44.19764	4.79795	0.960615
11	4	1.379798	47.93217	38.30462	9.627545	0.920571
12	4	1.411378	46.74045	40.72227	6.018178	0.877598
13	4	1.424675	46.23867	45.33092	0.907759	0.860073
14	4	1.473708	44.38837	39.7401	4.648272	0.798185
15	4	1.512013	42.94292	39.13569	3.807227	0.75263
16	4	1.587564	40.09192	33.84708	6.244833	0.669224
17	4	1.502418	43.30499	36.86914	6.43585	0.763823
18	4	1.674902	36.79616	33.24267	3.553488	0.582182
19	4	1.45006	45.28074	36.9447	8.336042	0.827511
20	4	1.348444	49.11533	47.74856	1.36677	0.965228
21	4	1.325854	49.96778	46.08643	3.881353	0.998712
22	4	1.52735	42.36416	39.96676	2.397407	0.735031
23	4	1.591417	39.94652	36.26473	3.681783	0.665183
24	4	1.697567	35.94086	31.35388	4.586975	0.561058

Beginning of 1989 Cropping Season

Plot#	Depth	Bulk Density	Total Porosity	Micro Porosity	Macro Porosity	Void Ratio
1	1	1.472273	44.44254	35.35811	9.08443	0.799938
2	1	1.38705	47.65847	33.39377	14.2647	0.91053
3	1	1.44651	45.41474	33.39377	12.02096	0.831996
4	1	1.172786	55.74391	31.58054	24.16337	1.259577
5	1	1.350861	49.0241	35.13146	13.89264	0.961712
6	1	1.458976	44.94432	33.69598	11.24834	0.816342
7	1	1.444621	45.48601	35.88697	9.599035	0.834391
8	1	1.439408	45.68273	33.99819	11.68454	0.841035
9	1	1.335449	49.60571	37.32245	12.28325	0.984351
10	1	1.314068	50.41254	38.83348	11.57906	1.016638
11	1	1.430417	46.022	35.35811	10.66388	0.852607
12	1	1.410774	46.76326	37.62466	9.138599	0.878402
13	1	1.574116	40.59939	34.67815	5.921244	0.683485
14	1	1.320943	50.1531	38.60683	11.54627	1.006143
15	1	1.31573	50.34982	34.52705	15.82277	1.014091
16	1	1.414778	46.61216	35.13146	11.4807	0.873085
17	1	1.48013	44.14604	35.88697	8.259065	0.790383
18	1	1.372016	48.22582	37.0958	11.13002	0.931464
19	1	1.381082	47.8837	37.02025	10.86345	0.918785
20	1	1.371487	48.24578	36.56694	11.67884	0.932209
21	1	1.316863	50.30705	36.79359	13.51346	1.012358
22	1	1.136899	57.09814	37.85131	19.24682	1.330902
23	1	1.42596	46.19021	31.73164	14.45857	0.858397
24	1	1.446736	45.40618	34.6026	10.80358	0.831709
1	2	1.298051	51.01695	32.4116	18.60535	1.041522
2	2	1.202554	54.62062	31.20278	23.41784	1.203643
3	2	1.468344	44.5908	35.20701	9.383785	0.804754
4	2	1.242369	53.11814	32.56271	20.55543	1.133022
5	2	1.346253	49.19801	33.84708	15.35093	0.968426
6	2	1.354488	48.88725	34.98036	13.9069	0.956459
7	2	1.415987	46.56654	34.67815	11.88839	0.871486
8	2	1.531656	42.20166	31.42943	10.77222	0.730154
9	2	1.432306	45.95072	36.18918	9.761542	0.850163
10	2	1.385464	47.71834	33.99819	13.72016	0.912717
11	2	1.503249	43.27363	34.4515	8.822137	0.762848
12	2	1.309761	50.57505	34.98036	15.59469	1.02327
13	2	1.436537	45.79107	33.01602	12.77505	0.844714
14	2	1.476579	44.28004	31.88274	12.39729	0.794689
15	2	1.328347	49.8737	31.58054	18.29316	0.994961
16	2	1.397552	47.26218	32.56271	14.69948	0.896173
17	2	1.663494	37.22666	29.54065	7.686014	0.593032
18	2	1.580689	40.35136	30.06951	10.28185	0.676484
19	2	1.575552	40.54523	32.2605	8.284724	0.68195
20	2	1.533696	42.12468	30.67392	11.45076	0.727852
21	2	1.528332	42.3271	31.80719	10.51991	0.733916
22	2	1.543367	41.75975	31.20278	10.55697	0.717025

23	2	1.548882	41.55163	29.7673	11.78433	0.710911
24	2	1.307495	50.66058	33.09157	17.56901	1.026776
1	3	1.537851	41.96787	28.93623	13.03164	0.723184
2	3	1.546691	41.63431	28.70958	12.92473	0.713335
3	3	1.493049	43.65852	31.12723	12.53129	0.774892
4	3	1.654352	37.57163	29.01179	8.559845	0.601836
5	3	1.647854	37.81682	28.10517	9.71165	0.608152
6	3	1.56709	40.86454	28.55848	12.30606	0.691032
7	3	1.4966	43.52452	32.56271	10.96181	0.77068
8	3	1.47197	44.45395	40.11786	4.336087	0.800308
9	3	1.417271	46.51807	36.49139	10.02669	0.869791
10	3	1.536718	42.01064	35.43367	6.576974	0.724454
11	3	1.423164	46.29569	42.00665	4.289046	0.862048
12	3	1.581369	40.3257	31.73164	8.594057	0.675763
13	3	1.592853	39.89235	31.50499	8.38736	0.663681
14	3	1.580916	40.3428	30.37171	9.971091	0.676243
15	3	1.512315	42.93151	31.50499	11.42653	0.75228
16	3	1.690239	36.21741	27.2741	8.943305	0.567826
17	3	1.739952	34.34145	28.40737	5.934073	0.523031
18	3	1.697114	35.95796	30.52282	5.435148	0.561474
19	3	1.599879	39.6272	32.03385	7.593356	0.656375
20	3	1.52667	42.38982	35.88697	6.502848	0.735804
21	3	1.538985	41.92511	32.2605	9.664608	0.721914
22	3	1.612723	39.14253	30.67392	8.468613	0.643184
23	3	1.553944	41.36061	27.4252	13.93541	0.705338
24	3	1.628438	38.54952	27.57631	10.97322	0.627326
1	4	1.561499	41.07551	29.16289	11.91262	0.697087
2	4	1.526519	42.39553	30.67392	11.72161	0.735976
3	4	1.492445	43.68133	34.07374	9.607588	0.77561
4	4	1.680946	36.56808	29.7673	6.800778	0.576493
5	4	1.665533	37.14968	29.7673	7.382382	0.591082
6	4	1.696132	35.99503	28.18072	7.814309	0.562378
7	4	1.390828	47.51592	45.70867	1.80725	0.90534
8	4	1.332049	49.734	48.57963	1.15437	0.989416
9	4	1.358416	48.739	45.93533	2.803674	0.950802
10	4	1.421124	46.37267	40.42007	5.952605	0.864721
11	4	1.357888	48.75896	47.59746	1.161498	0.95156
12	4	1.492823	43.66707	35.05591	8.611163	0.77516
13	4	1.440768	45.63141	38.60683	7.024581	0.839297
14	4	1.674297	36.81897	30.52282	6.296151	0.582754
15	4	1.633651	38.35281	27.2741	11.0787	0.622133
16	4	1.633953	38.3414	31.12723	7.214173	0.621834
17	4	1.71094	35.43623	30.82502	4.611209	0.548856
18	4	1.471744	44.4625	34.7537	9.708799	0.800585
19	4	1.460864	44.87304	40.72227	4.150772	0.813995
20	4	1.387957	47.62426	43.66878	3.955479	0.909281
21	4	1.374433	48.13459	40.94893	7.185663	0.928068
22	4	1.483379	44.02345	13.14597	30.87748	0.786462
23	4	1.58696	40.11472	36.56694	3.547786	0.669859
24	4	1.785887	32.60804	29.01179	3.596253	0.483856

APPENDIX E. MODELS TESTED IN THE LABORATORY STUDY

The following models were fitted to the data sets from the topsoil and the subsoil samples separately. The highest corelation coefficient and the model surface were used as the strategy for model selection.

$\mathrm{BD} = a + b\mathrm{CI} + c\log(\mathrm{MC}) + d(\log(\mathrm{MC}))^2$ [*MODEL*_1]

$\mathrm{BD} = a + b\mathrm{CI} + c\log(\mathrm{MC}) + d(\log(\mathrm{MC}))^2 + e\,(\log(\mathrm{MC}))^3$ [*MODEL*_2]

$\mathrm{BD} = a + b\mathrm{CI} + c(\log(\mathrm{MC}))^2 + d(\log(\mathrm{MC}))^3$ [*MODEL*_3]

$\mathrm{BD} = a + b\mathrm{CI} + c\mathrm{MC} + d\log(\mathrm{MC}) + e(\log(\mathrm{MC}))^2$ [*MODEL*_4]

$\mathrm{BD} = a + b\mathrm{CI} + c\mathrm{MC} + d\log(\mathrm{MC}) + e(\log(\mathrm{MC}))^2 + f(\log(\mathrm{MC}))^3$ [*MODEL*_5]

$\mathrm{BD} = a + b\mathrm{CI} + c\mathrm{MC} + d(\log(\mathrm{MC}))^2 + e(\log(\mathrm{MC}))^3$ [*MODEL*_6]

$\log(\mathrm{BD}) = a + b\log(\mathrm{CI}) + c\log(\mathrm{MC}) + d(\log(\mathrm{MC}))^2$ [*MODEL*_7]

$\log(\mathrm{BD}) = a + b\log(\mathrm{CI}) + c\log(\mathrm{MC}) + d(\log(\mathrm{MC}))^2 + e(\log(\mathrm{MC}))^3$ [*MODEL*_8]

$\log(\mathrm{BD}) = a + b\log(\mathrm{CI}) + c(\log(\mathrm{MC}))^2 + d(\log(\mathrm{MC}))^3$ [*MODEL*_9]

$$\log(BD) = a + b\log(CI) + cMC + d\log(MC) + e(\log(MC))^2 \qquad [MODEL\_10]$$

$$\log(BD) = a + b\log(CI) + cMC + d\log(MC) + e(\log(MC))^2 + f(\log(MC))^3 \qquad [MODEL\_11]$$

$$\log(BD) = a + b\log(CI) + cMC + d(\log(MC))^2 + e(\log(MC))^3 \qquad [MODEL\_12]$$

$$CI = a(BD/2.65)^n e^{-bMC} \qquad [MODEL\_13]$$

$$CI = (C1 \times BD^{C4})/[C2 + (MC - C3)^{C5}] \qquad [MODEL\_14]$$

where

BD = Bulk Density

MC = Average moisture content

CI = Cone Index (penetration resistance)

a, *b*, *c*, *d*, *e*, *f*, *n*, C1, C2, C3, C4 and C5 are coefficients.

Models 1 through 12 were fitted to this data set using the GML procedure in the SAS package (SAS, 1985). Model 13 was converted to a linear model through a log-transformation before using the above procedure. Model 14 was tested 8 times by changing the parameter C5 from 2 to 9, using the Marquardt non-linear procedure in the SAS package (SAS, 1985).

The R^2 values for the different models for the topsoil and the subsoil samples are summarized in Table 12.

Table 12. Accuracy of Predicting Bulk Density by Different Models.

Model Number	R^2	
	Topsoil	Subsoil
1	0.701463	0.835712
2	0.721414	0.910236
3	0.70886	0.833994
4	0.725551	0.910236
5	0.751396	*
6	0.72843	0.910236
7	0.836742	0.880599
8	0.861864	0.941673
9	0.846179	0.879271
10	0.866774	0.941673
11	0.895627	*
12	0.870117	0.941673
13	0.743992	0.826666
14 (C5 = 2)	0.848784	0.858831
14 (C5 = 3)	0.872907	**
14 (C5 = 4)	0.898897	0.863958
14 (C5 = 5)	0.923137	0.765894
14 (C5 = 6)	0.940328	0.863973
14 (C5 = 7)	0.947736	0.765857
14 (C5 = 8)	0.949229	0.863972
14 (C5 = 9)	0.949224	**

* Identical to preceding model (the last coefficient = 0).

** Model did not fit full data set.

APPENDIX F. MOISTURE CONTENT DATA FROM PENETROMETER TEST SECTIONS

Beginning of 1987 Cropping Season

Plot	Section	Depth (cm) 0-5	5-10	10-15	15-20	20-25
1	1	3.758595	6.48242	6.665219	7.004913	7.18
1	2	3.655069	6.004922	6.566452	6.989187	7.095233
1	3	4.175166	6.38933	8.082747	6.81357	8.529141
2	1	2.630523	5.46973	6.948672	7.363838	9.306006
2	2	5.404264	9.434107	9.953169	9.840237	11.58062
2	3	3.876018	6.321028	6.970285	8.309427	9.654889
3	1	3.847679	6.347192	6.179954	5.865872	6.652914
3	2	5.362625	6.432183	7.018551	6.856486	9.479005
3	3	4.063496	6.930706	7.060965	7.26902	8.66165
4	1	5.171937	6.304639	5.666856	6.015684	6.292701
4	2	4.926939	6.225759	6.887499	6.588707	7.653225
4	3	5.659295	6.926143	7.791016	7.940661	15.28033
5	1	9.076302	9.275732	9.658671	10.12377	11.886
5	2	9.406275	10.68809	10.34846	10.44897	11.23495
5	3	11.89294	9.337732	12.71487	10.58254	10.04428
6	1	4.69494	5.715042	5.753053	6.370715	7.901039
6	2	4.582425	5.638126	5.609629	5.902369	7.064553
6	3	3.056481	5.554207	5.614175	5.708503	5.26848
7	1	4.969428	8.931757	9.718996	11.45396	19.38048
7	2	5.718691	7.288081	8.753212	10.4597	13.54932
7	3	3.717513	8.38425	8.735619	9.938034	14.56827
8	1	6.936386	7.355345	7.104387	10.22346	14.73475
8	2	3.80139	6.215566	8.226889	8.646088	10.42453
8	3	3.669035	5.976016	6.635787	8.297902	13.59442
9	1	7.017158	6.209717	7.928433	10.29349	13.81409
9	2	7.944867	9.14431	9.461608	9.545248	10.66671
9	3	10.36144	7.306216	6.021757	7.487486	8.533231
10	1	9.143172	10.02923	10.94256	12.17608	13.59201
10	2	7.587378	10.58813	10.49218	9.223013	12.75375
10	3	7.745005	8.966052	9.067837	10.62496	16.26471
11	1	5.650226	7.044741	6.412789	6.608877	7.698275
11	2	6.433637	7.677578	8.525613	8.259048	12.72958
11	3	7.925799	8.062864	7.915048	9.800404	13.88246
12	1	2.848042	6.274804	7.101997	8.255908	9.904824
12	2	4.34173	7.182133	8.089887	9.168513	11.19868
12	3	4.933327	8.63046	8.472091	10.81541	16.72378
13	1	3.317864	5.20027	5.508881	6.780856	11.25373
13	2	3.217981	5.827687	5.767015	8.062434	12.40368
13	3	2.788202	5.212644	7.985512	11.68114	17.30004
14	1	4.804601	5.627882	6.187805	8.378749	13.28196
14	2	5.402697	7.506253	7.218232	7.774589	9.775742
14	3	5.014178	5.870269	6.624353	8.183744	11.74116
15	1	5.904224	5.054009	5.097292	6.424214	8.46843
15	2	6.703375	5.072337	5.217449	5.527795	8.004527
15	3	6.206535	5.682812	6.321655	11.08674	14.93326

16	1	5.146786	5.781963	5.457217	7.89643	13.20258
16	2	4.2193	5.226515	5.24908	4.882666	6.590305
16	3	3.029044	4.45157	5.0624	5.746766	8.502224
17	1	6.641875	6.515055	6.023541	5.869309	7.884909
17	2	6.102872	4.734172	5.367358	4.691619	6.356786
17	3	7.709805	5.681271	5.098994	5.076229	5.102882
18	1	7.857745	10.79145	10.67449	11.12784	14.51979
18	2	8.198592	11.00761	9.60795	10.25009	11.87175
18	3	7.166626	7.416123	6.799285	7.30393	7.961002
19	1	4.418922	6.118295	7.282167	8.468381	11.26852
19	2	4.836226	5.001578	6.109593	7.061039	9.986126
19	3	3.945436	5.52444	5.538533	7.110784	8.819027
20	1	3.720944	5.670147	5.922875	7.547651	10.59193
20	2	2.31238	4.657336	5.595534	8.044448	11.21312
20	3	2.868012	4.144339	4.92334	6.05541	7.814898
21	1	9.349607	8.679477	8.951364	11.25797	14.72899
21	2	8.701826	9.307358	9.794898	11.09276	14.12913
21	3	14.39676	10.51207	9.397754	9.109275	11.07401
22	1	4.834396	8.272537	6.767362	8.666092	11.60539
22	2	7.218857	8.034338	8.240182	8.947559	10.77876
22	3	5.02882	6.763017	8.003765	8.773882	12.65384
23	1	3.539713	5.931475	5.892285	7.30422	10.22535
23	2	3.327364	4.65867	4.83987	5.068187	6.865321
23	3	3.220041	5.189542	5.269638	5.442083	8.124879
24	1	3.053692	5.613904	5.1186	4.5526	5.344421
24	2	3.967255	4.428451	5.369286	4.433372	4.959843
24	3	2.296213	3.905405	4.23368	5.303445	5.886313

Beginning of 1988 Cropping Season

		Depth (cm)				
Plot	Section	0-5	5-10	10-15	15-20	20-25
1	1	17.04541	17.27088	18.15539	17.60664	15.19978
1	2	16.38314	18.46036	18.02901	17.80755	16.03318
1	3	17.48817	18.12671	16.92008	17.9575	17.94825
2	1	3.864312	5.909527	7.852738	6.757457	6.101866
2	2	5.391588	5.649422	5.757209	6.503861	6.633509
2	3	6.281662	9.128537	3.852654	6.149336	5.160017
3	1	17.68108	18.76358	17.79237	17.68633	16.37427
3	2	16.68497	18.5387	18.41085	19.00429	16.13951
3	3	20.65708	20.98908	20.6415	18.4732	16.76253
4	1	16.31788	17.54519	17.65838	15.75309	15.00253
4	2	13.68289	17.53682	18.88022	16.46068	15.21511
4	3	18.91349	21.08282	18.91311	19.19191	21.98699
5	1	7.740416	5.381088	5.269999	4.429809	7.284825
5	2	6.663325	5.855031	5.756913	6.267042	6.034039
5	3	6.510484	6.53765	4.013377	5.034338	6.544692
6	1	11.53159	13.03881	12.27527	11.1464	12.46496
6	2	11.17056	11.47687	10.28788	9.908433	11.90102
6	3	12.78215	15.31172	12.72847	13.95516	14.07371
7	1	8.112988	8.325768	8.544148	10.27311	12.27931
7	2	6.397756	7.467914	7.636495	8.525305	12.76685
7	3	8.86626	4.320738	5.914148	7.873503	11.42687
8	1	15.35859	19.91054	17.03164	18.60674	22.01938
8	2	13.09003	16.58759	16.88078	16.62878	18.29864
8	3	15.37436	18.30216	17.4712	20.61841	25.66137
9	1	20.06475	18.4628	14.17986	16.72704	18.09943
9	2	12.12858	17.22405	16.8284	17.5602	20.32729
9	3	13.00193	15.40611	15.25656	15.17679	16.48603
10	1	8.475689	6.140086	8.038866	7.970516	9.455617
10	2	9.127259	8.108686	6.567189	10.04617	10.64204
10	3	8.43102	8.734995	6.792039	9.215805	12.56622
11	1	15.19477	17.54311	16.79184	16.82097	17.60643
11	2	14.97533	15.46597	16.15056	18.41083	19.87088
11	3	14.92051	17.79799	16.99154	19.77313	20.69109
12	1	17.4864	16.46469	15.61023	11.84165	12.8734
12	2	13.75879	16.90516	16.00221	16.18262	17.58104
12	3	13.69345	15.62357	16.21936	16.89819	21.44841
13	1	11.70791	21.12113	23.09586	14.55194	16.59243
13	2	9.47751	13.04899	13.72955	14.10653	15.4937
13	3	11.39321	13.97633	14.45673	13.70692	16.00658
14	1	5.532588	6.047585	5.372991	5.716455	10.92956
14	2	6.802382	5.351022	4.070121	6.901095	11.77315
14	3	5.14386	4.487635	4.410933	5.68909	6.233451
15	1	11.55148	9.338268	9.848147	10.6303	12.64219
15	2	10.4052	11.91296	11.83767	10.11969	9.402695
15	3	11.43586	11.34898	11.80581	12.94791	13.60614

16	1	12.45494	13.5776	12.942	15.44537	22.79813
16	2	10.98277	12.81359	11.50188	11.83438	10.32076
16	3	13.73117	12.34536	10.27831	11.71742	10.87377
17	1	14.02961	14.43937	15.59384	17.51448	21.07738
17	2	12.14847	13.75892	13.30908	12.85779	13.38059
17	3	11.55247	13.43068	13.96942	12.96578	12.90388
18	1	6.339711	6.317598	5.613362	5.2792	12.19042
18	2	6.763961	4.64339	3.572947	6.262509	8.707375
18	3	3.432991	3.522657	2.911422	4.050161	2.187061
19	1	11.19098	11.7132	12.36852	9.046132	10.56685
19	2	13.50927	13.3849	13.14201	12.54384	13.01786
19	3	10.69772	13.68618	13.2921	10.93117	11.64391
20	1	13.49067	14.1558	14.17189	16.24364	20.43636
20	2	12.75661	13.83811	13.72558	15.26214	19.95394
20	3	14.35356	17.35285	14.85823	14.16424	14.64936
21	1	7.573058	5.580353	7.003417	10.05612	12.51209
21	2	3.560348	6.434203	6.513335	8.96791	15.16562
21	3	10.29077	8.711909	5.652899	5.259291	7.338479
22	1	3.634836	5.704599	5.362515	7.33303	10.37604
22	2	3.783017	5.346141	4.604667	4.933892	7.912657
22	3	3.17252	3.097302	6.199826	7.969925	9.767353
23	1	6.766941	9.964374	10.8156	7.575533	7.687634
23	2	9.035382	10.42529	10.34578	9.975927	9.676301
23	3	7.875933	11.08837	11.56136	10.64735	8.45035
24	1	10.87308	14.59793	13.84734	12.72908	12.34985
24	2	11.16711	20.97443	14.28769	12.57324	11.92595
24	3	12.63475	15.11142	14.36311	13.17201	13.41411

End of 1988 Cropping Season

		Depth (cm)				
Plot	Section	0-5	5-10	10-15	15-20	20-25
1	1	26.93369	25.47211	26.48777	24.43918	19.00588
1	2	27.79623	25.8783	26.64544	26.08671	20.88155
1	3	25.39009	26.07576	26.94861	23.9062	19.95001
2	1	27.40628	25.80365	28.42179	26.00062	20.97402
2	2	27.26806	24.75338	28.3051	25.18071	20.9404
2	3	28.08513	27.9364	30.01452	21.92864	20.11926
3	1	25.85001	24.63641	23.42157	22.70899	19.9018
3	2	26.79262	25.07374	24.72205	21.77107	18.81407
3	3	28.41208	27.18391	23.82411	23.0762	20.84123
4	1	29.88595	24.53549	23.48782	22.11062	18.83985
4	2	31.39861	24.17408	21.85888	21.49743	21.14542
4	3	28.03446	28.92406	22.09077	21.76882	26.04269
5	1	30.68923	24.85704	22.34991	19.64442	19.44137
5	2	28.54014	24.65229	26.01641	17.53469	18.37337
5	3	24.10059	23.22094	22.88477	20.9783	18.33419
6	1	30.17642	22.16555	21.31358	20.34571	18.85681
6	2	26.35289	25.6734	20.71008	18.38981	16.96393
6	3	28.20927	25.98642	21.66632	22.30113	18.44542
7	1	31.51501	28.77213	25.23184	25.91306	31.40369
7	2	29.1178	28.86859	24.09891	23.1062	25.99508
7	3	24.61674	27.14053	24.84404	22.55714	26.53025
8	1	28.06101	26.20122	22.36531	23.40031	25.57678
8	2	28.68798	25.98323	21.9812	21.17691	25.91559
8	3	28.2526	27.64678	24.96021	24.91606	28.56989
9	1	30.69258	26.01532	23.76497	21.46692	22.05608
9	2	29.30511	25.51606	27.02763	21.90562	21.77007
9	3	26.51506	26.55929	24.4024	19.04205	19.80982
10	1	30.92841	27.08783	25.1993	22.05328	20.31216
10	2	29.15128	29.42687	30.36322	24.71047	25.00781
10	3	27.64701	28.27246	29.43343	23.51103	23.93714
11	1	28.82196	26.54539	21.5559	22.22656	20.60129
11	2	26.05648	25.32529	22.54541	21.75277	22.25291
11	3	30.96898	30.41319	21.89123	22.58926	25.95088
12	1	32.78701	29.85697	25.18347	21.46303	21.6461
12	2	25.35135	28.98061	23.36856	21.0432	22.09805
12	3	28.78356	28.93674	25.7348	25.21025	28.62967
13	1	23.60716	25.25859	23.58036	19.67247	19.69946
13	2	27.53892	25.42424	23.99713	14.68342	19.68232
13	3	28.2887	26.36496	21.80946	19.4828	18.97095
14	1	27.52098	26.83711	22.4418	18.21818	20.83438
14	2	29.26313	26.46875	24.59389	22.78959	19.09211
14	3	24.90716	25.57428	21.22774	17.35287	20.53781
15	1	26.16043	26.93906	21.72855	19.73818	21.36759
15	2	30.55907	26.2045	25.5831	19.22752	17.60864
15	3	29.38412	25.16456	21.5834	19.63735	20.22448

16	1	28.91114	25.69744	21.93762	18.29245	21.11242
16	2	26.01396	25.08709	26.19411	21.14911	17.26535
16	3	26.33817	25.30586	21.53665	19.21366	16.47841
17	1	28.51417	32.76059	24.0347	20.24402	19.94357
17	2	27.32819	24.43087	19.76494	17.25867	18.52823
17	3	24.41532	20.93319	16.30482	16.75928	16.15043
18	1	32.77323	24.50987	23.36465	18.4134	19.35967
18	2	25.7094	22.81795	19.48383	18.19977	17.58912
18	3	21.87812	20.5108	18.0469	18.45337	17.01331
19	1	24.05685	25.3713	25.05541	18.69	17.74366
19	2	26.32001	23.51604	21.92715	19.65148	19.47451
19	3	25.81401	24.38665	24.37653	18.41505	16.9873
20	1	28.40329	20.09888	18.88995	21.15888	26.69653
20	2	25.50681	25.86899	20.373	21.35213	26.06623
20	3	26.90114	22.14235	21.24809	19.0516	18.53816
21	1	29.2097	27.30527	22.24836	19.53138	23.4009
21	2	28.54194	24.14117	22.3811	19.32221	21.02236
21	3	31.2721	23.48315	21.82117	18.88956	18.77501
22	1	26.89942	25.65633	23.15696	17.25842	18.86417
22	2	27.12113	22.55563	23.54297	18.63638	18.70007
22	3	28.92506	25.14166	20.46014	18.22631	19.59722
23	1	24.36902	24.58376	22.51094	16.4825	16.98769
23	2	26.02217	22.56601	23.57307	16.81588	17.72599
23	3	24.04149	26.48639	23.60014	18.66022	19.3865
24	1	21.00706	20.83726	20.14329	17.37332	14.67894
24	2	23.41813	22.55774	22.95468	17.05889	15.93314
24	3	24.09037	23.54847	23.96439	16.54628	15.63474

Beginning of 1989 Cropping Season

		Depth (cm)				
Plot	Section	0-5	5-10	10-15	15-20	20-25
1	1	26.43847	25.676712	24.6179	21.13876	19.13056
1	2	26.64634	25.373008	23.4231	20.56857	19.58026
1	3	29.46236	26.441206	24.4585	19.71336	18.58583
2	1	26.10619	26.380134	26.6957	20.58014	20.06338
2	2	26.85228	23.238504	27.6675	21.7817	19.87979
2	3	25.11385	25.115841	25.8614	20.90651	18.51992
3	1	21.85711	24.055034	24.9938	20.11562	17.40258
3	2	21.87261	21.79418	24.9895	22.43733	18.79483
3	3	25.48975	24.064078	25.2697	23.77135	17.86516
4	1	20.95616	23.088153	21.9347	16.47345	16.5973
4	2	21.13735	22.507905	21.7822	17.979	16.76285
4	3	23.19509	24.591525	23.925	19.61871	18.17207
5	1	29.10276	22.184963	19.18	16.95537	18.4118
5	2	25.70495	22.265471	24.6404	18.00099	16.98964
5	3	25.57284	25.03233	24.345	23.55898	17.08187
6	1	37.30364	27.560341	33.0074	29.7949	25.83753
6	2	33.88801	32.935485	28.9764	26.19012	24.87792
6	3	39.90741	33.334386	34.6469	28.49655	25.24217
7	1	25.42926	26.513161	23.3908	22.63003	24.11533
7	2	23.56498	22.454458	21.5951	20.90984	26.14636
7	3	25.92826	22.841749	26.9756	20.02657	19.8881
8	1	24.61035	24.808384	21.5102	20.74298	23.75148
8	2	21.58418	24.401202	22.5433	19.28023	23.09161
8	3	17.85939	23.818755	23.6859	26.79691	30.76989
9	1	37.20162	34.051573	30.4816	28.40129	30.76255
9	2	35.54415	32.285065	31.6	29.90593	32.38391
9	3	37.26817	37.423489	33.9235	29.34121	26.73307
10	1	29.42255	24.191033	29.7652	19.17338	20.45067
10	2	28.87839	26.872327	24.6006	24.03798	23.68809
10	3	28.94119	26.352057	28.5581	22.41803	20.64479
11	1	20.89152	22.789341	19.3768	18.89214	22.1662
11	2	18.75023	19.232715	19.7254	19.87328	23.64607
11	3	18.80732	20.240791	19.8482	18.19788	19.47244
12	1	38.75785	35.262871	35.8067	28.63202	27.6265
12	2	38.0412	33.820263	31.9109	32.03395	32.626
12	3	36.98796	33.011471	31.6855	31.0406	34.29608
13	1	19.75794	19.903205	22.2616	19.8528	19.12807
13	2	18.65066	20.021994	20.8135	20.72866	19.74627
13	3	19.92137	20.060246	20.0716	17.08398	18.7962
14	1	25.12687	24.436578	20.5318	17.62151	19.99108
14	2	26.44573	23.459818	21.0189	17.83198	18.76269
14	3	25.52123	22.204854	17.835	16.38813	17.12111
15	1	28.52788	23.015499	19.3207	17.8246	18.60586
15	2	27.60571	23.719615	21.1783	18.44768	18.40508
15	3	28.27917	23.60402	22.1977	18.09527	22.21065

16	1	27.22445	28.925279	29.0295	20.09256	22.51556
16	2	28.36859	27.272893	25.8957	18.64508	17.97361
16	3	27.35454	25.792945	23.9059	16.76295	18.0479
17	1	17.07977	18.637422	17.8567	17.74604	22.50755
17	2	17.91057	20.502655	18.7072	14.72978	14.86517
17	3	19.30578	18.669124	15.6377	14.84872	14.72221
18	1	29.07831	21.900777	23.9137	17.58138	18.67545
18	2	25.36575	23.586176	19.7681	17.10302	17.3139
18	3	23.19404	20.012185	20.3524	19.81435	16.01331
19	1	27.73647	24.215416	19.2773	19.43137	18.18125
19	2	25.76677	22.198256	20.4012	18.43701	19.72719
19	3	25.20757	23.253579	21.8482	19.05239	18.15496
20	1	17.00201	19.714089	16.4827	18.39429	23.85469
20	2	17.10611	19.384428	19.5989	17.85042	23.35344
20	3	19.86011	22.074072	18.4817	15.97378	17.49273
21	1	26.04837	21.212325	17.7749	18.49659	21.66236
21	2	24.41703	23.195232	22.0171	17.93063	19.64238
21	3	27.35162	22.405725	21.3067	18.22815	17.30101
22	1	25.13703	23.075226	17.4344	16.75084	19.6598
22	2	24.96716	22.936533	20.6196	17.22619	18.3455
22	3	26.80192	23.642837	21.5188	18.33863	18.4853
23	1	25.45743	24.072792	21.6733	20.41211	19.03364
23	2	25.29595	27.72577	21.1008	18.90191	18.6597
23	3	25.74681	26.397032	21.3574	17.41347	17.92714
24	1	16.13588	16.97304	18.1672	17.41387	14.15007
24	2	15.23055	17.52733	19.9558	18.303	15.33748
24	3	17.59677	19.578356	21.1636	17.13657	14.75218

VITA

Dangallage Nimal Jayatissa was born to Mrs. C. Samarasinghe and the late Mr. D. Jayaneris on June 20, 1956, in Mirigama, Sri Lanka. He received his primary education at Buddhist Mixed School, Gaspe, Sri Lanka, and Dharmashoka Maha Vidyalaya, Banduragoda, Sri Lanka. Then he entered Bandaranayake Madya Maha Vidyalaya, Veyangoda, Sri Lanka, for his high school education, where he was graduated in December, 1975. Jayatissa then entered the University of Peradeniya, Sri Lanka, and received his Bachelor of Science Degree in Agriculture in 1981 from the Faculty of Agriculture. Soon after graduation, he joined the Department of Agricultural Engineering, Faculty of Agriculture, University of Peradeniya as a temporary instructor; he became a permanent faculty member in 1982. He entered the Graduate School of Virginia Polytechnic Institute and State University in 1983 and received his Master of Science degree in Agricultural Engineering in April of 1986. After returning to Sri Lanka, he married Ms. Jayanthi Pathirage. After serving for four months as an assistant lecturer at the University of Peradeniya, he returned to Virginia Polytechnic Institute and State University in September of 1986 to study for the degree of Doctor of Philosophy in Agricultural Engineering. Their daughter Heshani was born in April 1988. Jayatissa plans to complete the doctoral degree in February of 1990, and he and his family will return to the University of Peradeniya, Sri Lanka, where he will be an assistant lecturer in Agricultural Engineering.

DJayatissa