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THE UNIVERSITY OF ALBERTA

A STUDY OF CONE INDEX READINGS IN AN AGRICULTURAL SOIL

by

(C) SHIN NGIN CHIN

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "A Study of Cone Index Readings in an Agricultural Soil" submitted by S.N. Chin in partial fulfilment of the requirements for the degree of Master of Science.

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Supervisor

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Date . . . .

ABSTRACT

The purpose of this study was to determine the consistency of Cone Index readings in an *in-situ* soil condition common in agricultural practice.

Vehicle traffic compaction, tillage and surface conditions were studied for their effects on Cone Index readings. The tractor used was an International Harvester, model IHC 966, with a gross weight 13,800 lb. The compaction levels were obtained by varying the rear tire inflation pressure from 10 to 30 psi. The surface conditions were summerfallow and stubble fields, and plots were tilled with a cultivator to a depth of 6 inches or left *in-situ*.

Soil strength parameters (Cone Index, cohesion and friction) as well as soil properties (bulk density and moisture content) were measured and the results evaluated statistically by an analysis of variance. A multiple regression analysis was made on the interrelationship of Cone Index to the soil moisture content for a given mean bulk density.

The following observations were made:

1. The hand-operated recording penetrometer gave consistent mean Cone Index readings over a depth of 9 inches when the soil surface experienced vehicle traffic compaction.
2. Cone Index measurements on tire lug patterns differed significantly from those taken between the tire lug patterns.
3. The Cone Index of a given soil type may be predicted from soil moisture and density data after the soils have been compacted by vehicle traffic.

4. The Cone Index measurements on tilled soil posed several problems because of a lack of uniformity in the soil density profile.

5. Cone Index measurements in agricultural soils show wide variability because of the tillage practices and soil moisture fluctuation. Measurements taken for a particular site are repeatable, however, the representative Cone Index for a given area is a statistical quantity. A standard deviation in the range of 14 psi was observed.

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1. INTRODUCTION

The introduction of pneumatic tires on both industrial and agricultural prime movers has been one of the most significant advances in modern technology. Evaluation of appropriate terrain-parameters to predict the vehicle performance is of major importance.

'Off-the-road' vehicle design is based on the following factors:

1. Vehicle design parameters.
2. Implement-vehicle interactions.
3. Soil-vehicle interactions.

Beginning with Bekker's 'Theory of Land Locomotion' (1956), the development of vehicle mechanics in terms of soil and vehicle interaction has been the subject of much research and discussion.

A. The Problem.

Traction is developed in the mutual contact surface of the tractive device and the terrain. Vehicle performance is the ability of the vehicle to develop sufficient traction to propel itself and to ensure that the drawbar loads are pulled efficiently. The optimum vehicle performance depends on the soil strength parameters as they affect the soil-vehicle interaction. These surface soil parameters, however, change dramatically from the hardness of a hard stubble surface to a soft saturated clay. Vanden Berg et al (1961) found that when the tractive device is operating near its maximum tractive capacity in loose soils, the power-transmission efficiency is often less than fifty percent. The soil parameters, which influence vehicle behaviour, determine the vehicle performance to a large extent.

Most of the difference in opinion seems to be centered on deciding which are the fundamental factors affecting the soil-vehicle system. The pertinent soil-parameters affecting stress deformation at the soil-vehicle interface give a simple relationship from which other complicated equations are developed to describe vehicle performance. The majority of these equations give partially satisfactory results for a given experimental soil condition. No universal set of traction equations has been accepted for predicting vehicle performance over a variety of soil conditions.

Soil conditions are described by parameters such as shear strength, tensile and compressive strength, elastic-plastic behavior, moisture content, particle size distribution, density and temperature. These soil properties show a wide range of variation in diverse soil conditions. Some parameters show seasonal variation in accordance with fluctuations in moisture level within the soil profile, others vary when the soil is tilled for cultivation. Also, conflicting data exist when different instruments are used to measure a single soil parameter. These variations, coupled with the dynamic effect of the three dimension soil-vehicle system, give the problem its complexity.

There is some promise in the use of a cone penetrometer to obtain an indexing system of vehicle mobility and the prediction of vehicle performance. The Cone Index is the average penetrometer reading determined over a finite depth of soil in an undisturbed condition. The Cone Index is a composite soil parameter used as a means of evaluating the mechanical strength of the soil.

B. Objectives.

The objectives of this study were to:

1. determine the consistency of Cone Index readings in an *in-situ* soil condition common in agricultural practice,

2. study the effect of tillage and compaction on the consistency of Cone Index readings,

3. study the effect of soil moisture and density on shear strength and Cone Index readings.

II. LITERATURE REVIEW

A. Previous Study of Soil-Vehicle System.

Researchers in traction have recognized the lack of definitive relationships between the vehicle performance and the surface on which the vehicle is operating. This has prompted a great deal of research in the study of military, mining, agricultural and forestry vehicles and the terrain characteristics significant in predicting the performance of these vehicles.

A basic approach in describing the mechanics of the soil-vehicle system is based on theory developed from soil mechanics. Micklethwaite (1944) was the first to apply Coulomb's well-known equation

$$S_{max} = c + p \tan \phi \quad \ldots \ldots \ldots \ldots \quad (1)$$

where,

S_{max} = maximum shear stress in soil (lb/in^2)

c = cohesion (lb/in^2)

p = pressure normal to shear plane (lb/in^2)

ϕ = angle of internal friction (degrees)

to predict the maximum tractive effort of a vehicle.

Bekker (1956), at the Land Locomotion Laboratory, Warren, Mich., U.S.A., concluded that no general theory was possible without the use of soil stress-deformation relationships. Using an analytical approach, Bekker proposed that vehicle behaviour could be interpreted in terms of soil reaction on a simple plate loading test. The relationship between the applied pressure on the penetration plate and the sinkage could be described by the following equation:

$$p = \left(\frac{k_c}{b} + k_\phi\right) Z^n \quad \ldots \ldots \ldots \ldots \quad (2)$$

where,

p = pressure on penetration plate (lb/in^2)

Z = sinkage (in)

n = rate of strain change with load

b = width of ground contact area of plate (in)

k_c = cohesion modulus of sinkage

k_ϕ = friction modulus of sinkage.

Janosi and Hanamoto (1961) further proposed that the results of horizontal shear plate tests could be related to Coulomb's equation as:

$$S = (c + p \tan \phi)(1 - e^{-j/k}) \quad . . . . (3)$$

where,

j = soil deformation in the horizontal direction

k = deformation modulus of the soil shear-stress strain curve.

Equations 1, 2 and 3 were then applied to simple vehicle models, namely rigid tracks and rigid wheels, and theoretical relationships were obtained with tractive parameters such as drawbar pull and slip. Reece (1964,1965) conducted various pressure sinkage experiments to verify Bekker's equation (2). Reece suggested that this equation is dimensionally faulty because both k_c and k_ϕ have dimensions that are functions of the soil exponent n and are not constants. Reece proposed an equation of the form $p = f(\frac{Z}{b})$ instead of $p = f(Z)$. Values of modified Bekker's constants for incompressible material in terms of c, ϕ and the bulk density (γ) can then be determined using Terzaghi's bearing capacity theory developed by Meyerhof (1951).

Nuttall and McGowan (1961) were the first to conduct model experiments using similitude principles. Some success was achieved by using the Cone Index or a single parameter obtained from the plate penetration test to describe the soil. Knight and Freitag (1962) and Rush (1967) used an empirical approach based on the Cone Index in the study of soil trafficability. Foster et al (1958) suggested that the Cone Index is a measure of the bearing tractive capacity of the soil. The trafficability of a given soil condition could then be evaluated by correlating the Cone Index with vehicle parameters.

Recently, Freitag (1965) and Wismer (1966) used the Cone Index as a parameter in the dimensional analysis of the performance of a pneumatic tire on various soil conditions. Wismer and Luth (1972) predicted the performance of wheeled vehicles operating on cohesive-frictional soils. The Cone Index provided an adequate measure of the soil strength. Turnage (1972) applied this technique in selecting the appropriate tires and predicting the performance of army vehicles for off-road vehicle operations.

Most agricultural and forestry soils can be classified as cohesive-frictional. This class of soil is compactable and therefore soil strength varies when subjected to wheel loading. This suggests a measurement technique that includes wheel loading effects. The Cone Index, with both cohesion and friction, provides a good estimate of soil strength.

B. Soil Factors Affecting Vehicle Mobility.

Terrain conditions affecting vehicle performance are: soil properties that influence the stress-strain relationship of the soil beneath a moving wheel (Bekker 1960, Persson 1967 and Smith 1966), and surface condition and geometry that affect wheel slippage and sinkage (Bekker 1960, Waterways Experiment Station, 1964).

The Coulomb-Mohr equation (1) indicates that shear resistance of soils consist of two components, namely cohesion and friction. Frictional forces act at interparticle contact areas thus resisting particle sliding, whereas cohesive forces bind particles together (Terzaghi and Peck, 1948). The magnitude of the frictional forces depends on the soil texture and moisture content, and to some extent on the condition of the interparticle area of contact. Cohesion is a function of the cementing material and the moisture binding the particles (Aitchison, 1960). Terzaghi (1959) stated that for sand the shear resistance depends solely on the normal stress on the potential surface of sliding; that is, $S = p \tan \phi$, when $c = 0$. The value of ϕ varies from 30° to 50° with a difference as high as 15° between the densest and loosest states (Strong and Buchele, 1962). Nichols (1932) showed that for plastic agricultural soils, shear strength is proportional to the normal pressure, and decreases with moisture content. Maximum shear strength is obtained near the lower plastic limit. Shear strength for plastic and non-plastic soils are similar when an appreciable amount of colloidal material is present. Greacen (1960) studied the effect of moisture content on saturated and unsatutated agricultural soils and showed that when a shear force is applied, the soil compresses to the ultimate void ratio, after which there is negligible change.

The rolling resistance aspect of vehicle mobility is based on Bekker's pressure sinkage equation , $p = [\frac{k_c}{b} + k_\phi] Z^n$. Hanamoto and Hegedus (1958) using the Bevameter to measure 'Bekker soil values', showed that both k_c and k_ϕ decrease as moisture content increases. Task and Skejei (1958) verified these relationships for a number of clay-sand ratios and grain sizes. The soil exponent n was found to be constant for all moisture contents, grain sizes and clay-sand ratios.

The bearing capacity theory is considered by many researchers (Reece 1965, Wong and Reece 1967, and Wiendeck 1968) to give a good estimate of soil shear strength in the prediction of vehicle sinkage and tractive capability. Terzaghi and Peck (1948) developed the soil bearing capacity equation:

$$q = cN_c + \gamma DN_q + \frac{1}{2}\gamma BN_f \qquad (4)$$

where,

q = ultimate bearing capacity (lb/ft^2)

B = width of footing (ft)

c = soil cohesion (lb/ft^2)

D = depth from ground surface to bottom of footing (ft)

γ = unit weight of soil (lb/ft^3)

N_c, N_f, N_q = Terzaghi's bearing capacity factors as functions of ϕ.

The above equation factors give pressure sinkage relations in terms of c, ϕ and γ for a given failure pattern.

The Cone Index as a composite soil parameter is a measure of bearing-tractive capacity of the soil (Foster, Knight and Rula, 1958). Bearing capacity and tractive capacity are both functions of shear strength of the soil. Vehicle immobilization is caused by a concurrent failure in bearing and tractive capacity.

C. <u>Measurement of Soil Strength Parameters</u>.

The important criterion in measuring soil parameters is to simulate the loading conditions of the vehicle. The measured soil parameters should reflect the soil conditions beneath the moving wheel or track. In the classification of soil for vehicle mobility and trafficability, the use of penetration tests have been quite successful. Since Berhstein's (1913) needle penetrometers, various penetrometers (Waterways Experiment Station (W.E.S.) non-recording penetrometers, Robertson and Hansen (1950), Carter (1967) recording penetrometers) have been used to study soil penetration resistance. Evans (1948) used a penetrometer with a circular plate and a recorder to measure a constant rate penetration resistance. Bekker (1950) used the technique of plate penetration to determine the 'Bekker soil values'. Dexter and Tanner (1973) studied the forces on spheres penetrating into the soil.

Measurements of soil friction ϕ and cohesion c were first proposed by Mickelthwaite (1944). Soil vehicle performance was based on the vertical and horizontal stress-strain relationships and the geometry of the terrain (Bekker, 1969). Military engineers at the Land Locomotion Laboratory (Bekker 1960, Liston 1965) have developed the Bevameter for *in-situ* measurements of the shear stress component c and ϕ. The test constraints are that they be made on or near the surface under drainage and a rate of shear simulating those of a vehicle tractive device. Conflicts in results obtained by using different shear apparatus indicate the difficulties in measuring the shear strength components of a given soil condition (Bailey and Weber 1965, Dunlap et al 1966).

D. The Cone Index.

The Cone Index as defined previously is the average force required to cause penetration of the cone probe over a given depth divided by the cone base area. Full resistance to penetration is reached when the base area is flush with the soil surface. The depth of penetration, therefore, can be referenced either at the cone base or tip. An average penetration resistance over a finite depth is an indicator of soil uniformity and consistency. The American Society of Agricultural Engineers (A.S.A.E.) R313.1 (1968) recommends a penetration depth of six inches. Dwyer (1973) determined the Cone Index for a particular site for a penetration depth of nine inches.

The total resistance to penetration reflects the soil conditions near the tip of the probe where localized failures occur. As the cone probe enters the soil, it encounters resistance to compression, friction between soil and metal, and the shear strength of the soil, which involves both internal friction and cohesion. The resistance to penetration is therefore treated as an independent composite parameter.

E. The Penetrometer.

The penetrometer is basically a device used to obtain a quantitative measure of soil consistency. Penetrometers are classified into two groups based on the type of loading:

1. constant-rate penetrometers,
2. impact-loading penetrometers.

Most penetrometers used are of the constant-rate type, where a variable force is required to maintain a steady rate of penetration. In the impact-loading type, the energy stored in a spring or dropping weight is used to drive the penetrometer into the soil media. The fixed amount of energy is a measure of the soil consistency, however, this energy does not detect the variation of soil consistency with depth.

Two quantitative models are used to describe the behaviour of cone penetration. One model expresses the force per unit area required to cause penetration (Gill and Vanden Berg 1968) and the other expresses the energy required to displace the soil beneath the probe for a given depth (Zelenin 1950).

Penetrometers are commonly used when the material mass exhibits heterogeneous consistency and is rheologically complex. Most soil conditions encountered fall within this class of engineering materials since the stress-strain time properties are not easily evaluated. Penetrometer probes are usually of small cross-sectional area, slightly larger than the shafts. Penetrometer probes of different geometrical configurations had been used in the study of soil resistance to penetration. In order to simulate the soil condition near a wheel, the cone probe is most often employed.

(a) Advantages of Using a Cone Probe.

1. The cone probe provides a quick and simple method to evaluate the hardness or density of a material through penetration.
2. The relatively light loads used do not introduce secondary effects such as shear failure and relatively small test samples can be used.
3. The use of a cone implies the inclusion of interface properties such as soil-metal friction and adhesion.

(b) Theoretical Considerations.

Theoretical attempts to describe the penetration of a cone probe in terms of stress-strain properties of the soil have not been particularly successful (Freitag 1968). Most theoretical analyses do not consider the dynamic effects at relatively deep depths of penetration, however, they do provide an understanding of the nature of cone penetration. Leviticus and Ehrlich (1970), in an attempt to study the dynamic effects of soil slippage near a wheel, used a cone probe which penetrated into the soil and could be rotated at various velocities. In their analysis, an equation was developed to incorporate the interface properties. A pressure distribution along the cone of the form $P = kZ^n$ is assumed to be independent of the coefficient α. With this assumption an equation was derived for certain standard conditions.

$$S_p = \mu p_c + \alpha \quad \ldots \ldots \quad (5)$$

where,

S_p = upward shearing stress tangent to the cone

p_c = pressure normal to the cone

μ = surface-soil coefficient of friction

α = surface-soil adhesion.

(c) Limitations.

Some critics, for example Reece (1964), do not favor the use of cone penetration resistance as an independent composite parameter in soil-vehicle relationships, mainly because a composite parameter combines the effects of one or more independent soil parameters. Osman (1964) showed that the forces on a soil cutting blade can be defined in terms of c, ϕ, γ, α and μ, but not in terms of any combination of these parameters. Reece (1964) stated that the soil-vehicle problem is similar to that of the soil cutting blade and the use of the Cone Index as a parameter in the relationship is inadequate. Smith (1966) showed that the penetrometer did not describe the effects of a wet soil surface condition on vehicle pull.

Until a complete soil dynamic theory based on accessible independent soil parameters is developed, the use of composite parameters such as Cone Index and bearing strength in model experiments are extremely useful. Freitag (1968) stated that the indeterminacy of the simple penetrometer test appears to present an insurmountable obstacle if it is imperative that both cohesion and friction be known. In practical cases when either the parameters can be determined or separation of the two parameters is not necessary, the penetrometer can be of direct use. The cone penetrometer may thus provide a basis for an in-depth study of a rheologically complex material such as soil.

F. Factors Affecting Cone Penetrometer Readings.

The W.E.S. Penetrometer (1948) was basically developed as an indexing system to classify soil for trafficability. Since then, many researchers (Shuman 1965, Freitag 1968, Gill 1968) have investigated the geometrical and physical factors that affect cone penetration readings.

(a) The Size of Cone Shaft Relative to the Diameter of the Cone.

Freitag (1968) noted that as the cone penetrates into the soil, the displaced soil tends to move upwards and pass into the space left by the cone. If the shaft is relatively small compared to the cone diameter, the pressure relief will tend to reduce the penetration resistance. If, however, the shaft is approximately the size of the cone diameter, the drag of the soil on the shaft will cause an increase in soil resistance. With the exception of soft, sticky clays the friction of soil on the shaft is insignificant.

(b) Effects of Cone Sizes and Apex Angles.

Work by W.E.S. (1948) showed that the shape of the cone tip had little effect on the penetration resistance for a given area of cross-section. However, recent research (Shuman 1965, Freitag 1968) has shown that the actual size of the cone can influence the magnitude of penetration resistance. Freitag (1968) measured the penetration resistance in wet, fine-grained soil and showed that the resistance per unit area was greatest for the smallest cone and smallest for the largest cone. Gill (1968) showed that the lower the apex angle, the lower the specific resistance of the soil to deformation. The specific resistance of the soil to deformation by a penetrometer is calculated by assuming a uniform distribution of stress on the surface of the tool. The size of the cone should then be taken into account if a small cone is used to estimate the pressures expected for a larger cone. Shuman (1965) reported that the only apparent effect in the variation of tip sizes is in the magnitude of the penetrometer load-depth readings. The frictional relationships remain unchanged.

(c) Effect of Penetration Speed.

The speed of penetration into the soil affects the pressure for penetration. Freitag (1968) found that when the ratio of speed to cone diameter was used as a common basis, a single relation existed for all speeds and cone-size combinations. In wet, fine-grained soils the penetration resistance was relatively low at low speeds of penetration and increased with higher speeds. However, in sandy soils, little or no difference was observed other than inertia effects. Leviticus and Erlich (1970), using the rotating cone penetrometer, assumed that dynamic effects are minimal at low velocities and that any difference in interface parameters compared to that measured at higher speeds, can be attributed to velocity-dependent properties of the interface bonds.

(d) Effect of Surface Roughness.

Freitag (1968) studied the effects of surface roughness of the cone on penetration resistance. In fine-grained soils the increased resistance could be expressed by the larger projected base area caused by adhering clay. In sand, the roughness caused a larger penetration resistance than could be explained by the increased, projected base area.

G. Relation of Soil Properties to Penetration Resistance.

Soil moisture and density data for in situ soils are few since the collection of these data require a long period of time to cover the natural moisture range. Williford and Larson (1968) found that the best relationship between Cone Index and individual factors was obtained when the Cone Index was referenced to the depth of the cone tip rather than the cone base. Bulk volume weight is exponentially related to Cone Index for sandy and silty clay loam soils (Williford and Larson 1968). Cone Index cannot be easily correlated with moisture content since soil strength decreases with increasing moisture content (Greacen 1960). Mirreh and Ketcheson (1972) indicated that soil resistance to penetration can be predicted more successfully if related to bulk density and matrix pressure simultaneously. Bulk density and moisture content, as well as the soil structure and history at the time of testing, are important factors influencing penetration resistance.

H. Relationship Between Soil Strength and Penetration Resistance.

Since the attempt (Freitag 1965) to relate tractive performance of vehicles to cone penetration resistance reading, various investigations (Shuman 1965, Smith 1966, Williford 1967) have been conducted to study the

In pure cohesive soils a unique relationship exists between cohesion and penetration resistance, however, when a friction component is present the relationship depends on the state of compaction as well as the soil properties (Smith 1966). A good linear relationship was observed between Cone Index and cohesion for silty clay loam, but not for sandy loam. Soil tests by W.E.S. engineers (1964) reported that the combined influence of cohesion and friction on Cone Index is complex. Freitag (1968) found that for lean clay relatively smooth isopleths were obtained when Cone Index was plotted relative to cohesion and friction axes on the basis of unconsolidated-drained triaxial shear test data. A given Cone Index could thus be attained with many different combinations of cohesion and friction. Williford (1967) noted that there was no apparent relationship between Cone Index and either adhesion or soil-metal friction for either silty or sandy loam soil.

I. Effect of Compaction and Tillage on Cone Penetration Resistance.

Agricultural soils are quite susceptible to compaction from activities such as wheel traffic. The penetration resistance can be used to detect compaction change in an unsaturated soil. Soil bulk density increases with further compaction effort until 'over compaction' is reached when the mechanical properties of the soil change drastically. The penetrometer can be used as a non-quantitative evaluation of this effect. The effect of tillage, wheel compaction and the duration of wet-dry cycles is probably the reason for a lack of homogeneity in the density profile in the soil (Strong and Buchele 1962). These factors tend to deteriorate the soil structure; the action of weather will cause a return to the original consolidated state.

J. Use of Cone Index in the Prediction of Vehicle Mobility.

Knight and Freitag (1962) developed the mobility index system to predict vehicle trafficability. The mobility number is defined as:

$$\frac{C_I bd}{w} \left(\frac{\delta}{h}\right)^{1/2} \frac{1}{1 + \frac{b}{2d}}$$

where,

C_I = mean cone penetration resistance through a depth of six inches

b = tire section width

d = tire undeflected diameter

w = vertical load on tire

δ = tire deflection under load

h = tire section height.

The vehicle performance could then be predicted from the mobility number and tractive performance parameters. Wismer and Luth (1972) derived traction equations using the Cone Index as a measure of soil strength to describe the tractive performance of individual wheels. Mehra (1972) used the mobility number to predict tractive performance in different soil surfaces. Dwyer (1973) in an attempt to relate the tire performance to soil mechanical properties predicted the coefficient of rolling resistance within $\pm$ 0.05 when empirical relations were made from the mobility number. An important practical point when comparing the usefulness in predicting tractive performance made from the correlation of soil strength parameters is that the penetrometer measurements could be made rather quickly.

To estimate the Cone Index beneath a moving wheel operating on fine-grained soils, Knight and Freitag (1962), used a 'rated' Cone Index.

readings by the remoulding Cone Index. The remoulding index is obtained by dividing the Cone Index of the soil after the confined soil sample is compacted with a hundred blows of a two and a half pound tamper falling twelve inches by the Cone Index before the blows were applied. Wismer and Luth (1972) suggested that for soft soils, where tire deflection has little influence on trafficability; the Cone Index measured after the soil has experienced vehicle traffic may be a good evaluation of the soil condition beneath the wheel.

K. Applicability of Current Cone Index Measuring Procedure.

Knight (1956) and the U.S. Department of Army (1959) showed that the use of Cone Index as an estimate of soil trafficability, for army vehicles operating on a particular terrain, involves a great deal of personal judgement. Gardner (1973) reported that the current procedure does not explicitly state which Cone Index measurements (mean, median, or some other mathematically determined number) should be used to represent the overall area. In addition, the procedure does not state how the locations, from which Cone Index measurements are taken, are to be selected. Many researchers feel that a distance of one foot is an approximate separation distance for Cone Index measurements (Domier 1974). Gardner (1973) suggested, as a guide, that for a given area A, there are $N = A/D^2$ possible independent measurements, where D is the separation distance. The measurements are, however, not fully independent, since, in a low spot where the soil moisture content is relatively high Cone Index readings may tend to approach a specific value.

III. EQUIPMENT

A. Apparatus Used to Measure Soil Physical Parameters.

a. The Hand Operated Recording Penetrometer.

The recording penetrometer used in this study was designed by Carter (1967) for quick field and laboratory measurements (Figure 1). The cone penetrometer consisted of a thirty-degree circular stainless steel cone of 0.5 sq. in. area that was fixed at the end of a 0.625 in. diameter shaft (ASAE R313.1). The shaft was mounted on an aluminum frame carrying the recording X-Y chart. The force on the spring loaded penetrometer handle was recorded by the vertical displacement of the pen. The depth of penetration was proportional to the horizontal movement of the chart. A simple gear mechanism was used to move the chart horizontally.

In preliminary tests, the cone was pushed into the soil at a uniform rate of approximately 72 in. per min. In some areas of hard soil, this rate of penetration was not possible to achieve, however, a lower constant rate was maintained. The soil surface reference point was manually recorded when the tip of the cone was flush with the soil surface. Continuous readings to a depth of more than 11 inches were recorded on the 6 in. x 3 in. chart. Five replicates within a circle of 1.5 ft diameter were used to establish the Cone Index and to verify the presence of unique layers in the soil profile. Readings taken on wheel tracks were made within an area of 1.5 x 1.5 ft.

b. The Cohron Sheargraph.

The Cohron Sheargraph was manufactured by Soiltest Inc. Evanston, Ill., U.S.A. The shear head of the instrument is circular

Figure 1. Hand operated recording penetrometer.

with a 2 sq. in. area in contact with the soil. The coil spring is calibrated for both axial loading and torsion. The shear stress versus normal stress curve is recorded on the pressure sensitive chart. Figure 2 shows the use of the sheargraph.

After preparing the test area with a flat spade, the shear head was placed on the soil. Then the handle of the sheargraph was pushed down vertically until the outer ring of the shear head had penetrated the soil while the inner surface of the shear head transmitted the normal load to the soil surface. Rotation was stopped and normal stress reduced when the shear head started to move relative to the soil.

Six different normal stresses were used on the same chart to obtain the soil-to-rubber test results.

c. Soil Moisture and Density (Drive Cylinder Test).

Equipment for measuring soil density and moisture is shown in Figure 3. The test area was cleared of loose soil and vegetation before the drive cylinder was forced into the soil. The cylinder was carefully removed from the soil by digging around the specimen. Both ends of the specimen were trimmed and the weight of the cylinder and wet soil were recorded. The soil was then removed from the cylinder and oven dried (110° ± 5°C). The moisture content (dry basis) was computed as the percentage weight of water in the dry soil. A steel tube, three feet in length, with internal diameter 3/4 in., external diameter 15/16 in. and core length 15 in., was used for taking soil samples. The soil samples were used to obtain the soil-moisture profile during the preliminary studies.

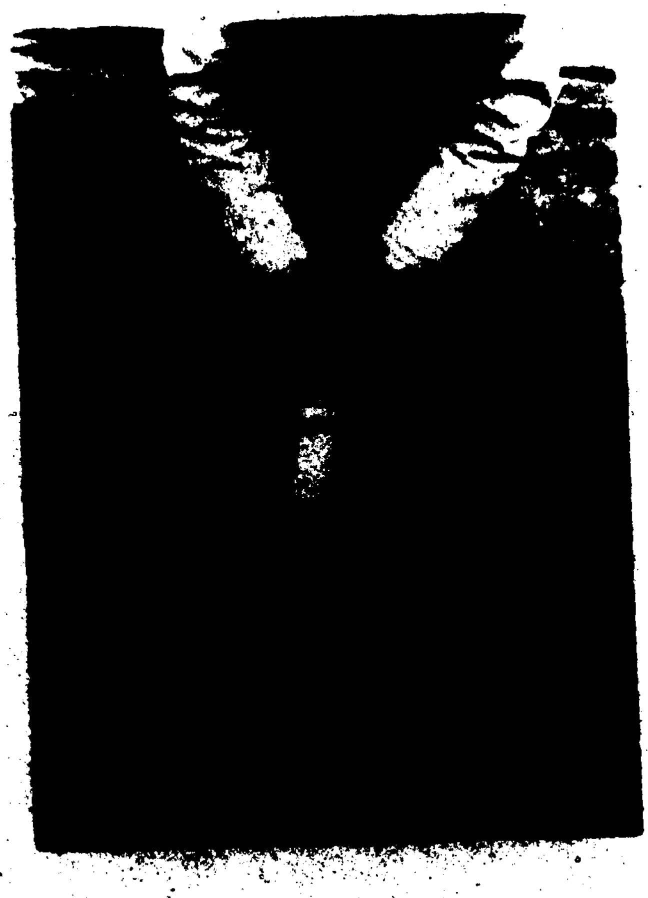

Figure 2. Cohron Sheargraph.

Figure 3. Equipment for measuring soil [illegible] and moisture content.. [illegible], weighing scale, soil [illegible] and core sampler.

B. Penetrometer Calibration.

With the penetrometer handle removed, a light plate was mounted on the penetrometer. Weights were then placed on the plate and the deflection of the coiled springs were recorded by the pen. Depth calibration by direct measurements were made. Calibration of the force and depth line are shown in Figure 4.

C. Experimental Area and Soil Type.

The experiment was conducted at the Ellerslie Research Centre, University of Alberta. The soil in the test area is classified as Malmo silty clay loam. The grain size distribution of the soil at the experimental site is shown in Appendix III. The experiment was conducted on both summerfallow and stubble fields.

D. Test Vehicle.

The International Harvester, model IHC 966 (Diesel) farm tractor shown in Figure 5 was used in the field test to provide soil compaction. The rear tire inflation pressures were varied from 10 to 30 psi and the vehicle was driven across the plots at a constant speed of 3.5 miles per hour without drawbar load. The pertinent vehicle data is given in Appendix 1.

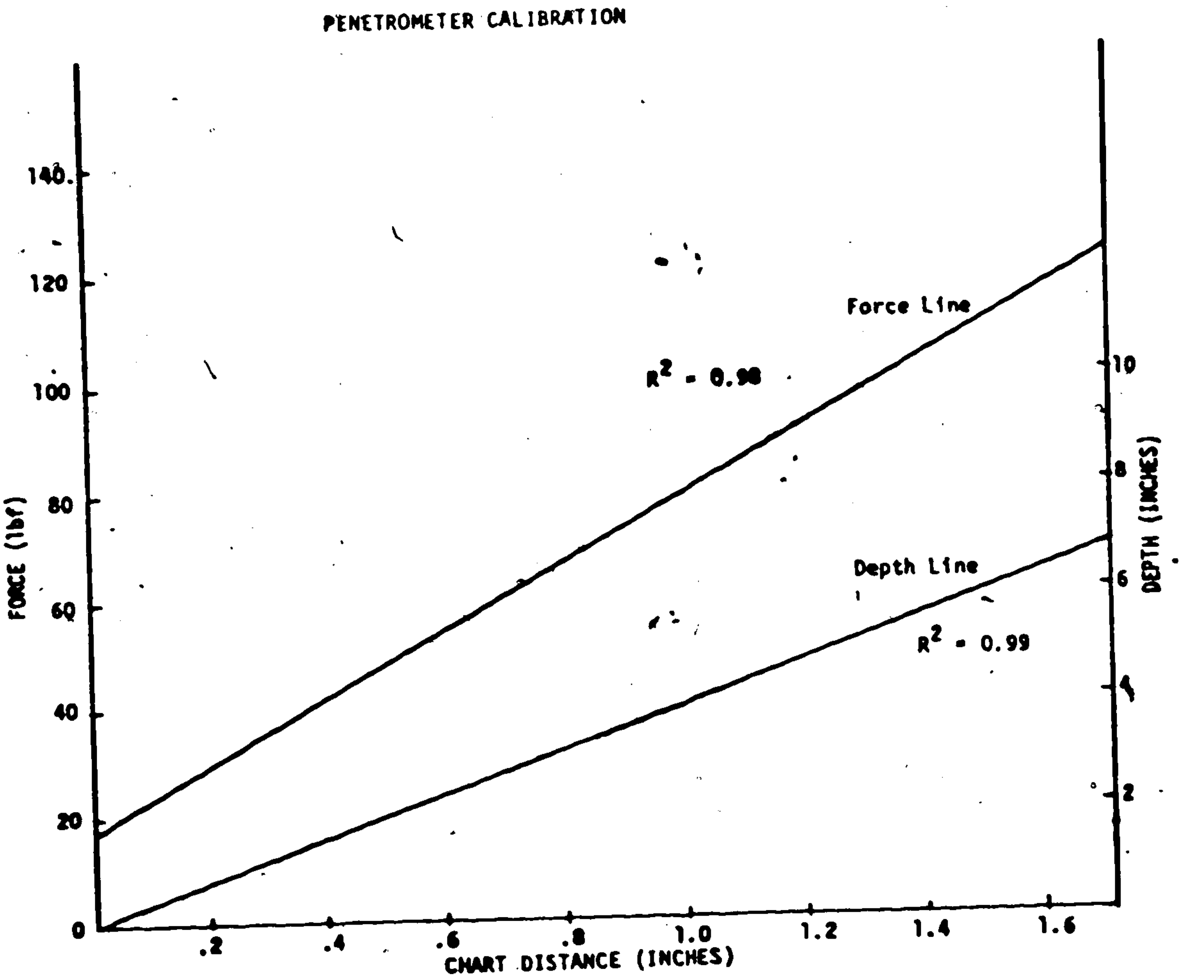

Figure 4. Penetrometer calibration.

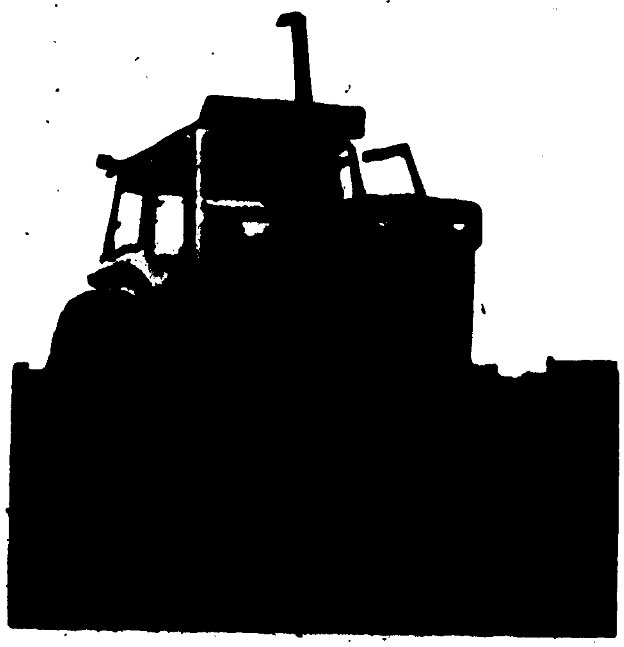

Figure 5. Tractor used for soil compaction.

[illegible]CEDURE

A. Experimental Design.

The experiment was designed to study the consistency of Cone Index readings and other soil parameters over a given natural moisture range. The effect of two conditions of soil surfaces of the same soil and the influence of tillage and vehicle compaction were considered.

The experiment was conducted over a three month period during which soil moisture of the top 3 inches varied from 25 percent to 45 percent. Two fields were chosen, each measuring 240 yds x 30 yds. One field was summerfallow the previous year and the other was stubble. The fields were then divided into 48 plots, each measuring 10 yds x 30 yds. and assigned their particular treatment combination.

The treatments within each field were:

1. Either tilled or untilled. A 15 ft "chisel plough" cultivator was used to provide a tillage depth of approximately 6 in. The tilled soil surface was then levelled using a 15 ft parallel diamond harrow. The tillage treatment was applied only once at the beginning of the experiment.
2. Three levels of vehicle compaction with rear tire inflation pressures of 10, 20 and 30 psi were used. As a control treatment zero compaction was designated when no vehicle traffic was permitted.

Three replicates on each field were used to account for the variation within each field.

The experiment may be classified as a 4 x 2 x 2 factorial design. The treatment combinations were randomized within replicates and the replicates within fields.

B. Field Test Procedure.

Within a treatment combination in a plot the following soil parameter measurements were made:

(a) Cone Index Measurements.

Cone Index measurements were made immediately after the specific compactions were applied to the soil surfaces. Cone Index readings were taken on the lugs and between the lug markings. On plots with no vehicle traffic, Cone Index readings were taken directly. For each case, five readings per chart were taken in an area of 1.5 ft. x 1.5 ft. Eight sets of readings per plot were made. Typical examples of penetration curves are given in Appendix IV.

(b) Soil Density and Moisture Measurements.

Core samples (size: 2.86 in. diameter and 2.67 in. length) were taken using the drive-cylinder method. Six replicates per plot associated with nearby Cone Index measurements sites were made. The soil density and moisture content was obtained by the oven-dry technique. The soil sampler was used to obtain five samples at random over both fields to observe the soil moisture profile. The above procedure was repeated three times during the wet and dry periods.

(c) Shear Strength Measurements.

Three measurements per plot were made at the beginning of the experiment. In plots which were tilled, the soil had to be prepared by compacting with a spade to obtain reasonable measurements of c and ϕ.

A complete set of the soil measurements was made in approximately six weeks. The entire soil measurements were made in two cycles of six weeks each. The shear measurements were made only during the first cycle. The frequency of rain causing saturated soil conditions often impeded soil measurements throughout the 3.5 month period.

V. ANALYSIS OF DATA

A. Evaluation of Cone Index Readings and Other Soil Parameters.

To evaluate the Cone Index readings for a particular site, the depth of penetration must be considered in the analysis. The Cone Index in this context may be defined as the overall average force required to cause penetration to a depth of 9 in. divided by the cone base area. A planimeter was used to obtain the average force for a penetration depth of 9 in. on each chart. Three planimeter readings per curve were made and the average of the 15 readings was taken. The cone penetration energy was also obtained as the overall average area under the curve to a penetration depth of 9 in. The same procedure was repeated for all the sets of cone penetration resistance readings taken in the field.

The shear components c and ϕ were obtained from the shear graph chart paper. A best fit line was drawn through the most dense area of the soil ultimate stress curves and points of peak shear stress when they occurred. The intersection of the average ultimate line and the shear stress axis gave the apparent cohesion of the soil. The angle of the line with the normal stress axis is the angle of friction.

A simple FORTRAN IV program was written to evaluate the soil density and moisture from core samples obtained in the field. The soil density was computed as:

$$\text{wet density} = \frac{w_1 - w_2}{v} \quad (\text{lb ft}^{3})$$

where,

w_1 = weight of cylinder and wet specimen (lb)

w_2 = weight of cylinder (lb)

v = volume of cylinder (ft ^{3})

$$\text{dry density} = \frac{w_s}{v} \quad (\text{lb/ft}^3)$$

where,

w_s = weight of dry soil (lb)

v = volume of specimen (ft^3).

The soil moisture content (percentage dry weight) was computed as:

$$M.C. = \frac{(w_1 - w_2) - w_s}{w_s} \times 100 \text{ per cent}$$

B. Analysis of Variance.

To evaluate the effects of the treatments (surfaces, compaction and tillage) and their combinations outlined in the experimental design, an analysis of variance was used. A library program (Analysis of Variance, Weingardt 1975) was used to make a complete factorial analysis of variance. The theoretical model used was:

$$Y_{ijklm} = \mu + S_i + F_{j(i)} + T_k + ST_{ik} + FT_{jk(i)} + C_l + SC_{il} + FC_{jl(i)} + TC_{kl} + STC_{ikl} + FTC_{jkl(i)} + e_{m(ijkl)}$$

where,

Y_{ijklm} = m^{th} observation on the i^{th} soil surface (S) on the j^{th} replicate (F) on the k^{th} soil tillage (T) on the l^{th} compaction level (C).

μ = population mean

e = error term

i = 1,2

j = 1,2,3

k = 1,2

l = 1,2,3,4,

m = 1,2,3, ...8.

To evaluate the difference of Cone Index readings taken on the tire lugs and between the tire lug patterns, the following model was used:

$$Y_{ijklmn} = \mu + S_i + F_{j(i)} + T_k + ST_{ik} + FT_{jk(i)} + C_l + SC_{il} + FC_{il} + TC_{kl} + STC_{ikl} + FTC_{jkl(i)} + L_m + SL_{lm} + FL_{jm(i)} + TL_{km} + STL_{ilm} + FTL_{jkm(i)} + CL_{lm} + SCL_{ilm} + FCL_{jlm(i)} + TCL_{klm} + STCL_{iklm} + FTCL_{jklm(i)} + e_{ijklmn}$$

where,

Y_{ijklmn} = n^{th} observation on the i^{th} soil surface (S) on the j^{th} replicate (F) on the k^{th} soil tillage on the l^{th} compaction level (C) on the m^{th} lug tire pattern (L)

i = 1,2

j = 1,2,3

k = 1,2

l = 1,2,3

m = 1,2

n = 1,2,3, ...8

C Multiple Regression Analysis.

To obtain prediction equations relating various parameters to cone index readings a multiple linear regression analysis was carried out on lugs and between lugs data. A library program available at the University of Alberta Computing Center was used (Grobben 1970).

The model used was:

$$Y = a + b_1 mc + b_2 bd + b_3 mc^2 + b_4 bd^2$$

where,

Y = soil performance parameter

mc = moisture content (percent)

bd = dry bulk density

The exact form of relationship between these soil properties and cone index is not clearly established. Hence, for an unknown function, a polynominal will give a good approximation to the true function over the range of interest. For the given natural moisture range, the data are adequately fitted when a first or second degree polynominal is used.

VI. RESULTS AND DISCUSSION

A. Preliminary Test.

Initial measurements were undertaken to determine whether there were any consistent relationships between cone penetration resistance and moisture content at different penetration depths in *in-situ* soil conditions. Quadruplicate measurements were taken at random locations in both summerfallow and stubble fields which had been compacted under natural circumstances. The results of penetration resistance against depth for three different soil moisture ranges are given in figure 6. The soil moisture for each case was computed as a mean over a depth of nine inches using the oven dry method. The curves in figure 6 show that resistance to penetration increases with depth at the initial state but remains fairly constant for depths greater than approximately three inches. For natural soil conditions, the resistance to penetration increases continuously with depth (W.E.S. 1964). This behavior was not observed in both fallow and stubble fields probably because they had a history of soil tillage and compaction, and were subjected to annual cycles of freezing and thawing.

Soil moisture is an important factor influencing the soil resistance to penetration as shown in figure 6. The resistance to penetration of the soil increases when the soil moisture content decreases. In preliminary tests, very little change in penetration resistance was observed for soil moisture content (wet weight basis) greater than 34 percent. This may be attributed to the particular soil type (silty-clay loam) present in the experiment area. Soil resistance to penetration remains fairly constant as soil moisture reaches field capacity (Carter, 1967).

The variation in penetration resistance at each depth was found to be less than ± 12 percent from the mean value. Carter (1967),

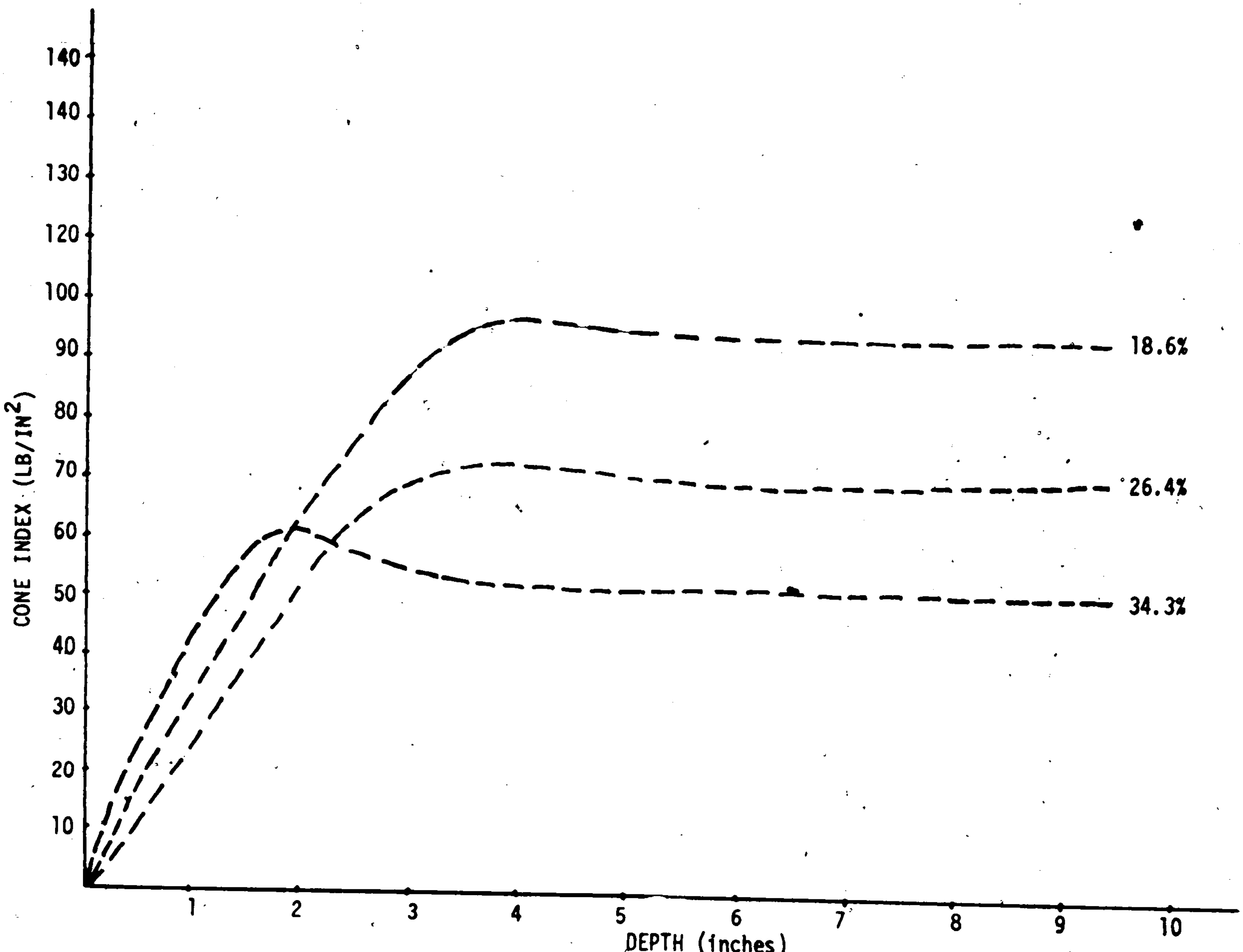

Figure 6. Penetration resistance against penetration depth curve for three different moisture contents in stubble and summerfallow surfaces.

using the same instrument, indicated that measurements were repeatable to ± 10 psi and ± 0.02 ft. Errors in strength measurements resulting from a variable speed of penetration were negligible for insertion rates of 0 to 1 fps. This variation includes the instrument response differences and the differences due to operator's pressure on the instrument handle throughout the entire range of penetration depth.

To minimize the effect of the variations described above, an experimental design was used so that the large number of soil penetration resistance data collected at various sites in different treatment plots could be analysed statistically.

B. Cone Index Readings.

The Cone Index for each particular site was computed as a mean of five penetration curves over a depth of nine inches. The general means of the Cone Index readings for the various treatment levels are given in Table 1. The mean Cone Index taken on the fallow surface was greater by approximately 7 psi (refer Table 1). This difference may be because of an accumulation of soil moisture due to the presence of root systems in the stubble surface. The effect of tillage on the surfaces was more pronounced. Differences in Cone Index readings of approximately 20 psi were found between tilled and untilled surface. On the tilled surface the reference point of zero resistance to penetration was difficult to establish before any natural consolidation occurred. A similar difference in Cone Index readings was observed when Cone Index readings were taken on and between the tire lug patterns. This is reflected as an increase of soil resistance to penetration in the initial 3.5 in. depth.

In general, the resistance to penetration increased with greater compaction on the soil surface. This was reflected by a higher Cone Index reading when the rear tire inflation pressure was increased above

TABLE 1: MEANS FOR CONE INDEX READINGS

			Cone Index (lb/in²)
Surface			
	Summerfallow		96.5
	Stubble		88.2
Tillage			
	Untilled		101.7
	Tilled		82.0
Compaction			
	Uncompacted		71.6
	Rear tire inflation pressure	10 psi	80.2
		20 psi	96.6
		30 psi	119.0
Tire Lug Patterns			
	Between lugs		81.0
	On lugs		102.7

10 psi (refer Table 1). The influence of high moisture content, however, could reduce the Cone Index readings significantly. The soil strength is weakened at high soil moisture contents thus reducing the resistance to penetration. The individual means for the treatment levels are shown in Table 2. The discrepancies of Cone Index readings taken between the tire lug patterns at a compaction level of 10 psi compared to the uncompacted surfaces were due to non-uniform soil moisture levels. Weather reports indicated that a precipitation of 2.05 in. of rainfall occurred two days before the measurements were made (Can. Climatological Station Report: July, 1974).

Varying soil moisture creates a serious source of error in penetrometer field use. Comparison of the different treatment means in Table 2 is difficult because of the error due to varying soil moisture. However, a general trend of higher resistance to penetration was observed for higher compaction levels when measurements were made on the tire lug patterns. The mean Cone Index readings for each compaction level generally showed a standard deviation of 14 psi.

Carter (1967) suggested that all measurements should be obtained from soil at field capacity moisture content. Uniform soil moisture, assessed by depth and location, resulting from physical forces could be expected only at field capacity. The purpose of this study, however, was to investigate Cone Index variation under conditions suitable for field operations.

The analysis of variance for Cone Index readings taken on both fallow and stubble surfaces are shown in Table 3 and 4. Separate analyses of variance were made to observe the difference when cone penetration resistance measurements were taken on and between the tire

TABLE 2: MEAN CONE INDEX READINGS FOR INDIVIDUAL TREATMENTS.

Fallow Surface		Cone Index (psi) Compaction levels Rear tire inflation pressures			
	Uncompacted	10 psi	20 psi	30 psi	Means
*L		91	103	135	97
Tilled	53				
**BL		65	80	94	73
L		109	130	160	121
Untilled	85				
BL		79	100	108	93

Stubble Surface		Compaction levels Rear tire inflation pressures			
	Uncompacted	10 psi	20 psi	30 psi	Means
L		84	95	113	88
Tilled	61				
BL		54	78	94	72
L		94	109	140	107
Untilled	84				
BL		68	87	87	81

* L Readings taken on tire lug patterns.

** BL Readings taken between tire lug patterns.

TABLE 3: ANALYSIS OF VARIANCE FOR CONE INDEX READINGS TAKEN ON TIRE LUG PATTERNS.

Source of Variation		Degrees of Freedom	Mean Squares	F Value
Surface	S	1	11304.0	13.86*
Error (1)	F/S	4	815.64	
Tillage	T	1	45608.0	179.02**
	TxS	1	1254.30	4.92
Error (2)	TF/S	4	254.77	
Compaction	C	3	74295.0	50.12**
	CxS	3	2621.0	1.77
Error (3)	CF/S	12	1482.4	
	CxT	3	877.71	1.87
	CxTxS	3	229.97	0.70
Error (4)	CTF/S	12	468.24	

* significant at the 5 percent level of probability.

** significant at the 1 percent level of probability.

TABLE 4: ANALYSIS OF VARIANCE FOR CONE INDEX READINGS TAKEN BETWEEN TIRE LUGS PATTERN.

Source of Variation		Degrees of Freedom	Mean Squares	F Value
Surface	S	1	1213.4	1.05
Error (1)	F/S	4	1157.4	
Tillage	T	1	29940.0	116.92**
	TxS	1	565.92	2.21
Error (2)	TF/S	4	256.07	
Compaction	C	3	23857.0	21.58**
	CxS	3	1103.2	0.99
Error (3)	CF/S	12	1105.6	
	CxT	3	918.83	2.30
	CxTxS	3	229.56	0.58
Error (4)	CTF/S	12	399.51	

** significant at the 1 percent level of probability.

lug patterns.

The results showed significant differences between levels of soil surface conditions, tillage and vehicle traffic compaction. Both tillage and level of vehicle traffic compaction showed statistical significance at the one percent probability level. The conditions of soil surfaces showed significant differences only at the 5 percent probability level when measurements were taken on the tire lug patterns (Table 4). No significant differences were observed on either surfaces with cone index measurements taken between tire lug patterns. This may be attributed to the lugs compacting the soil surface to a denser consistency. None of the interactions of the treatments were significant.

An analysis of variance for Cone Index readings taken on and between the tire lug patterns is shown in Table 5. In this analysis the effect of lugs is treated as a treatment and its combined effect with other treatments (surface conditions, tillage and vehicle compaction) is investigated. The results showed that the difference in taking cone index readings on and between the tire lug pattern is significant at the one percent probability level. The interaction of treatments where lugs are involved as some treatment combination is significant at the 5 percent probability level. An increase in magnitude of Cone Index readings taken on tire lug patterns probably resulted in this significant difference.

The soil in plots that were left untilled was consolidated naturally giving a fairly homogeneous structure. The soil in plots that were tilled with a cultivator to a depth of 6 inches had a loose homogeneous structure. Cone Index measurements were not easily obtained

TABLE 5: ANALYSIS OF VARIANCE FOR CONE INDEX READINGS TAKEN ON AND BETWEEN TIRE LUG PATTERNS.

Source of Variation		Degrees of Freedom	Mean Squares	F Value
Surface	S	1	16846.0	7.78*
Error (1)	F/S	4	2164.7	
Tillage	T	1	43226.0	127.23**
	TxS	1	912.41	2.69
Error (2)	TF/S	4	339.74	
Compaction	C	2	72145.0	32.32**
	CxS	2	18.541	0.01
Error (3)	CF/S	8	2232.4	
	CxT	2	485.56	1.26
	CxTxS	2	561.43	1.46
Error (4)	CTF/S	8	385.80	
Lugs	L	1	0.12026E+06	1958.71**
	LxS	1	3407.1	55.49
Error (5)	LF/S	4	61.396	
	LxT	1	1095.1	13.60*
	LxTxS	1	90.115	1.12
Error (6)	LTF/S	4	80.541	
	LxC	2	2053.0	6.56*
	LxCxS	2	1382.8	4.42
Error (7)	LCF/S	8	313.15	
	LxCxT	2	410.23	4.77*
	LxCxTxS	2	43.417	0.51
Error (8)	LCTF/S	8	86.031	

* significant at the 5 percent level of probability.

** significant at the 1 percent level of probability.

for tilled soil conditions, since hardly any resistance to penetration was recorded in the first 3 to 4 inches. Immediately after tillage the soil had a homogeneous loose structure in which soil strength parameters were difficult to obtain. The effect of vehicle traffic compaction and the action of weather caused this loose homogeneous structure to collapse and the soil returned to the semi-consolidated state. Consolidation of tilled soil produces non-homogeneity in the soil as some areas tend to be more active than others following periods of heavy rainfall. This problem was more severe in the fallow field as there were poorly drained areas, which resulted in non-uniform soil moisture conditions.

The soil was further compacted as the rear tire inflation pressure was increased. The soil condition in both fields was capable of further compaction even when a rear-inflation pressure of 30 psi was used. In plots where the soil was tilled, the soil was initially more susceptible to compaction by vehicle traffic. Wismer and Luth (1973) suggested that Cone Index measurements on soil surface after vehicle compaction were more consistent in evaluating the soil strength beneath the wheel. The mean Cone Index readings for each compaction level generally showed a standard deviation in the range of 14 psi. The large standard deviation of Cone Index readings obtained in the field indicated a wide variation. The researcher must therefore take a reasonable sample size to ensure that the actual mean is obtained. For example, Guenther (1965) indicates that for a confidence coefficient of 0.95 on a confidence interval of one standard deviation, thirty samples are necessary for a 0.99 probability so that this limit is attained. From Sampling Theory, The Cone Index readings taken on twenty sites for a given treatment combination showed that the confidence interval is less than 13 psi for a probability of 0.99.

Different shaped pressure-depth curves were sometimes obtained for penetration tests in plots that had no vehicle compaction. A lack of uniformity in soil density profiles of some of the test sites may be responsible for variation of penetration resistance tests located 1.5 ft apart. This lack of uniformity was detected by using a neutron density meter manufactured by Nuclear-Chicago. The soil in plots that were tilled but experienced no vehicle traffic never did return to the original consolidated state under natural weather action throughout the experimental period. These plots had a pronounced lack of soil uniformity throughout the test period.

C. <u>Cone Penetration Energy</u>.

The cone penetration energy is the mean energy (in-lb) resisting the penetration of cone penetrometer over a depth of 9 inches. The mean area under the force-depth curve recording on the penetrometer recording chart gave a measure of the cone penetration energy.

The analyses of variance for cone penetration energy data measured on and between the tire lug patterns are given in Tables 6 and 7 respectively. A similar trend of statistical difference between treatment levels of surface condition, tillage and vehicle compaction as accounted in Cone Index-measurements, predominates.

D. <u>Soil Strength Parameters</u>.

The two components of soil shear strength, namely cohesion

TABLE 6. ANALYSIS OF VARIANCE FOR CONE ENERGY READINGS TAKEN ON TIRE LUG PATTERNS.

Source of Variation		Degrees of Freedom	Mean Squares	F Value
Surface	S	1	0.22873E+06	13.6454*
Error (1)	F/S	4	16762.0	
Tillage	T	1	0.92339E+06	185.7462**
	TxS	1	26659.0	0.0815
Error (2)	TF/S	4	4971.2	
Compaction	C	3	0.1499E+07	49.7486**
	CxS	3	54044.0	0.2021
Error (3)	CF/S	12	30151.0	
	CxT	3	17069.0	1.7712
	CxTxS	3	4731.5	0.4910
Error (4)	CTF/S	12	9637.0	

* significant at the 5 percent level of probability.

** significant at the 1 percent level of probability.

TABLE 7. ANALYSIS OF VARIANCE OF CONE ENERGY READINGS TAKEN BETWEEN TIRE LUGS PATTERNS.

Source of Variation		Degrees of Freedom	Mean Squares	F Value
Surface	S	1	20287.0	0.8699
Error (1)	F/S	4	23323.0	
Tillage	T	1	0.5923E+06	108.518**
	TxS	1	11090.0	2.0319
Error (2)	TF/S	[illegible]	5457.9	
Compaction	C	3	0.47077E+06	22.8773**
	CxS	3	22967.0	0.3810
Error (3)	CF/S	12	20578.0	
[illegible]	CxT	3	18579.0	2.276
	CxTxS	3	5445.4	0.6671
[illegible] (4)	CTF/S	12	8162.5	

** significant at the 1 percent probability level.

(c) and friction (ϕ) measured using the Cohron sheargraph were found to be quite variable. Plots that experienced vehicle traffic compaction showed fair consistency when c and ϕ were measured on the vehicle tracks. However, for plots that were tilled excavation of the loose soil with a shovel was necessary before any measurements were possible. The mean values of c and ϕ measured on the fallow and stubble fields were $0.36 \pm .08$ lb/in^2, 34.6 ± 2.4 degrees and 0.48 ± 0.14 lb/in^2, 38.7 ± 1.2 degrees respectively. Higher mean values of c and ϕ were found in stubble surface due to the surface condition of the soil. The reason for this variability in c and ϕ may be due to a lack of homogeneity in the density profile caused by the treatments and the effects of wetting and drying cycles upon the soil during this period. Variation of c and ϕ with depth were not apparent. No correlation could be made between Cone Index and either the cohesion or the friction angle ϕ.

E. Soil Moisture Content and Bulk Density Measurements.

Initial measurements of soil moisture and density profiles indicated a fairly wide variation throughout the experimental area. The effect of natural weather conditions and the presence of low spots where rainfall collected probably caused this variability. Variations of bulk density and moisture content with depth were as large as approximately 10 percent within the same plot. To study the effect of vehicle compaction on soil properties and also to collect sufficient data for the given area soil moisture and density measurements were restricted to the top 3 inches of the soil profile. The means for soil moisture content and dry bulk density for the different treatment levels are shown in Tables 8 and 9 respectively. Soil moisture and density measured as a mean over this tractive layer of the soil profile showed much better consistency.

TABLE 8. MEAN SOIL MOISTURE PERCENTAGE FOR INDIVIDUAL TREATMENTS.

Fallow Surface	Uncompacted	Compaction levels Rear tire inflation pressures 10 psi	20 psi	30 psi
Tilled	33.1	33.5	35.2	31.6
Untilled	29.5	35.9	34.4	30.4

Stubble Surface	Uncompacted	Compaction levels Rear tire inflation pressures 10 psi	20 psi	30 psi
Tilled	41.6	34.8	40.0	34.2
Untilled	41.0	37.2	40.5	35.6

TABLE 9. MEAN BULK DENSITY (LB/FT^3) FOR INDIVIDUAL TREATMENTS.

Fallow Surface

		Compaction levels Rear tire inflation pressures		
	Uncompacted	10 psi	20 psi	30 psi
Tilled	59.3	65.3	66.7	69.1
Untilled	65.7	64.4	66.6	67.5

Stubble Surface

		Compaction levels Rear tire inflation pressures		
	Uncompacted	10 psi	20 psi	30 psi
Tilled	53.0	58.7	58.2	63.9
Untilled	57.1	61.1	61.7	65.0

Soil moisture within individual compacted plots showed a variation of approximately ± 4.8 percent. Uncompacted plots had higher variation in the range of ± 5.4 percent. Similar trends were observed in wet bulk density measurements. Variation of bulk density was in the range of ± .42 lb/ft^3 and 5.6 lb/ft^3 for compacted and uncompacted plots respectively. Measurements of these soil properties were avoided during periods of frequent rain followed by spells of hot weather. This condition was more severe in areas that were poorly drained, which easily resulted in non-uniform soil moisture conditions. The soil in plots that were tilled was in a semi-consolidated state, making measurement of these soil values rather difficult.

The analysis of variance for soil moisture is given in Table 10. The results showed no significant difference for levels of tillage, surface condition and vehicle traffic compaction. The interaction of tillage and vehicle traffic compaction showed a significant difference at 5 percent probability level. On the untilled surface soil moisture content decreased with higher compaction level. On the tilled surface, however, the moisture content increased for the 10 and 20 psi compaction level and decreased for the 30 psi compaction level.

The soil moisture varied from 26 percent to approximately 45 percent during the experimental period. Fluctuation in weather conditions often required collection of samples for moisture determination during periods of non-uniform soil moisture conditions. However, due to the large number of soil moisture data gathered, the variability resulting from areas that were poorly drained were reduced to a minimum.

The analysis of variance for soil dry bulk density is given in Table 11. The results showed significant difference for levels of

TABLE 10. ANALYSIS OF VARIANCE FOR MOISTURE CONTENT DATA.

Source of Variation		Degree of Freedom	Mean Squares	F Value
Surface	S	1	1886.4	2.76
Error (1)	F/S	4	683.78	
Tillage	T	1	0.85592	0.06
	TxS	1	64.619	4.43
Error (2)	TF/S	4	14.582	
Compaction	C	3	259.46	1.64
	CxS	3	239.47	1.51
Error (3)	CF/S	12	158.47	
	CxT	3	61.087	7.54**
	CxTxS	3	7.0671	0.87
Error (4)	CTF/S	12	8.1042	

** Significant at the 1 percent probability level.

TABLE 11. ANALYSIS OF VARIANCE FOR DRY BULK DENSITY DATA.

Source of Variation		Degree of Freedom	Mean Squares	F Value
Surface	S	1	2314.2	82.18**
Error (1)	F/S	4	28.161	
Tillage	T	1	519.14	69.32**
	TxS	1	2.6545	0.36
Error (2)	TF/S	4	7.4891	
Compaction	C	3	717.65	15.31**
	CxS	3	50.058	1.07
Error (3)	CF/S	12	46.869	
	CxT	3	717.65	15.31**
	CxTxS	3	17.403	2.02
Error (4)	CTF/S	12	8.6086	

** Significant at the 1 percent probability level.

tillage, surface conditions and vehicle traffic compaction. The treatment interaction, except for the combination of tillage and compaction, showed no significant difference. The soil bulk density increased with increasing level of rear inflation pressure. Soil surfaces that were tilled and compacted showed an increase of bulk density of approximately 3 lb/ft^3. The beginning of soil consolidation in tilled soil that experienced no vehicle traffic compaction, produced non-homogeneity in the soil as some areas were less active in consolidation than others because of soil moisture fluctuation. For tilled soil in a semi-consolidated state, difficulties were encountered in obtaining soil samples for bulk density measurements without compacting the soil when using the drive cylinder method.

F. Relationship of Soil Moisture Content and Cone Index for a Given Mean Bulk Density.

A multiple linear regression model was used in the analysis for each level of vehicle traffic compaction as an attempt to predict the Cone Index from a knowledge of soil bulk density and moisture content. The form of the polynomial fitted was,

$$Y = a + b_1 m_c + b_2 b_d + b_3 m_c^2 + b_4 b_d^2$$

where,

Y = soil performance parameter

m_c = soil moisture content (percentage)

b_d = dry bulk density (lb/ft^3)

as outlined in section V-C.

The soil samples for the determination of these two soil properties were taken from core samples in the top 3 inches of the soil profile, where penetration resistance recordings were measured. The means for wet bulk density for the different vehicle compaction levels showed a variation in the range of 10 lb/ft^3. The soil moisture, however, had a wider range. Therefore, in the regression curves obtained from the empirical equation, the mean bulk density was fixed at 60 lb/ft^3 for Cone Index readings taken on and between the tire lug patterns. Preliminary analysis did not show a good relation between bulk density and Cone Index, because the range of bulk density was relatively small within each compaction treatment level imposed. The range of soil moisture variation was therefore considered necessary in the relationship to predict the Cone Index.

Figure 7 shows a typical relationship between Cone Index (and cone penetration energy) and soil moisture content for a given wet bulk density of 60 lb/ft^3. There is a relatively small difference in Cone Index (and cone penetration energy) between the two soil surface conditions. In general, the fallow surface showed a slightly higher Cone Index reading than the stubble surface for any particular moisture level. Both soil composite parameters decreased as the moisture content increased. For a moisture content less than 30 percent the Cone-Index-moisture content curve is nearly linear and of negative slope, however, for a moisture content greater than 30 percent the negative slope decreases, that is, the rate of decreasing Cone Index readings for higher soil moisture level is less. Yong and Warkentin (1966), in their research studies, showed that for clay in saturated conditions the Cone Index is almost negligible. Soil friction and adhesion between clay particles for clay under saturated conditions are

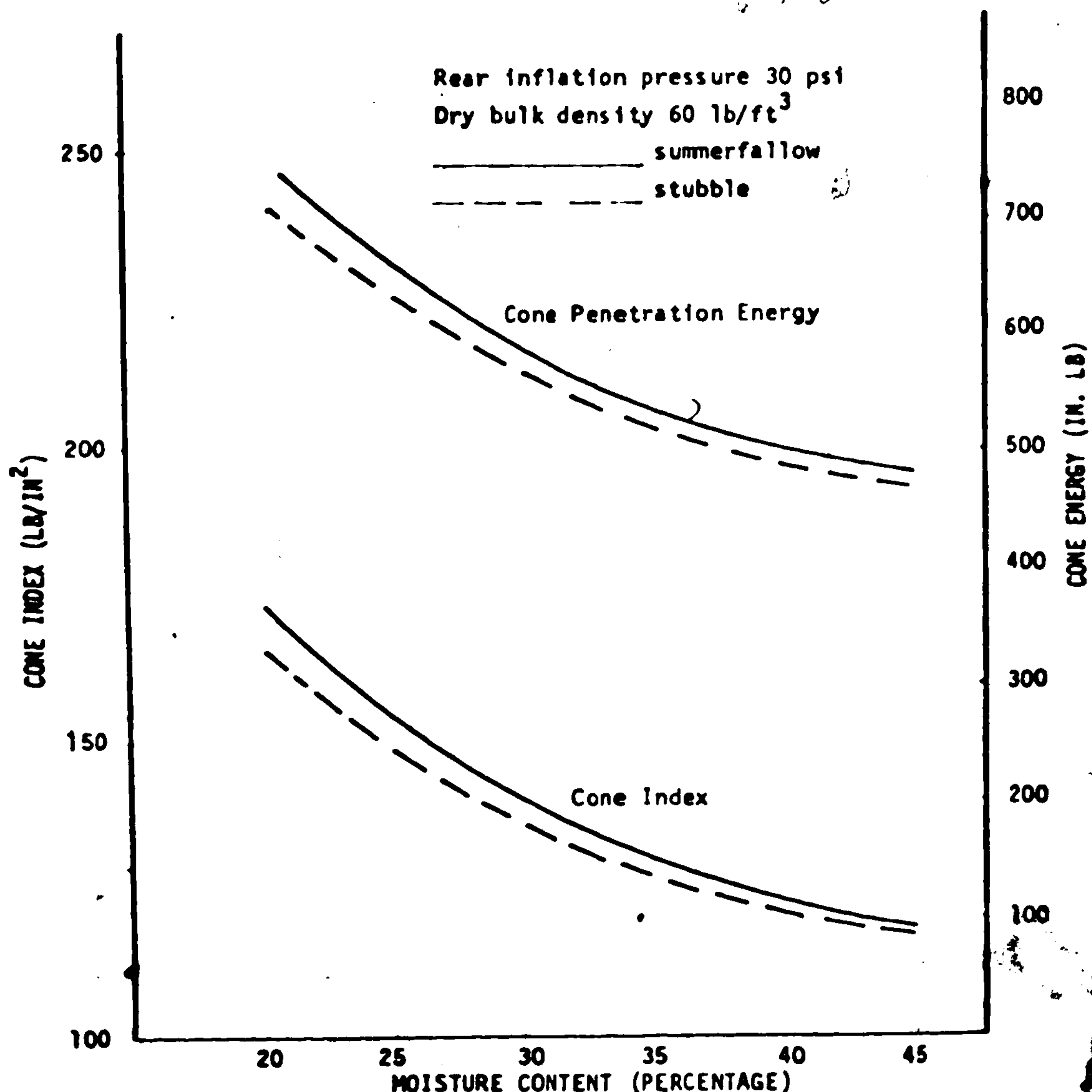

Figure 7. Typical cone index and cone penetration energy for various moisture contents.

practically negligible because water films form the only interparticle contact. As can be seen from figure 7 the curves after changing slopes gradually approach a constant value near the saturation moisture content. However, under actual field condition the soil type (Malmo silty-clay loam) provided detectable resistance to penetration even in poorly drained areas where the moisture content was about 45 percent. After heavy rainfall the wetting point of the infiltration moisture could be detected by noting penetrometer readings at the particular depth where a sudden increase in resistance was recorded. Cycles of hot weather and rain produced a non-uniform moisture gradient in the soil profile which affected Cone Index readings. Plots that were compacted by vehicle traffic had more uniform moisture gradients in the top 3 1/2 inches of the soil profile. The Cone Index readings recorded in these plots showed good consistency.

Figure 8 and 9 shows the Cone Index-moisture curves at a given wet bulk density of 60 lb/ft^3 for both tilled and untilled soil surfaces respectively. The polynomial fit for these curves gave squares of the multiple correlation coefficient (R^2) ranging from 0.74 to 0.86. The Cone Index data for plots that experienced no vehicle compaction did not fit the multiple regression model used. Poor correlation coefficient values in the range of 0.4 to 0.6, were obtained in these cases. Uncompacted soil surfaces, both tilled and untilled, did not show consistency in Cone Index measurement within the experiment moisture range probably because of the non-uniform soil density profile as the soil moisture gradients varied. Readings taken on tire tracks (10 psi compaction level) after two or more weeks were not substantially higher than those taken on the same untilled soil surfaces. The consistency of

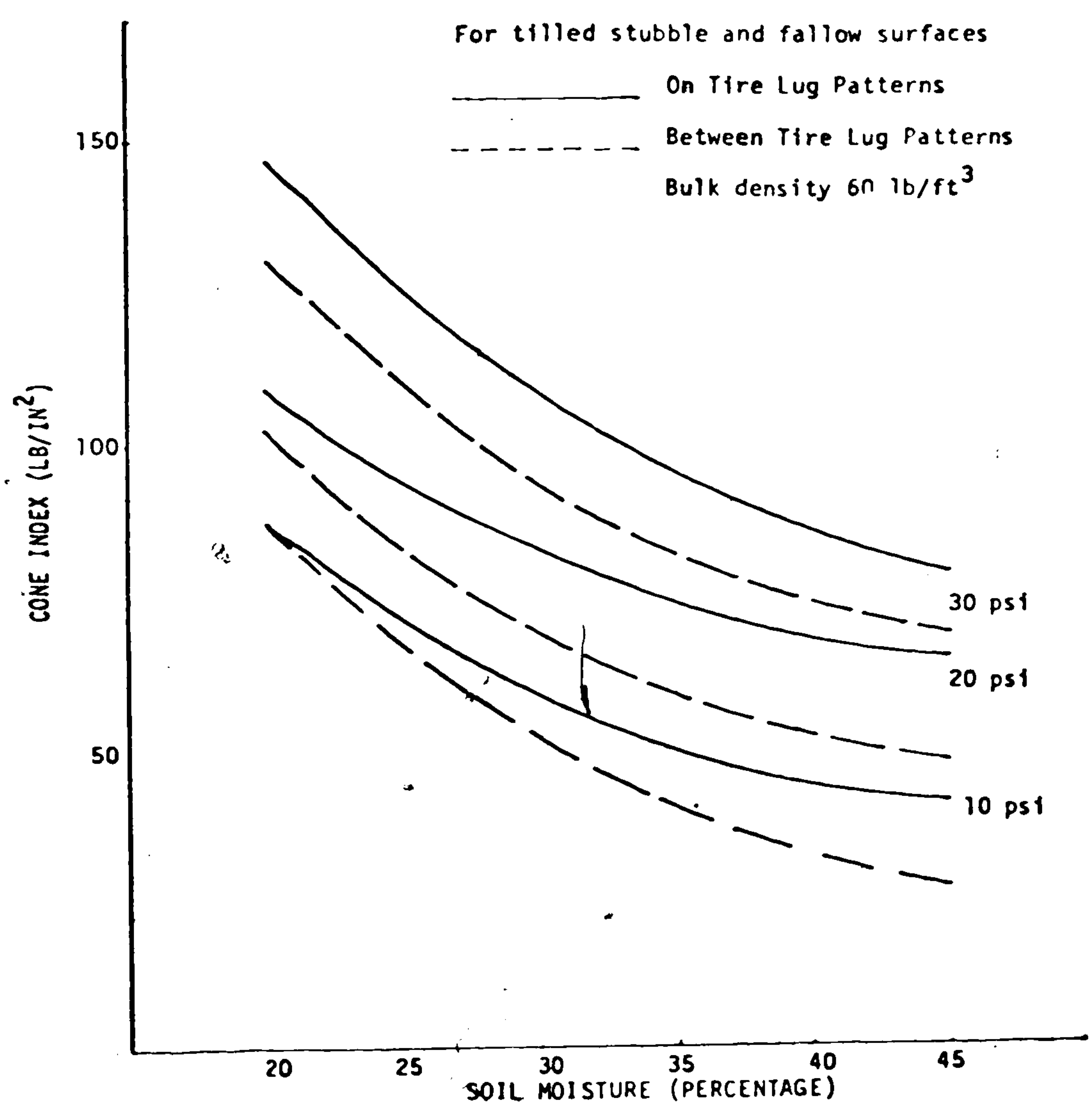

Figure 8. Cone index readings taken on tilled surfaces at three levels of rear inflation pressure for the soil moisture range.

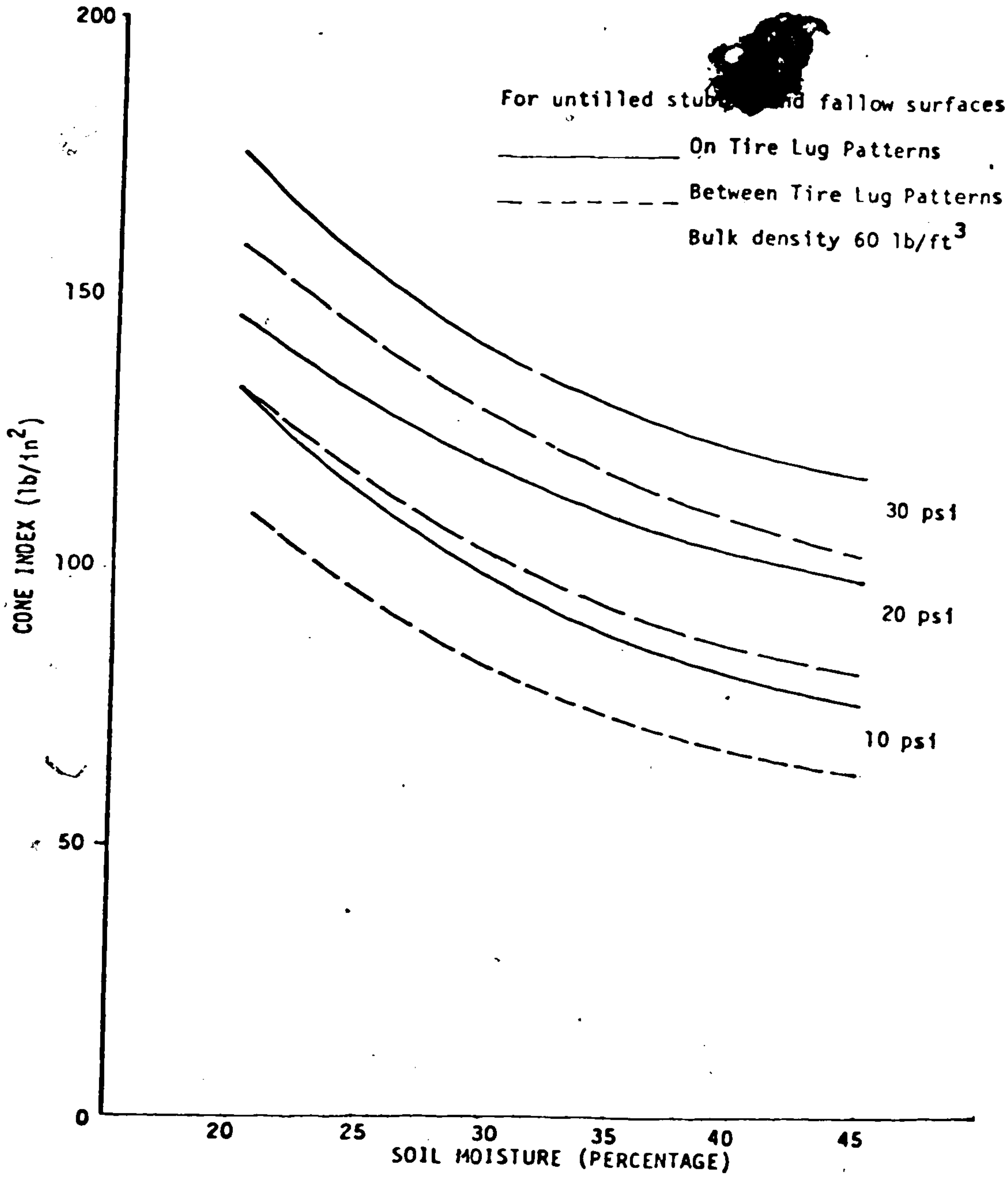

Figure 9. Cone index readings taken on untilled soil surfaces at three levels of rear inflation pressure within the soil moisture range.

Cone Index readings at higher compaction levels remained fairly constant throughout the experimental period.

Figure 10 gives the Cone Index moisture content relations at two wet bulk densities 60 ft/ft^3 and 70 lb/ft^3. The curves for each compaction level encompassed most of the bulk density measurements met in the field. The difference in Cone Index between the two bulk densities at a given moisture level increased for high compaction levels. The influence of soil moisture on the behavior of soil resistance to penetration suggests the importance of interrelating the Cone Index as a function of soil moisture and density. The swelling and shrinking phenomena exhibited by cohesive-frictional soil during wet and dry cycles may further suggest the consideration of other parameters such as precipitation and soil temperature variations.

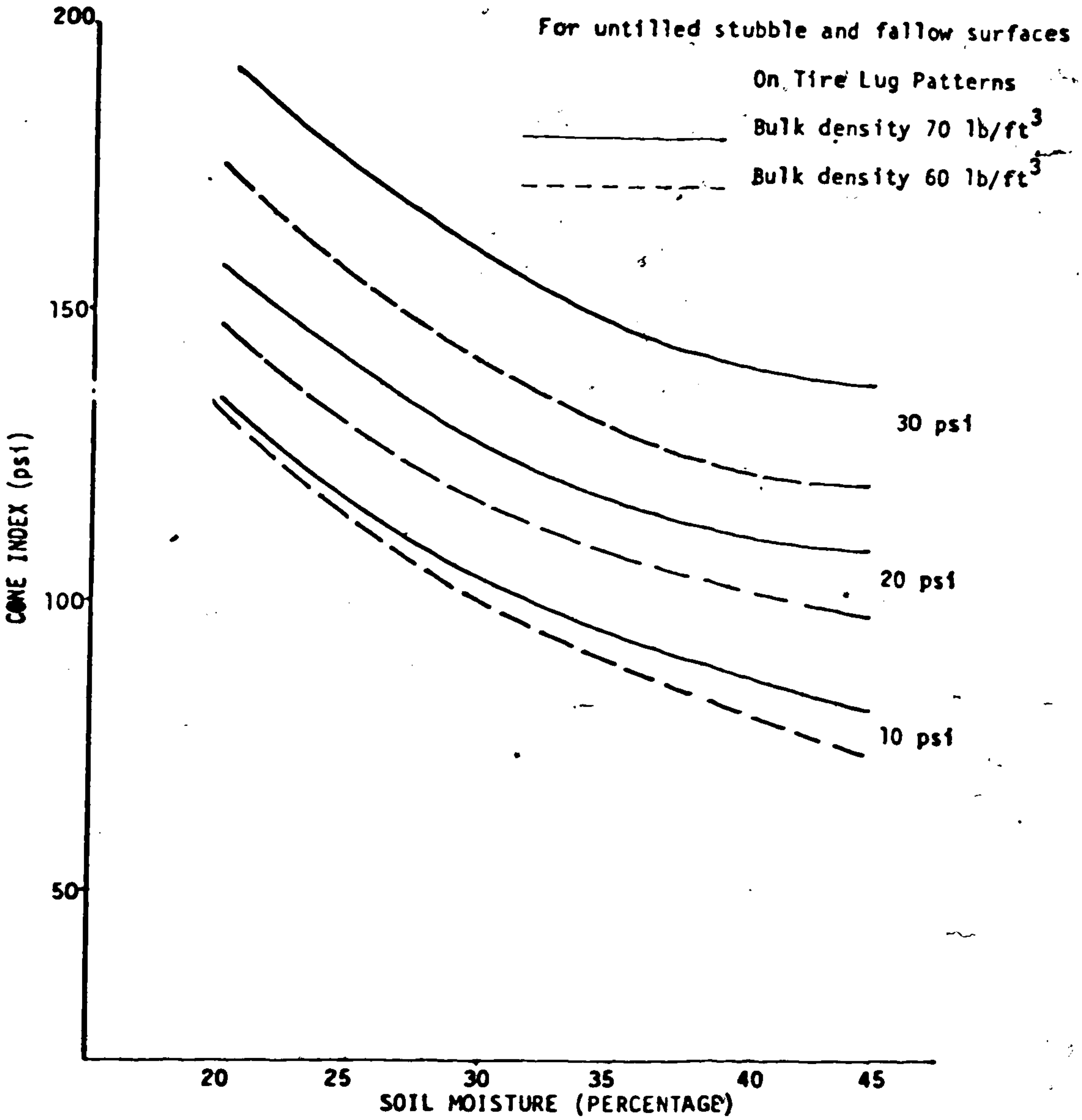

Figure 10. Cone index readings for two bulk densities at three levels of rear tire inflation pressure within the soil moisture range.

VIII. SUMMARY AND CONCLUSIONS

The results of the study conducted for this thesis gave the following inferences with regard to the measurement of Cone Index readings of an agricultural soil.

1. The hand operated penetrometer gave repeatable results only after the operator had gained some experience in sustaining a constant pressure on the instrument handle to achieve an approximate constant rate of penetration. In some sites, a constant penetration rate was not possible because of the underlying hard soil pan. Similarly, on poorly drained sites the soil offered little resistance to penetration.

2. The representative Cone Index for a particular area is a statistical measure of the average soil strength. Measurements taken on twenty four sites for a given treatment gave a standard deviation in the range of 14 psi. The Cone Index readings taken on the twenty four sites showed that for a probability of 0.99, the .95 confidence interval is less than 13 psi for one standard deviation. This variation may be attributed to the effect of varying soil moisture during wet and dry cycles.

3. Surface, tillage and vehicle traffic compaction had significant effects on Cone Index readings. The accumulation of soil moisture in the top 3 inches of the soil profile due to the presence of root systems in the stubble field resulted in lower Cone Index values.

For the silty clay soil on both fallow and stubble surface, the penetration resistance increased for the initial 3 to 4 inches but then remained more or less constant as depth increased. This behavior may be attributed to a history of tillage, traffic compaction and the effects of weather conditions.

5. Cone Index readings taken on the tire lug pattern were significantly greater than those measured between the tire lug patterns. With lugs considered as a separate treatment, the interaction with other treatments showed a significant difference. This difference was attributed to higher magnitude readings measured on the tire lug patterns.

6. The resistance to penetration in the uncompacted soil surface was variable. A similar behavior was detected in tilled uncompacted soil surfaces even after the soil structure reached a semi-consolidated state. This inconsistency in Cone Index readings was probably caused by a lack of uniformity in the soil density profile.

7. The Cone Index could be predicted for the silty clay loam soil when inter-related to the experimental moisture range for a given wet bulk-density measured in the field. The second degree polynomial used in the multiple regression analysis gave a good fit for all vehicle traffic compaction levels. Surfaces with no traffic compaction had low multiple correlation coefficient values. The shrinking and swelling phenomena associated with agricultural soils

during wet and dry cycles emphasize the importance of this inter-relation when predicting the Cone Index of a given soil.

8. The relationship of Cone Index and soil strength parameters (c and ϕ) for cohesive-frictional soil were not adequately elucidated because of the limited range of c and ϕ measured using the sheargraph.

VIII. RECOMMENDATIONS FOR FUTURE WORK

1. A power driven penetrometer would reduce the amount of data necessary to achieve repeatable results due to the variation in penetration rate. The penetrometer and associated instrumentation has to be portable or mounted on a vehicle. An integration circuit could be used in the instrumentation to give digital readings of the Cone Index as a mean over a selected depth.

2. For cohesive-friction soils, different penetrometer probes with different angles and base areas or perhaps a spherical probe used at a constant penetration rate, may measure Cone Index readings more reliably.

3. Cone Index is a composite soil strength parameter. The value measured at a given site is dependent on soil properties such as soil structure, soil moisture and bulk density. The Cone Index for a given area is a statistical quantity. The researcher should ensure a sufficiently large population sample to arrive at a reliable mean value.

4. Cone Index measurements should be related to traction parameters of different tractors to predict vehicle performance in agricultural soils. Vehicle mobility in difficult conditions could thus be predicted from Cone Index measurements. The effects of tire contact area and tread configuration on vehicle mobility and traction capability could be investigated in relation to Cone Index readings.

5. Comparative studies of Cone Index readings in agricultural soils could give useful information on soil compaction due to vehicle traffic. Soil conditions detrimental to plant growth may be predicted.

6. Cone Index readings should be used as a composite soil strength parameter in evaluating the behavior of soil cutting tools.

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APPENDIX I: TEST VEHICLE INFORMATION.

INTERNATIONAL HARVESTER, MODEL IHC 966.

Weight

Gross	13,800 lb. (including driver)
Front axle	4,200 lb.
Rear axle	9,600 lb.

Tires

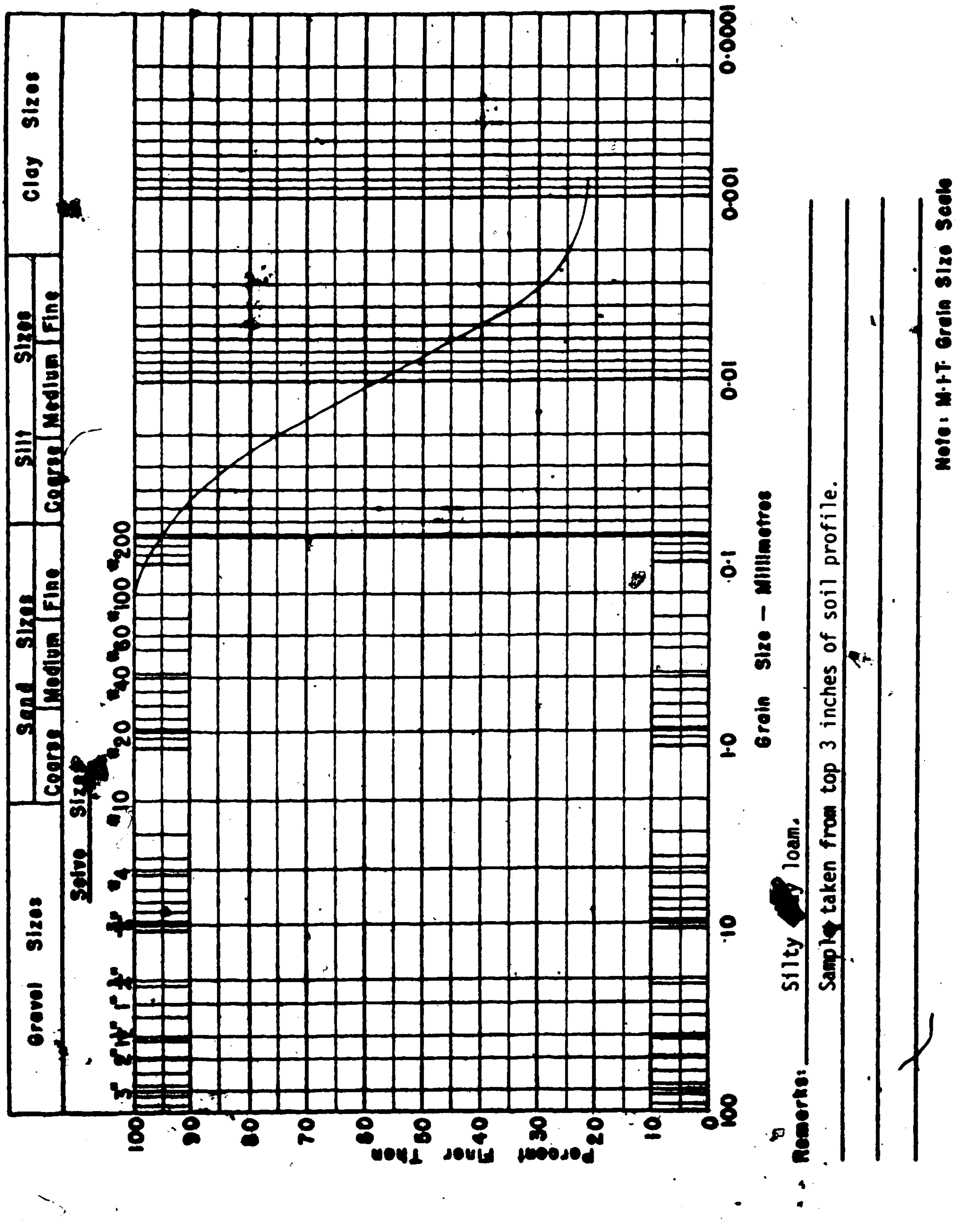
Nominal width (in.)	Front	10.0	Rear	18.4
Rim diameter (in.)	Front	16.0	Rear	34.0
Nominal outside diameter (in.)	Front	35.2	Rear	65.4
Inflation Pressure (psi)	Front	20.0	Rear	Varied
Ply Rating	Front	6	Rear	6

APPENDIX 2: SOIL CLASSIFICATION TEST.

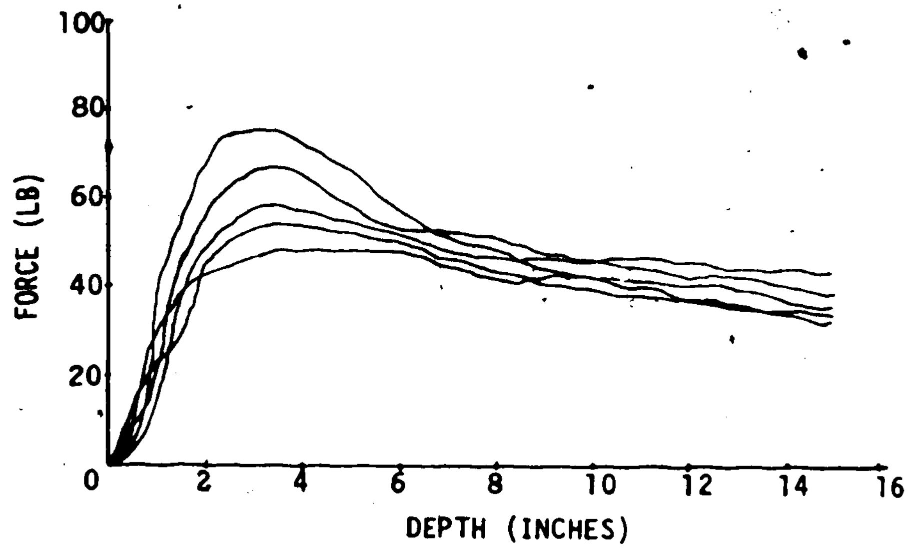
Soil	Liquid Limit	Plastic Limit	Plasticity Index	Classification*
Malmo silty-clay loam	39.6	30.7	8.9	OL (organic silt-clay of low plasticity)

* Unified Soil Classification.

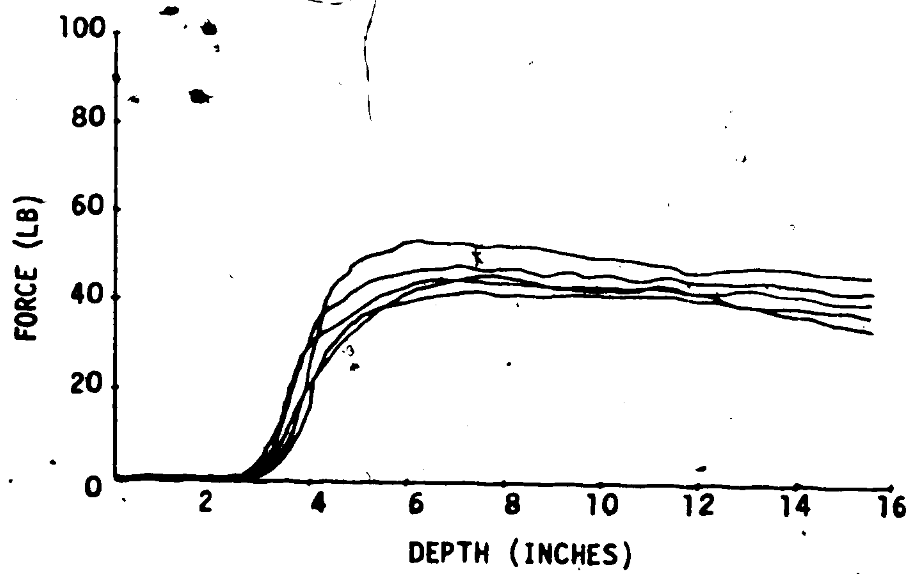
APPENDIX III: GRAIN SIZE ANALYSIS OF TEST SOIL.



APPENDIX IV: TYPICAL PENETRATION CURVES.



Typical force-depth curve measured on a tire lug pattern.



Typical force-depth curve measured between a tire lug pattern.