# Soil Compaction:
## A Literature Review



NOVA

ALBERTA GAS TRANSMISSION DIVISION

# SOIL COMPACTION AND PIPELINE CONSTRUCTION ... A LITERATURE REVIEW

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## FOREWORD

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This study was commissioned to evaluate the available literature on soil compaction as it relates to pipelining: the effect on soil conditions; crop growth and yield; methods of measuring and factors affecting the degree of compaction. This report was prepared by Karen R. Cannon, a private consultant and Sandra Landsburg, a department staff member. The report may be cited as:

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# ABSTRACT

The degree of soil compaction is dependent on many variables including soil type and soil conditions as well as vehicle type and traffic density. Soil compaction can lead to limited plant development because of poor aeration, low nutrient and water availability, slow water permeability and mechanical impedance to root growth. Documented studies concerned with pipeline construction have indicated that soil compaction can be a problem. Soil compaction is dealt with by acceptance, alleviation, avoidance and controlled traffic. The extent of soil compaction is often determined by measuring the change of a parameter as a consequence of a compacting effort.

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## 1.0 INTRODUCTION

Concerns about soil compaction on pipeline rights-of-way (RsoW) have increased with the introduction of heavier, more powerful construction equipment. RsoW are prone to compaction because of the repeated high traffic associated with construction procedures. Soil compaction levels resulting from heavier construction equipment extend much deeper into the soil profile than those associated with conventional farm machinery. This subsurface compaction is not alleviated by regular tillage practice and is only slowly affected by natural seasonal freezing and thawing or periodic wetting and drying cycles.

Soil compaction can lead to poor root penetration, difficult cultivation, poor seedbed preparation, increased soil strength, reduced water infiltration, increased surface water runoff and decreased soil porosity (Lull 1959; Swan et al. 1987). Root and crop growth can be affected because of limited root elongation and distribution due to restricted movement of gases, water and nutrients. Where pipeline RsoW cross agricultural land there is potential for landowner concerns about reduced crop production caused by soil compaction.

Limited data are available on the effect of pipeline construction on soil compaction. Such knowledge is important because each soil system can respond differently to various construction procedures. Degree of compaction depends mainly on variables including soil type and soil conditions along with vehicle type and traffic density. Studies are needed to understand the problem of soil compaction so that it can be dealt with more effectively. The ability to predict which soils may be more susceptible to compaction would allow preventive measures to be taken during pipeline construction.

## 2.0 OBJECTIVE

The objectives of this literature review were to determine the:

- methods of measuring soil compaction;
- effects of compaction on soil;
- factors affecting the degree of compaction;
- effect of soil compaction on crop growth and yield;
- effects of pipeline construction on soil compactness; and
- the control and alleviation of soil compaction.

## 3.0 REVIEW OF RELATED LITERATURE

### 3.1 EFFECT OF COMPACTION ON SOIL CONDITIONS

Soil compaction can be caused by both internal and external forces. Internal forces are those that originate within the soil itself, such as freezing, drying, swelling and shrinking. External forces are those that are applied to some boundary of the soil and include buildings, vehicles and various tillage equipment (Cohron 1971). The effect of these actions or forces is a decrease in volume occupied by pores and an increase in density and strength of a soil mass (Swan et al. 1987). When a soil is subjected to an applied stress, the resultant volume change can be attributed to several factors including compression of solid particles, compression of liquid and gas in the pore spaces, changes in liquid and gas content in the pore spaces and rearrangement of soil particles (Harris 1971). These factors can occur either alone or in combination. The decrease in large pores results in decreased infiltration, drainage and aeration as well as in increased erosion. The increased soil strength of compacted soils can affect root penetration.

### 3.1.1 Content and Transmission of Water

The influence of soil bulk density on moisture retention of soil was determined on nine topsoils from Africa. They ranged in texture from sand to clay loam and were subjected to compaction to various bulk densities by mechanical pressure (Hill and Sumner 1967). Increasing the bulk density of sands resulted in an increased capacity to retain moisture at a constant matric potential. The magnitude of this effect decreased with increasing matric potential. In the clays and clay loams, increasing the bulk density again resulted in increased moisture holding capacity. However, the magnitude of this effect increased with increasing matric potential. In the plant available moisture range of most of the soils, moderate compaction (1.1 to 1.5 Mg $m^{-3}$) increased moisture content at constant matric potential (Hill and Sumner 1967). Increasing the bulk density greater than 1.7 Mg $m^{-3}$ decreased moisture content at constant matric potential. This effect was most noticeable at high soil moisture contents.

Water permeability is sensitive to soil compaction. In silt loam and clay loam soils of Louisiana, water permeability nearly ceased when compactive effort exceeded 1260 kPa and 590 kPa, respectively (Meredith and Patrick 1961). The authors concluded that water permeability was closely related to non-capillary porosity. Water content and its transmission were altered by soil compaction because of the changes in void volume, shape and size.

Permeability of water in the soil, as a result of a compactive effort reflects the soil moisture content at the time compaction occurs. Hydraulic characteristics of a compacted clay soil subjected to one, five, 10 or 15 passes of tractors with contact pressures of 31, 42 and 62 kPa were determined (Raghavan and McKyes 1983). The proctor optimum water content (moisture content at which maximum compaction occurs) of the clay soil was determined to be 31.5%, while water content of the plastic and liquid limits were 41% and 55%, respectively. At moisture contents above the plastic limit (41%) the permeability was slow at all compactive efforts (0 to 1000 kPa). The permeability reduction with increased compaction effort was less for the soil with 17.4% water compared to soils with 29.7% water.

### 3.1.2 Content and Transmission of Air

Air in soil is important because it is a source of oxygen for plants, root ventilation and microbes. Aeration of soils depends on the large pores that drain quickly after a rainfall (Grable 1971). The measure of oxygen diffusion in the soil relative to its diffusion in air is referred to as relative diffusivity (Grable 1971). Deficient aeration for plants occurs when relative diffusivity is below 0.02 (Grable and Seimer 1968). Air-filled porosity should exceed a lower limit of 10 to 12% for adequate root respiration and root growth (Grable and Seimer 1968). Increasing the bulk density of a soil results in decreased total volume of pores and a change in pore-size distribution toward a smaller proportion of larger pores as well as a reduction in air diffusivity.

When soil is compressed, pore-size distribution suffers a greater relative change than do bulk density or total porosity (Vomocil and Flocker 1961). Total pore volume consists of capillary porosity which is associated with water retention and non-capillary porosity which stores and conducts gases. At higher levels of compaction (greater than 1260 kPa) almost all non-capillary pores of silt and clay loams are destroyed (Meredith and Patrick 1961).

### 3.1.3 Content and Transmission of Heat

Thermal conductivity and diffusivity of soils is affected by moisture, texture, structure and bulk density (Nakshabandi and Kohnke 1965; Willis and Raney 1971). At similar moisture contents, thermal conductivity and diffusivity were highest in gravel and sand, intermediate in loams and lowest in clay soils (Nakshabandi and Kohnke 1965). Thermal conductivity of these soils increased with increased bulk density. This effect was attributed to increased contact between individual particles. When compared to additions of water, increasing bulk density had only a small effect on thermal conductivity and diffusivity. When dry, all soils investigated (fine sand, silt loam and clay) had thermal conductivities of approximately $2.5 \times 10^{-4}$ cal/sec. cm °C. Adding small amounts of water increased the thermal conductivity of sand dramatically. For example, at 5% moisture content the thermal conductivity of sand was $40 \times 10^{-4}$ cal/sec. cm °C, while silt loam only obtained that conductivity at 32% moisture. Increases in the thermal conductivity of the clay soil were even more gradual in response to the addition of water.

### 3.1.4 Soil Nutrient Status

Compaction of soil influences diffusion and mass flow mechanisms by which nutrients move to roots. Kemper et al. (1971) stated that compaction can increase unsaturated conductivity by increasing the proportion of micropores that remain filled with water under medium matric potentials. At water potentials greater than field capacity, unsaturated conductivity was shown to double when a freshly cultivated clay loam soil with a bulk density of 1.1 Mg $m^{-3}$ was compacted to 1.5 Mg $m^{-3}$. This information suggests that at a constant pressure gradient if the soil solution moves twice as fast so will the included nutrients. Compaction of a clay loam from 1.1 to 1.6 Mg $m^{-3}$ almost doubled the diffusion coefficient of $CaCl_2$ in the soil (Kemper et al. 1971). Movement of mobile ions, such as nitrates and sulphates, occurs mainly by mass flow, while less mobile ions, such as phosphorous and potassium, move mainly by diffusion.

Compaction also influences the amount of nutrients mineralized from soil organic matter because of reduced aeration. For example, a study by Parr and Reuzer (1959), found that total straw decomposition in a silt loam after six weeks incubation with 5.0, 2.5 and 0% oxygen in the aerating gas was 86, 70 and 13% respectively, when compared to straw decomposition incubated at 21% oxygen. After 30 days, increasing the aerating gas from 0% oxygen to 21% oxygen brought about a rapid rise in the rate of straw decomposition.

Nitrification is also influenced by oxygen concentration in the soil. A study by Amer and Bartholowmew (1951) demonstrated that the minimum oxygen content for nitrification in a silt loam soil in Iowa was below 0.4% but greater than 0.2%. Half as much nitrate was produced at 2.1% oxygen content when compared to 20% oxygen. A reduction in the oxygen content from 20 to 11% had a negligible effect on nitrification.

### 3.1.5 Soil Strength

Soil strength is the ability of the soil to resist being moved by an applied force (Swan et al. 1987). Compaction of the soil decreases the volume occupied by pores and increases the density and strength of the soil mass. Increased soil strength of compacted soils affects the ability of roots to penetrate the soil.

Soil strength of fine sandy loam and clay loam soils decreased with increasing moisture content and volume of voids present as well as an increase in percent clay (Gerard et al. 1982). The strength of soil in the top 15 cm of the fine sandy loam was most influenced by soil moisture and volume of voids, while for the 30 to 60 cm depth soil strength was most influenced by moisture and bulk density. Soil strength at all depths for the clay loam was most influenced by soil moisture and bulk density.

### 3.1.6 Depth of Soil Affected

High axle loads and wet soil conditions have been shown to increase the depth of compaction (Soehne 1958; Eriksson et al. 1974; Raghavan et al. 1976; Taylor et al. 1980; Voorhees et al. 1986). Well-drained and poorly drained clay loam soils in Minnesota were compacted with 9 Megagram (Mg) and 18 Mg axle weights (Voorhees et al. 1986). Under dry conditions most of the increase in bulk density was confined to the top 30 cm for the well-drained soil. There was no detectable effect on bulk density at the 50 cm depth. However, under wet conditions for the well-drained soil, the effect on bulk density of the 18 Mg axle load was measured in excess of 50 cm. Results further indicated that increases in bulk density due to the 18 Mg axle load for the poorly drained soil under wet conditions were detected at the 60 cm depth. For both soils, the 18 Mg axle load increased bulk density at depth more than the 9 Mg axle load did. These authors concluded that changes in bulk density below depths of 30 cm reflect general differences in soil water content at time of loading.

## 3.2 EFFECTS OF SOIL COMPACTION ON CROP GROWTH AND YIELDS

Soil characteristics that are directly affected by soil compaction include soil moisture, soil aeration, soil temperature, soil nutrients and soil strength. All of these factors can limit plant development. Compacted soils generally have poor aeration, low nutrient and water availability, slow permeability and mechanical impedance to root growth.

### 3.2.1 Soil Moisture

Soil moisture appears to influence the ability of roots to overcome soil resistance. A positive relationship between root penetration and soil moisture percentage suggests that the bulk density at which no roots penetrate is dependent on the soil moisture content (Taylor and Gardner 1963; Taylor and Ratliff 1969; Mirreh and Ketcheson 1973). For example, at a soil matric potential of 1/5 bar, 80% of cotton taproots penetrated a fine sandy loam with a bulk density of 1.65 Mg $m^{-3}$ while only 20% of taproots penetrated the soil at 2/3 bar (Taylor and Gardner 1963). At any given bulk density taproots had a greater probability of penetrating soils with lower rather than higher soil matric potentials. Maximum corn root elongation occurred at lowest soil resistance and lowest soil water matric potential in a study conducted by Mirreh and Ketcheson (1973). With negligible soil resistance, elongation occurred well at all soil matric potentials. However, at high soil resistance, root elongation only occurred at low matric potentials, while roots in soils of higher matric potentials were shorter, thicker and more spiral-shaped. Similar results for cotton and peanuts were reported by Taylor and Ratliff (1969). These authors found that increases in penetrometer resistance reduced top weights and root lengths only at high matric potential.

### 3.2.2 Soil Aeration

A study by Grable and Seimer (1968), suggests that 12 to 15% air porosity in soils is required for growth of plants. Soil water suction was maintained at 0, 3, 18, 48 and 68 cm of water for the 0 to 15 cm depth of a silty clay loam. Germination and root elongation rates were dramatically increased from zero to maximum as soil water suction increased above the air entry level. Water limited root elongation between 0 and 20 cm soil water suction. Root elongation, however, decreased at the high water suction used in this experiment and the effect was attributed to the resulting increase in soil strength. Similar results were observed by Gingrich and Russel (1956). At low moisture stress, oxygen concentration of the root atmosphere needed to be above 10.5% for maximum growth. Increases in soil moisture tension from one through 12 atmospheres resulted in progressively smaller increases in root elongation, fresh weight and dry weight. These growth properties were not sensitive in the range between one and three atmospheres.

In fine-textured soils, soil compaction did not completely inhibit root development if sufficient oxygen was present (Hopkins and Patrick 1969). Separate and combined effects of soil compaction and soil oxygen content on root penetration of Sudan grass in three Mississippi alluvial soils were determined. Results of this study demonstrated that root development decreased with increased compaction up to 840 kPa. Little penetration occurred above this value except in soils with high oxygen contents. This effect was observed for fine-textured soils at 21% oxygen, but not at 3% oxygen. At low levels of compaction (126 to 336 kPa) root penetration decreased from a maximum at 21% oxygen to no root penetration at 3% oxygen.

### 3.2.3 Soil Temperature

Temperature affects plant development and microbial activity, and as discussed previously, compaction of the soil influences soil temperature and thermal conductivity. Little information exists in the literature relating plant activities to combined effects of soil temperature and soil compaction. Trouse (1971) indicated that respiration rates and diffusion were reduced by cooler temperatures. Consequently, severely compacted soils, because of lowered porosity, may require higher temperatures for adequate exchange of gases during germination and root growth. Trouse further indicated that elevated temperatures near the soil surface could affect seedling growth and suggested that this temperature buildup would be less critical in denser soils. Reduction in temperature buildup could result from either increased thermal conductivity or increased moisture content in a compacted soil. Retention of excess water in compacted soils because of slow draining can reduce soil temperatures in the spring, which would slow plant germination and growth.

### 3.2.4 Soil Nutrient Status

Although compaction reduces root growth, it does not interfere with nutrition of plants. However, compaction does reduce the volume of soil exploitable by plants by restricting depth and extent of rooting, which in turn reduces the growth and development of the plant (Parish 1971).

Absorption of nutrients by tomatoes in silty clay loam and silt loam with different levels of bulk density was determined in California (Flocker and Nielsen 1962). Bulk densities ranged from 1.2 to 1.6 Mg $m^{-3}$ and appeared to have no effect on nutrient absorption. Total nutrient uptake increased as soil moisture tension decreased, but when soil moisture tension was maintained at 0.7 bars, total nutrients absorbed remained the same as bulk density increased. Parish (1971) indicated that plants grown in this experiment were under severe water stress and effects of nutrient limitations would be masked.

In contrast, another study found that compaction of a loamy sand in Georgia decreased cucumber yields, root growth and nutrient use efficiency (Smittle and Williamson 1977). At fertilizer rates of 11, 17, 22 and 23 kg N/ha, total yields for non-compacted soils were 17.7, 19.2, 20.3 and 23.3 metric tonnes per hectare (MT/ha), respectively, while yields for compacted soils were 8.4, 12.5, 13.8 and 13.9 MT/ha, respectively. At depths of 0 to 8 cm, 8 to 15 cm, 15 to 23 cm and 23 to 31 cm bulk densities for non-compacted soils were 1.54, 1.56, 1.58 and 1.67 Mg $m^{-3}$, respectively, while bulk densities for compacted soils were 1.52, 1.67, 1.72 and 1.72 Mg $m^{-3}$, respectively. The dry weight of roots at these depths for non-compacted soils were 336, 203, 154 and 83 mg/$dm^3$, respectively, and 271, 206, 6 and 0 mg/$dm^3$, respectively for compacted soils.

### 3.2.5 Mechanical Impedance

Soil strength increases as soil bulk density or soil matric potential increases. Research on medium-textured to coarse-textured soils demonstrated a sharp decline in root penetration percentage as soil strength increased from 3 to 15 bars, followed by a more gradual decline in root penetration percentage to 25 bars (Taylor et al. 1966). No root penetration occurred after 25 bars. The data exhibited a curvilinear trend between soil strength and root penetration.

A linear correlation between soil strength and root penetration percentage for a fine sandy loam was shown in a study by Taylor and Gardner (1963). Soil was compressed to five different bulk densities (1.55 to 1.85 Mg $m^{-3}$) at four different soil matric potentials (1/5 to 2/3 bars). An increase in soil strength resulted in a decrease in the rate at which roots grew through the soil. Seventy percent of cotton taproots penetrated the soil with a strength of 10 bars but only 30% of the roots penetrated the soil with strength of 20 bars. There was no root growth at soil strengths over 29.6 bars. Results of this experiment demonstrated a closer relationship between soil strength and root penetration than for soil bulk density and root penetration or between soil moisture and root penetration. These researchers concluded that soil strength was the critical factor controlling root penetration in sandy soils of the Southern Great Plains.

Depth of soil compaction affects plant yields. Subsurface compaction was shown to reduce wheat yields more than surface compaction when compaction effects were studied on field plant growth (Wittsell and Hobbs 1965). A silt loam with a bulk density of 1.2 Mg $m^{-3}$ was compacted to 1.6 Mg $m^{-3}$ in four compaction zones, including no compaction of soil, compaction of 0 to 15 cm, compaction of 0 to 30 cm and compaction of 15 to 30 cm. Wheat grain yields for the first year after compaction in the four compaction zones were 2966, 2354, 2071 and 2313 kg/ha respectively, while for the second year yields were 2529, 2354, 2475 and 2219 kg/ha respectively. Surface compaction reduced wheat yields for the first year, but not as much in the second year. This effect was attributed to reduced bulk densities through freezing and thawing and moisture changes. Although surface bulk density appeared to be reduced, hydraulic conductivity was affected for three years after compaction. All compaction treatments resulted in plants that were 5 to 7.5 cm shorter.

Subsurface compaction can also affect the development of root systems. The growth of alfalfa root systems was evaluated for nine years in a clay loam soil that was either packed to 60 cm or was not packed (Blake et al. 1976). Maximum bulk density (1.5 Mg $m^{-3}$) for the packed plot occurred in the 30 to 40 cm depth, just below the estimated plough depth, and was approximately 0.2 Mg $m^{-3}$ greater than the unpacked plots at this depth. Penetrometer resistance measurements indicated increased soil strength in the packed plots. When compared to packed plots, alfalfa roots grown on plots that were not packed displayed a greater distribution at all depths, of fine roots among the main root branches. As well, taproot branching in the top 30 cm was more evident in the unpacked plots. Packed plots had a high proportion of root weights in the surface 40 cm and a lower proportion below 40 cm when compared to plots that were not packed. Compaction reduced mean root weights by 11% in the surface 40 cm and by 30% in the 40 to 90 cm layer.

## 3.3 METHODS OF MEASURING SOIL COMPACTION

Soil compaction is seldom measured directly. Most often the change of a parameter as a consequence of a compacting force is determined. Some methods of measurement require a separate analysis before and after the compacting action. In this case, there is a need for a large number of samples for statistically reliable comparisons (Freitag 1971). Other methods can be done in situ which can greatly reduce the statistical uncertainty in comparisons. The researcher should be aware of how measuring devices affect soil compaction. Various procedures for measuring compactness can be grouped together. For example, some methods measure the state of compactness, others measure strength of soil while other methods measure compactness indirectly. Actual methodology has been recorded elsewhere (Black 1965), so discussion here will be limited to brief descriptions of the methods.

### 3.3.1 Bulk Density and Porosity

Bulk density is the ratio of the soil mass to the volume of soil particles plus pore space in a sample. It provides a measure of how close soil particles are packed together. However, bulk density does not provide information on the geometric arrangement of soil particles or the pore-size distribution (Freitag 1971). Total pore space and void ratio can be determined from the bulk density. Porosity is the ratio of non-soil volume to total volume and void ratio is the ratio of non-soil volume to actual volume of soil particles. A difficulty in determining bulk density is obtaining an accurate measurement of soil volume where soils are stony, cloddy, sticky or because of flowing sand. Therefore, bulk density is often measured by core samples in which the volume is known. Although accurate, core sampling can be slow, tedious and destructive, especially if a large number of samples are needed.

### 3.3.2 Radiation

Gamma rays and neutrons are both able to penetrate the soil for appreciable distances before interference from soil constituents alter the original energy characteristics. These alterations reflect the relative density of the soil (Freitag 1971). Radiation methods involve minimum disturbance of soil, short sampling time, easy access to subsoil measurements and also allow repeated measurements at the same point (Black 1965). However, radiation measurements require use of expensive electronic scalers and counters.

Sources of gamma rays are cobalt 60 and cesium 137 and this radiation is considered to be composed of photons. The gamma rays interact primarily with electrons in the soil mass. Changes in gamma ray energies, therefore, are related to density of soil particles. Gamma rays also interact with water particles. To obtain a dry density measurement, soil moisture content is also needed.

A source of neutrons is radium beryllium. Neutrons interact primarily with hydrogen atoms in the soil. The energy change of neutrons is related to the water present in the soil since the hydrogen content of soils is mainly in the form of moisture (Freitag 1971). Therefore, to determine bulk density, it is necessary to know the soil moisture content in terms of weight of water per unit of dry weight of soil (gravimetric moisture content).

### 3.3.3 Proctor Test

The Proctor test determines the optimum soil moisture content at which maximum compaction can be achieved by a given compactive effort. The maximum of Proctor density occurs at the optimum moisture content for compaction. This test is widely used in engineering construction (ASTM 1958).

### 3.3.4 Shear Tests

In testing for shear strength, external forces are applied to the soil sample to cause two adjoining parts to slide against each other (Black 1965). Shear resistance is the force developed in opposition to the sliding, and maximum shear resistance is a measure of shear strength. Shear vane and torsion shear devices are used to determine shear strength.

The shear vane device is a rod with four equally spaced vertical blades on the lower end. The torque required to slowly rotate the vane blades in the soil is measured and varies with structure, degree of soil disturbance, soil water content and soil bulk density (Black 1965). The vane shear test is quick and easy but is not recommended when soils are stony or dry and hard. The shear vane can be used to measure soil strength of soils near the surface and at depths of up to 1 m.

The torsion shear device consists of a circular head with serrations (grouses) for gripping the sample of soil to be sheared. The torque required to shear the soil by rotating the circular head parallel to the soil surface is measured (Freitag 1971). The torsion shear test measures soil strength only near the surface. Conducting this test and interpreting the data is more complicated than the vane shear test.

### 3.3.5 Cone Penetrometer

Soil strength is measured by determining the resistance of soil to the penetrating cone-shaped tip of the cone penetrometer. The penetrometer is advanced into the soil at a steady rate and the applied force versus depth is measured. This applied force is indicative of the shear resistance of the soil. The main difficulty in conducting this test is to apply consistent pressure to the cone penetrometer. This method of determining soil strength is quick and simple. Penetration resistance reflects the state of compaction and is influenced by moisture content and density as well as the size, shape and surface texture of the penetrating element (Freitag 1971).

### 3.3.6 Permeability

Since compaction reduces the diameter and continuity of pore space as well as total soil porosity, permeability of gases and liquids would also be reduced, providing a sensitive measurement of compaction. Conductivity is related to the amount of pore space which in turn is related to the bulk density of a given soil. To provide a description of the relative compaction state of a soil, the change in conductivity before and after the compaction force should be measured.

Hydraulic conductivity is a measurement of the ability of a soil to allow the transmission of water. A fixed head of water is applied to the soil and the flux after saturation is measured. This method is time consuming since a long time may be needed to achieve saturation of the soil. It is also difficult to ensure that the water is passing through the soil and not through root holes or large cracks. Factors affecting hydraulic conductivity include composition of soil, pore-size distribution, soil fabric and degree of saturation of the soil (Freitag 1971).

In contrast to the hydraulic conductivity test, air conductivity is best performed on perfectly dry soil which, however, cannot be achieved in field practice. Therefore, soil moisture must be taken into account. At a given soil moisture content, air conductivity decreases as soil compaction is increased, while at a given soil density air conductivity will decrease as moisture content is increased (Freitag 1971). Problems encountered in the field using air conductivity tests include proper sealing of apparatus to prevent unwanted air loss, the presence of root holes and cracks in the soil and water content of soils, which can block openings to the transmission of air.

### 3.3.7 Soil Fabric

Soil fabric is the geometric arrangement of soil particles and associated voids (Freitag 1971). Determination of soil fabric changes due to compaction is time consuming. Soil fabric analysis has been used to show the relationship between type of compaction stress and the corresponding structural response (Soane et al. 1981).

### 3.3.8 Pore-size Distribution

Pore-size distribution can be estimated by determining the water retained by the soil at various soil water potentials (Black 1965). Water is held in the soil primarily by capillary forces, which is determined by the size of pore spaces (Freitag 1971). Curves representing pore-size distribution, at various applied stresses to the soil, can be used to determine the effect of soil compaction.

Since compaction reduces total pore space and increases the proportion of small pores, there will be a shift in the shape of the curve.

## 3.4 FACTORS AFFECTING DEGREE OF SOIL COMPACTNESS

Both soil and equipment factors can affect compaction of a given soil. Soil factors include particle size distribution, particle density, organic matter content, soil moisture and mineralogy. Equipment factors include the compactive effort applied to the soil along with various machine parameters. Soil degradation due to compaction can be prevented or lessened by understanding soil behaviour under various stresses. Therefore, the first step toward control is the ability to predict compaction by various factors. It is, however, difficult to predict the degree of compaction in soils since it reflects the wide variability of soil characteristics along with natural and applied forces acting on the soil.

### 3.4.1 Texture

Seven sandy loam to clay loam soils (mainly podzols and luvisols) from New Brunswick with varying contents of clay (7.55% to 32.93%) were subjected to compaction by OTMS (Ottawa Texture Measuring System) equipment (Saini et al. 1984). With this equipment, a plunger is used to apply a dynamic load to soil confined in a rigid-wall container. Data collected were found to fit the following equation reasonably well:

$$Db = A \log P - C$$

where: Db = dry bulk density of the soil,
P = stress applied,
A = slope of line,
C = a constant.

The value of A is called the compactibility index. The steepness of the slope is a direct measure of the ease with which the soil can be compacted (Saini et al. 1984). Results of this study demonstrated that soils with highest clay contents had highest compatibility indexes suggesting that clay content is a factor affecting compatibility. Compatibility indexes ranged between 0.153 and 0.163 for soils with clay contents between 7.55% and 14.51%, while compatibility indexes for soils containing between 24.91% and 32.93% ranged between 0.217 and 0.245.

Compression of agricultural soils from eight soil orders from South America, North America, Africa and Pacific locations indicated that compression indexes increased linearly as clay content of the soil increased up to about 33% (Larson et al. 1980). At this point, the compression index remained approximately constant as clay content was further increased. Soils were applied stresses of 1 to 10 $kg/cm^3$. The type of clay present had an effect on the compression indexes as the maximum compression index for soils having expanding clays was 0.55 compared to 0.50 for highly weathered soils. Compression index values of pure clays have been shown to increase in the order kaolinite < hydrous mica < montmorillonite (Mitchell 1976, as cited in Larson et al. 1980).

In contrast, a study by Vanden Berg (1958) indicated different trends which were different from the two previous studies presented. Results demonstrated that the rate of change and total change in bulk density, for the range of mean stresses applied, was greater for a silty clay loam than for a clay. As well, rate of change in bulk density as a result of applied stress for a sandy loam was higher than for the silty clay loam. Vanden Berg concluded that the more sizes of soil particles present, the higher the probability of compaction of a soil when subjected to compactive forces.

Research conducted by Howard et al. (1981) to identify soil properties that were associated with high susceptibility to compaction on California forest and range soils, did not find density to be correlated with either silt or clay content. Correlations between dry density and soil properties suggested that organic carbon (Walkley - Black method) and water content were the most important independent variables.

In the study by Howard et al. (1981), relative susceptibility to compaction was interpreted to mean that with a uniform compactive effort, soils reaching a higher density were more susceptible to compaction than those soils that did not reach as high a density. Studies by Saini et al. (1984), and Larson et al. (1980), used compression indexes to determine relative susceptibility to compaction. It is important to realize that particle size density influences the measurement of bulk density. Since sand particles are usually more dense than clay, a sandy soil will have a higher bulk density than a clay soil (Harris 1971).

### 3.4.2 Moisture

Changes in bulk density occurred in response to four levels of compaction (105, 150, 210, 250 kPa) for two soils (podzolic grey luvisol and gleyed brunisolic grey luvisol) at various levels of moisture contents (Saini et al. 1984). For a partially saturated condition, both soils exhibited similar behaviour. The higher the moisture content of the soil the more it was compactible by a given compactive force until it reached a maximum bulk density near saturation. Similar results have been reported by others (Soehne 1958; Lull 1959; Harris 1971; De Kimpe et al. 1982). Above saturation contents, bulk density started to decline again with increased compactive force.

Moisture content at which maximum compaction occurs is called the optimum moisture content (Harris 1971). Saini et al. (1984), suggested that this level of water content be called "critical moisture content" because at this moisture content soils are susceptible to unfavourable soil compaction. In their study, these authors reported critical moisture contents ranging from 25.88 to 38.32%. Results from this study also showed that for higher pressures exerted on the soil, maximum densities occurred at lower moisture contents and for lower pressures maximum density was reached at higher moisture contents (Saini et al. 1984). These results indicate that lower ground pressure equipment could operate over a wider range of soil moisture conditions without creating serious soil compaction.

### 3.4.3 Organic Matter

Research by Saini et al. (1984) and De Kimpe et al. (1982) suggested that the organic matter content of soils may play a role in reducing compatibility of soils. Soils with high organic matter content had low compatibility indexes.

Additions of organic matter to compacted soils resulted in lowered shear strengths at any given compaction level for all moisture contents considered (Ohu et al. 1986). This was believed to be due to the decrease in bulk density of the soil with higher organic matter. However, reductions in shear strength at higher moisture contents in soils with high organic matter were not as rapid as in soils with lower organic matter levels. The moisture content at which soils with higher organic matter content flowed was higher than that of low organic matter soils. Therefore, low organic matter soils started behaving like a liquid while higher organic matter soils were still compactible. Shear strength of the soils increased with moisture content up to a maximum and then decreased as moisture contents were increased.

### 3.4.4 Structure

Bulk density of a soil, before compaction trials are initiated, has been shown to be important in determining compatibility since particle size density influences the measurement of bulk density. Compression of agricultural soils from eight soil orders (Larson et al. 1980), led to the classification of four groups of soils as to compressibility under agricultural conditions. The first group was represented by soils derived from volcanic ash with allophane as the dominant clay. Under most stresses these soils had relatively low bulk densities (0.6 to 1.1 Mg $m^{-3}$). The second group was represented by medium-textured highly weathered soils with iron oxides dominating the clay fraction. These soils had moderate bulk densities (0.8 to 1.0 Mg $m^{-3}$) at low stresses and moderate to moderately high bulk densities (1.3 to 1.5 Mg $m^{-3}$) at high stresses. The third group contained medium-textured soils with expanding type clays. At low stresses these soils had moderate bulk densities (0.9 to 1.2 Mg $m^{-3}$), while at high stresses had moderately high bulk densities (1.6 to 1.8 Mg $m^{-3}$). The fourth group was represented by coarse-textured soils with a large range in particle size. These soils usually had high bulk densities (1.3 to 1.8 Mg $m^{-3}$) at all stresses.

### 3.4.5 Conventional Tires

Most studies on compaction have been concerned with conventional tractor tires on agricultural vehicles. Properties of tires that can be varied independently include load, tire dimension and tire inflation (Soane et al. 1981). Adjustment of these properties can affect contact pressure. For example, contact pressures can be decreased by reducing total load, increasing section width of tires or by decreasing inflation pressure. Other factors that affect compaction under conventional tires include wheel slip, number of passes by vehicles in the field and vehicular speed.

#### 3.4.5.1 Load

Theoretical research by Soehne (1958), suggested that compaction close to the surface is mainly a function of contact pressure of the tractive device while compaction in subsoil is a function of the total load on the tractive device. This hypothesis has since been supported by several researchers (Eriksson et al. 1974; Raghavan et al. 1976; Taylor et al. 1980; Gameda et al. 1985; Voorhees et al. 1986).

Among factors varied in compaction research of the subsoil, wheel arrangement and total load showed the most important influences (Eriksson et al. 1974). Lasting changes in pore volume in the uppermost part of the subsoil started to appear under unfavourable conditions at the weight of 5.4 Mg on a single axle or 7.2 Mg on a tandem axle. There was no compaction of subsoil measured with small loads of 1.8 and 3.6 Mg. In favourable conditions, load could be increased to 7.2 Mg before measured changes in the subsoil occurred. Eriksson also observed that sand and silt soils were less affected by applied load than was clay soil.

Axle loads equivalent to current harvest and transport equipment have been shown to compact subsoil to considerable depths. Axle loads of less than 4.5 Mg (control), 9 Mg and 18 Mg were applied to well-drained and poorly-drained clay loams in Minnesota to study the effect of height axle loads on deep soil compaction (Voorhees et al. 1986). When the well-drained soil was dry, there was little difference between axle loads of 9 Mg and 18 Mg. Both loads significantly increased bulk density in the surface 15 cm, while 18 Mg produced significant changes to 30 cm. When the soil was relatively wet, the 18 Mg axle load increased bulk density more than the 9 Mg axle load did and increased the bulk density by 0.08 Mg $m^{-3}$ to a depth of 50 cm. In the poorly drained soil, axle loads of 9 and 18 Mg increased the bulk density in the surface 30 cm with 18 Mg increasing bulk density to a depth of 60 cm. Subsoil compaction was still evident for years after the heavy axle loading experiment despite winter freezing to depths of 90 cm.

### 3.4.5.2 Tire Dimensions

Results of a study to evaluate the influence of contact pressure on compaction found that bigger tires reduced surface compaction in the field (Raghavan et al. 1976). Tire sizes of 22.9 x 40.6 cm, 43.9 x 71.1 cm and 46.7 x 76.2 cm were used to demonstrate the effect of a given load on change in dry density on sand and loamy sand soils. The reduction in compaction was linked to resulting smaller ground pressure obtained with larger tires.

To offset increasing weights of large agricultural and construction equipment, tires have increased in size to keep lower contact pressures on the soil surface. It was believed that reduction of soil compaction would occur by reducing total contact pressure applied to the soil. However, increasing axle loads can increase subsoil compaction regardless of surface contact pressure. For example, a study by Taylor et al. (1980), was conducted to evaluate the effect of total load on subsurface soil compaction. Unequal total loads on two different size tires, resulting in approximately equal soil surface contact pressures, were run over soil pressure transducers buried at 18, 30 and 50 cm depths. At all depths, high soil pressures were produced by the larger tires. Results suggested that subsurface compaction is a function of total load. Subsoil may be compacted if total load is above a critical level irrespective of how the weight is spread over the soil surface.

### 3.4.5.3 Inflation Pressure of Tires

Changes in tire inflation pressures have been shown to alter the pressure distribution under a tire (Vanden Berg and Gill 1962). In a study to evaluate the pressure distribution between a smooth tire and the soil, a 27.9 x 96.5 cm tire with a load of 977 kg was passed over several types of soil. Recommended tire inflation pressure for a load of 977 kg was 98 kilopascal (kPa). Average contact pressures under the tire moving over firm sand when inflated to 98, 70 and

42 kPa were 109, 89 and 66 kPa respectively, while maximum pressures were 228, 224 and 245 kPa respectively, which were two to four times the initial inflation pressure measured. Surface area contact was also increased as inflation decreased because of tire deflection. Excessive deflection could lead to tire wall damage (Soane et al. 1981).

#### 3.4.5.4 Wheel Slip

Excessive wheel slip proved to be more important in causing compaction than additional wheel loading on silt and clay loams to depths of 15 cm (Davies et al. 1973). This effect was more pronounced for more powerful tractors. Results of this study indicated that wheel slip appeared to have caused substantial increases in sinkage and in shear strength while tractor weight caused only smaller effects. This was attributed to wheel slip realigning soil particles in an orientation parallel to the direction of the shear forces. Shear strength is influenced by the extent of parallel orientation of plate-shaped particles. Shear strength differences, due to wheel slip, were not significant for a light tractor at either 15 or 30% wheel slip, while for the larger tractor the increase in shear strength at 15% wheel slip was significant. Sinkage was similar for the two tractors at 0% wheel slip but at higher levels of wheel slip, sinkage was greater for the heavier tractor. These authors suggested that while some wheel slip is essential to develop traction, wheel slip should be kept as close to 10% as possible when working in moist soil conditions. Similar results have been reported for sand and sandy loam soils (Raghavan and McKyes 1977). High rates of wheel slip resulted in poor fuel economy, accelerated tire wear and smearing of the soil surface.

#### 3.4.5.5 Number of Passings

Maximum changes in dry density of a sand and sandy loam at depths between 20 to 30 cm caused by several passes using a given load for different tire sizes were determined (Raghavan et al. 1976). Results demonstrated a marked increase in dry bulk density for up to five passes and then a levelling off for further increases in the number of passes for 42.9 x 71.1 cm tires and a load of 1305 kg. Linear increases in dry bulk density for up to ten passes occurred for tire sizes of 28.6 x 61 cm and 46.7 x 76.2 cm with loads of 1594 and 1425 kg, respectively, before levelling off. The authors concluded that repeated passes of a vehicle in the field can detrimentally increase the dry density due to compaction by as much as 0.48 Mg $m^{-3}$.

In contrast, in a study to evaluate the multipass behaviour of a pneumatic tire in tilled soils (Taylor et al. 1982), 75% of the total change in bulk density and 90% of the total change in sinkage was found to have occurred on the first pass of a tractor. Initial bulk densities of a clay, sandy loam and silty loam were increased to 1.20, 1.56 and 1.57 Mg $m^{-3}$ respectively, while a total axle load of 16.3 kN increased the bulk densities of the soils to 1.22, 1.62 and 1.63 Mg $m^{-3}$ respectively. For all soils and loads, bulk density increased slightly or stayed the same after each of the next three passes. Data also indicated that a reduction in the dynamic load resulted in a small reduction in bulk density.

#### 3.4.5.6 Speed

Increases in speed were believed to reduce soil compaction because loading time would be decreased and, therefore, less soil movement would occur (Vomocil et al. 1958). Field experiments were conducted on a fine sandy loam to measure the effect of speed ranging from one to 19 km per hour on the compaction caused by the rear wheels of a tractor. Soil moisture contents of the soil when subjected to loading were 14.5, 16.0 and 20%. A reduction in speed increased the degree of compaction at each of the three moisture contents. However, in comparison to moisture content ranges the effect of speed was concluded to be unimportant.

Eriksson et al. (1974), suggested that a move toward higher working speeds might require increased inflation pressures for a given load since maximum permissible loads on tires at a given inflation pressure are set by the operating speed.

### 3.4.6 Dual Wheels

Dualizing of tractor drive wheels is done to increase the tire soil contact area. A study to determine subsurface soil compaction compared duals that consisted of 34.5 x 96.5 cm tires and a large single tire that was 46.7 x 106.7 cm (Taylor et al. 1986). Width between duals was 11 cm. Both sets of tires carried a dynamic load of 33 kN and to equalize the load rating, the duals were inflated to 179 kPa. The contact surface areas for the duals in the sandy loam and clay loam were 2 and 13% larger, respectively, than for the single tire. Pressure cells were buried at 18, 30 and 50 cm depths in a sandy loam and clay loam soil. Soil pressures beneath the single large tire were significantly higher than pressure beneath duals at each depth measured. Soil pressure between the duals was low at the 18 cm depth, but became statistically indistinguishable from those under the duals at the 50 cm depth. Initial surface bulk densities for the sandy loam and clay loam soils were 1.23 and 1.13 Mg $m^{-3}$ respectively, and bulk densities after the passage of the duals were 1.60 and 1.30 Mg $m^{-3}$ respectively, while after the passing of the single tire were 1.74 and 1.40 Mg $m^{-3}$ respectively. This study concluded that duals, with their larger contact area and reduced surface unit pressure, reduced soil pressures in the 18 to 50 cm depth range.

Voorhees and Hendrick (1977) and Eriksson et al. (1974), found that although reduction in compaction intensity or depth occurred, a greater part of the field was being compacted because of the larger contact surface area. Both sets of researchers confirmed that the fitting of duals does not solve the compaction problem.

### 3.4.7 Tracked Wheels

There has been interest in the use of tracked vehicles to reduce compaction. Reaves and Cooper (1960), reported results of comparative stress distribution measurements in a silt loam under a 30.5 cm steel tractor track and a 33 x 96.5 cm conventional rubber tractor tire. Each was loaded with 1636 kg and pulled a drawboard load of 682 kg. Contact length was 61 cm for the tire and 152.4 cm for the track. Data from this study showed that stresses were at least twice as great under the tire as under the track. Maximum stress occurred under the centre of both the tire and the track at the 7.6 cm depth and decreased laterally and vertically from that point. Similar conclusions were drawn by Soane (1973), in which changes in packing state and cone resistance were detected to a depth of 200 mm for a 505 mm wide track with average surface pressure of 35 kPa and contact length of 2 m. Maximum intensity of compaction was less than that under the conventional 31.5 x 91.4 cm tire carrying less than half the load (12.4 kN) as the track (28 kN).

Another study however, found no difference in compaction between tracked-wheel tractors and conventional wheel tractors on a sandy clay loam (Burger et al. 1984). This study compared the compaction effects of a skidder to a crawler. The skidder weighed 7627 kg and had 58.7 x 66 cm tires inflated to 140 kPa. The crawler weighed 14,863 kg and had 50.3 x 231.6 cm tracks. The skidder had a ground contact area of 3200 $cm^2$ while the ground contact area of the crawler was 23,300 $cm^2$. No significant differences in the change of total porosity, capillary porosity, non-capillary porosity or bulk density between the two machines occurred despite the greater contact pressure of the skidder.

## 3.5 EFFECT OF PIPELINE CONSTRUCTION ON SOIL COMPACTNESS

Conflicting information exists in the literature on the impacts of pipeline installation on soil compaction. Some studies have shown that pipeline construction can lead to soil compaction, while other studies have demonstrated that little or no compaction resulted from installation procedures. In some studies, reduction in soil bulk densities have been reported. Compaction can result because of repeated passage of equipment on the surface of a RoW, because of a denser subsoil being mixed with topsoil or even because the soil was too wet during construction. Reductions in soil compaction occur when a compacted horizon is broken up during the trenching operation. Soil compaction depends on the soil texture, moisture content, organic matter content, original soil structure, as well as compactive effort.

A study to evaluate the effect of pipeline construction on agricultural land was carried out for two seasons on the Sarnia-Montreal oil pipeline (Stewart and MacKenzie 1979). The soils studied included a clay loam developed on lacustrine sediment, a clay loam developed on glacial till and a sandy soil developed on fluvio-aeolian sand. The researchers found that surface bulk densities (0 to 15 cm) over all sites were higher on the RoW than off, with the trench zone tending to have the highest bulk density. Bulk density values were similar for the two years studied indicating little or no change with time. Bulk densities at 15 to 30 cm depths were less affected by zone of construction, but again there was higher compaction over the trench. Lower saturation water contents over the surface depths of the RoW compared to control sites indicated that total pore space was reduced. The lowered saturation water contents were consistent with soils of high bulk density and this effect was not noticeable over the trench zone. At lower depths, reduced saturation water contents were found only in the trench. Pipeline construction occurred in both fall and winter. During fall construction topsoil was salvaged, while during winter construction it was not possible to strip topsoil. Results of this study showed that the season of construction appeared to have little influence on compaction levels.

Considerable soil compaction has also been measured across the entire RoW on the same Sarnia-Montreal oil pipeline by Culley et al. (1982). Compaction was especially predominant on medium-textured to fine-textured soils. However, compaction did not appear to be a problem on coarse-textured soils. Bulk densities were 10% greater on the RoW than in adjacent undisturbed fields. The work area of the RoW was found to have the highest bulk density, in contrast to results reported by Stewart and MacKenzie (1979). Hydraulic conductivity decreased by an average of 38% in the trench and work areas compared to control sites. These authors also demonstrated similar results to Stewart and MacKenzie (1979) in that surface layers of the RoW had lower available water holding capacities than surface layers of control sites. This decrease was attributed to lowered total porosity. Strength of soil, measured by penetrometer resistance was greater on the RoW than off, averaging 67 and 50% more over trench and work areas, respectively. This increase in soil strength was believed to be due to increased clay content and decreased organic matter in the soil after the trenching operation.

The potential severity of soil compaction on a RoW in southwestern Ontario was presented in a study by Moncrieff (1984). The extent of soil damage was evaluated when eight kilometres of a RoW were turned into a homogenous saturated mixture of topsoil and subsoil after exposure to deteriorating weather conditions and heavy equipment movement. Yields on the RoW were approximately 40% lower than those on the adjacent field even after five years. These yield reductions were attributed to the conversion of the original structure of the B horizon into a massive structure. The resulting reduced air and water movement limited root penetration. Subsoiling procedures were necessary to break up the subsoil and provide surface drainage. This amelioration of the site led to improved yields that were found to be approaching and, in some cases, even exceeding those found on the adjacent undisturbed control.

Research in eastern Oklahoma on a fine sandy loam was conducted to study the extent physical characteristics of a soil were altered by a single ditch pipeline construction project (Zellmer et al. 1985). No attempt was made to separate or remove the topsoil during the trenching and backfilling operations. This study concluded that surface (0 to 15 cm) bulk density was not increased by pipeline installation in a semiarid environment. Bulk densities were also not increased by construction traffic on the RoW. The authors also found no significant difference between the bulk densities of the soil from the working side transect and the soil in the adjacent control transect. Bulk densities were lower in the trench than on the adjacent undisturbed control site in 16 of 20 control sets of observations. Similar trends were observed for subsurface (15 to 50 cm) bulk densities. In the cultivated soil, bulk densities averaged approximately 1.56 Mg $m^{-3}$ for the control site and 1.46 Mg $m^{-3}$ in the trench. Similar trends for pasture land occurred with bulk densities averaging approximately 1.46 and 1.27 Mg $m^{-3}$ for the control and trench locations, respectively. Lowered bulk densities for the pasture land were attributed to the extensive root system of the pasture compared to the cultivated soil.

Results from earlier studies by de Jong and Button (1973), indicated that pipeline installation neither harmed nor improved the physical properties of chernozemic soils. However, in solonetzic soils, lowered bulk densities resulted in improved permeability and aeration of the Bnt horizon. The saturation permeability and air filled porosity of the solonetzic Bnt horizon were considered undesirable before trenching. Trenching on solonetzic soil tended to decrease the bulk density at depth, while trenching on chernozemic soils occasionally resulted in increased bulk densities at depth. This compaction was thought to have occurred because of compaction by heavy machinery or by puddling of the exposed subsoil.

A review of bulk density information from seven NOVA Corporation of Alberta projects by Landsburg and Cannon (1989), suggests that pipeline construction does cause soil compaction on pipeline RsoW. However, as site and construction details were specific for each project, few similarities between projects were evident. Therefore, the development of a general conclusion is limited. Specific project conclusions that can be made are:

- Soil compaction measured by significantly increased bulk densities occurred in five of seven soil pipeline research projects. Where soil compaction did not occur, bulk densities did not change or decreased in the trench. Where soil compaction did occur, in all but one case, the increased bulk densities did not negatively affect the soil quality or land capability classification;

- Bulk density values for Luvisolic soils were decreased in subsoil materials in the trench. This resulted from breaking up the Bt horizon during pipeline construction operations;

- There were no significant differences in bulk density values in topsoil between stripped and non-stripped treatments for Chernozemic and Luvisolic soils;

- Use of the pipeline plough construction technique increased topsoil bulk densities in the trench for the first year of construction only;

- There were no significant differences between bulk densities for two-lift and three-lift materials handling construction procedures;

- Further research on soil compaction is required to determine at which bulk densities plant growth will be affected and therefore reclamation required.

## 3.6 CONTROL OF SOIL COMPACTION

### 3.6.1 Acceptance

Compaction occurs on both topsoil and subsurface materials. Although topsoil compaction can be alleviated by cultivation, subsurface compaction is harder to correct. Persistence of soil compaction below the plough layer can be detrimental to crop growth and development because of impeded internal drainage, decreased volume of large pores and increased root impedance.

A study by Blake et al. (1976) was conducted to determine the persistence of a layer of artificially packed soil beneath the plough layer (25 cm depth) in a clay loam. It was believed that deep annual frosts of a metre would benefit or account for the desirable structure found in northern mollisols. Results indicated that although freezing occurred to depths of one metre, the compacted layer still had a significantly higher bulk density and penetrometer resistance after growing corn for ten years. Bulk density decreases were expected if soil water conditions were suitable for ice lens formation. However, even heavy irrigation just before fall freezeup had no effect on packing persistence. Subsoil compaction persistence on a clay loam soil in Minnesota was measured four years after initial heavy axle loading (Voorhees et al. 1986). Annual winter soil freezing to depths of 90 cm did not alleviate compaction. However, compaction of surface depths was easily alleviated through normal tillage.

Measurements of long-term compaction effects on soil and plant growth by Shuler and Lowery (1986), found that residual effects of compaction to a 15 to 30 cm depth remained after three seasons in a silty loam in Wisconsin. Cone resistance was measured in soils under compaction from loads of less than 4.5 Mg (control), 7.2 Mg and 11.2 Mg. These authors concluded that freezing and thawing did not completely ameliorate subsoil compaction at depths of 15 to 30 cm.

Recovery of compaction to undisturbed levels is faster for surface compaction compared to subsurface compaction. Bulk density measurements at 5, 15 and 30 cm on compacted skid trails in forest soils in central Idaho indicated that after 23 years only the surface 5 cm had returned to undisturbed values by natural alleviation (Froehlich et al. 1985). On tractor skid trails in forest soils of Oregon, compaction was detected 16 years after logging operations had ceased (Froehlich 1979). At depths of 7.6, 15.2, 22.9 and 30.48 cm, bulk densities for undisturbed soils were 0.97, 0.91, 1.01 and 1.03 Mg $m^{-3}$ respectively, while bulk densities for skid trails 16 years after logging were 1.14, 1.07, 1.10 and 1.12 Mg $m^{-3}$ respectively. Soil compaction after tree length skidding in northern Mississippi increased for an average of 20% to 1.55 Mg $m^{-3}$ in wheel rutted soil, while between the ruts, compaction was only increased by 10%. Compaction between the wheel ruts was caused by movement of logs (Dickerson 1976). Micropores were reduced by 68% for wheel rutted soil and 38% between ruts, while micropore space increased 7% for both. Recovery by natural alleviation occurred in 12 years for the wheel rutted soil and in eight years between ruts. Larson and Allmaras (1971), found that besides freezing and thawing cycles, shrinking and swelling associated with wetting and drying of clay soils helped alleviate compaction. As well, fracturing and aggregation were caused by plant root growth and organic matter. These authors concluded that limited alleviation occurred in soil compaction especially at depths greater than 20 cm.

### 3.6.2 Alleviation

Subsoiling can be very effective in removing or fracturing compacted layers in a soil profile. Amelioration by subsoiling of an oil pipeline RoW that had been compacted into a massive structure was necessary to break up the subsoil and provide surface drainage (Moncrieff 1984). Yield reductions of 40% had occurred previous to the subsoiling because of reduced air and water movement. After subsoiling, yields were improved dramatically and approached those found off the RoW. Care must be taken to properly manage soil once subsoiling has been done.

To evaluate deep loosening techniques and subsequent wheel traffic on soil structure, three deep loosening methods were compared on a loamy sand (Soane et al. 1986). The three methods were deep loosening followed by mouldboard ploughing, mouldboard ploughing followed by deep loosening and simultaneous deep loosening and mouldboard ploughing. Subsoiling equipment operated at a working depth of 450 mm while the plough operated at a depth of 225 mm. Both the mouldboard ploughing followed by deep loosening and the simultaneous deep loosening and mouldboard ploughing reduced the undisturbed soil bulk density to a depth of 400 mm. The upper zone of the undisturbed soil profile had been compacted to a depth of 325 mm. Deep loosening followed by mouldboard ploughing resulted in higher bulk densities and penetration resistance than with the other two treatments. This effect was attributed to the compacting effect of the tractor during mouldboard ploughing. Subsequent wheel traffic on any of these treatments resulted in compaction (0 to 15 cm) under high ground pressure tires. High pressure tires caused further compaction below 15 cm for treatments where subsoiling and mouldboard ploughing were done separately. The soil profile remained relatively loose following low ground pressure tires when deep loosening and surface ploughing were done simultaneously. Use of low ground pressure tires can ensure that subsoiling will remain beneficial for further crops.

Other research has indicated that subsoiling may not be beneficial. For example, in Iowa subsoiling to a depth of 40 to 60 cm did not produce significant yield increases (Larson et al. 1960). Research was conducted on seven different soil series with widely contrasting soil properties. In Illinois, subsoiling to 45 cm on five different soil series significantly increased yields in only one out of eight experiments. Lack of response to subsoiling may have occurred because compaction was not a limitation to crop yield, because subsoiling did not effectively remove the compaction problem, or because of unfavourable soil moisture conditions at time of subsoiling.

Beneficial effects from subsoiling can be increased if it has already been determined that a compaction problem is present, that subsoiling will disrupt the compacted layer and if compaction of the loosened soil will be avoided (Swan et al. 1987).

The addition of peat moss to compacted soils was beneficial in improving hydraulic conductivity (Ohu et al. 1985). As well, organic matter addition increased available water and decreased bulk density and penetration resistance. The organic matter content of three soils (clay, sandy loam and clay loam) was increased to 3%, 10% and 17% on a percentage dry mass basis. All soils were subjected to three levels of compaction energy (5, 15 and 25 blows of a standard Proctor hammer). The benefit of increased organic matter was attributed to improved soil structure. This reduced soil crusting and surface sealing, allowed water infiltration and increased root proliferation through the soil profile. Research indicated a great potential for using organic matter to alleviate problems of soil compaction in crop production. However, large amounts of organic matter may be necessary to raise organic matter contents. For example, Unger et al. (1981), pointed out that 40.5 Mg $ha^{-1}$ of organic material was required to raise the organic matter by 1% over a depth of 0.3 m.

### 3.6.3 Avoidance

Reduction of the number of passes of machinery may help reduce soil compaction. Traffic can be reduced by combining such operations as cultivation and spraying in one pass. The amount of soil compaction is highly influenced by the moisture content of the soil. To reduce compaction damage, operations should be scheduled during the driest periods of the year.

Reduction of compaction under tires can be achieved by reducing vehicle mass and contact pressure of the wheel system. The total load is a significant factor in subsoil compaction. Contact pressure of the wheel system can be reduced by decreasing total load, increasing section width of tires or by deflating tires. Other factors that affect compaction under the wheel system include wheel slip, number of passes across the field by the vehicle and vehicular speed. As well, dualizing of the wheel or using tracked vehicles may reduce compaction by spreading weight over a larger surface area. The effects of these factors on soil compaction were discussed in detail in this literature review in the section concerned with factors affecting degree of soil compactness.

Cropping practices influence soil structure through soil amelioration from decomposing crop residues and addition of manures (Larson and Allmaras 1971). The kind and amount of crop residue and manure added to soil is influenced by agronomic practices, fertilizer additions and climate as it relates to crop growth and organic matter decomposition. Organic matter content increases result in a corresponding decrease in density of the soil.

### 3.6.4 Controlled Traffic

Controlled traffic is the practice of confining wheel traffic to specific areas in the field. The greatest amount of damage (reduction of large pore space in soil) occurs in the first pass of machinery used. Subsequent passes can increase compaction to a maximum, which is dependent on the weight of the equipment. Resulting soil compaction damage from heavy agricultural and construction equipment is therefore limited to certain areas and is minimal elsewhere. The practice of controlled traffic can be easily adopted for pipeline installation procedures because of the RoW configuration. Ground pressures for typical pipeline equipment are presented in Table 1.

Table 1. Ground Pressures for Typical Pipeline Equipment[1]

| Equipment Type | Size | Ground Pressure (kPa) |
|---|---|---|
| Dozers | D6 | 49-65 |
| | D7 | 59-71 |
| | D9 | 94-118 |
| Graders | 225 | 310 |
| Backhoes | 225 | 48 |
| | 235 | 55 |
| | 245 | 83 |
| Side Booms | | |
| (unloaded) | 561 | 76 |
| | 583 | 83 |
| | 591 | 103 |
| (maximum loaded) | 561 | 165 |
| | 583 | 220 |
| | 591 | 280 |
| Stringing Trucks | | |
| (loaded) | | 480 |

[1] Alberta Environment 1985.

## 3.7 SUMMARY

Soil compaction can lead to poor root penetration, difficult cultivation, reduced permeability, lower water storage capacity, decreased soil porosity, increased soil strength and increased erosion. Soil compaction is seldom measured directly and is often determined by measuring the change of a parameter as a consequence of a compacting force. Some methods of measuring soil compaction measure the state of compaction, others measure soil strength, while other methods measure compactness indirectly.

Degree of soil compaction was found to be dependent on soil factors such as soil type and soil conditions as well as equipment factors such as vehicle type and traffic density. Texture and moisture appeared to be the soil parameters that showed the most important influences on soil compaction. Increased axle loads associated with heavier construction equipment have resulted in increased subsurface compaction levels. Compacted soils can limit plant growth and crop yields through poor aeration, low nutrient and water availability, slow permeability and mechanical impedance to root growth.

Most documented studies concerned with pipeline construction have indicated that soil compaction can be a problem. Soil compaction occurred because of repeated heavy equipment traffic on the RoW, because of denser subsoil being mixed with the topsoil or because the soil was too wet when handled. Reductions in soil compaction can occur as a result of a compacted horizon being broken up during the trenching operation.

Compaction occurs on both topsoil and subsoil materials. Alleviation of topsoil compaction is easily accomplished by cultivation, but subsurface compaction is harder to correct. As well, subsurface compaction is only slowly alleviated by natural forces such as freezing and thawing cycles or by shrinking and swelling associated with wetting and drying of clay soils. Soil compaction can be dealt with by acceptance, alleviation, avoidance and controlled traffic.

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# ERRATA

The following are corrections for typographical errors or amendments found within the original document:

P.(v): Subsequent Figures



P. 6: Figure 1: Luvisolic Soil in Alberta
- produced by Alberta Bureau of Survey and Mapping (copyright 1983).

P.18, line 3: "55%" should read "100%".

P.39: The following references should be added to LITERATURE CITED section:


NOVA Corporation of Alberta. 1990. Contract Document for Pipeline Construction; Volume II, Alberta Gas Transmission Division. Calgary, Alberta. 382 pp.

NOVA Corporation of Alberta. 1988. Contract Documents for Pipeline Construction; Volume II. Alberta Gas Transmission Division. Calgary, Alberta. 382 pp.