Compaction by logging equipment
by P Bates

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Soil Science
Montana State University

Abstract:
The objective of this study was to determine whether soil compaction occurred in the upper three mineral horizons of soils trampled by a track-type tractor and a rubber-tired skidder. Tree felling and skidding were performed by loggers and closely resembled an actual logging operation. The soils sampled were formed in: 1) volcanic ash over quartzite till, 2) volcanic ash over quartzite residuum, 3) mixed volcanic ash and lake sediments over mixed glacial till, lake sediments and alluvium, 4)lacustrine deposits, 5) volcanic ash over calcareous argillite residuum, 6) volcanic ash over limestone till. The soils were trampled from one to eight times by each machine at both relatively wet and dry soil moisture conditions.

During the dry treatment, compaction was found only in those soils influenced by glacial till. The track vehicle increased the surface horizon densities of these soils an average of 25 percent (.20 g/cm^3). The rubber-tired vehicle caused compaction only in the soil influenced by limestone till where the surface horizon density increased 23 percent (.15 g/cm^3).

During the wet treatment, compaction occurred in all soils. Eight passes by the track vehicle caused surface horizon densities to increase an average of 33 percent (.25 g/cm^3;. The rubber-tired vehicle did not cause compaction in the soil formed in lacustrine material, however, it did increase surface horizon densities of the other soils an average of 24 percent (.17 g/cm^3).

The track vehicle was the most severe in terms of compaction. In some instances, it was the only vehicle which caused compaction, and in those instances where both vehicles caused compaction, density increases were generally greater under the track vehicle.

Higher soil moisture contents increased the susceptibility of all soils to compaction, but did not significantly increase the maximum densities obtained in soils which compacted at lower moisture contents.

When compaction occurred, it was limited to the surface horizon of all soils sampled.

In all cases where compaction was measured after less than eight passes by either piece of equipment, increasing the number of passes to eight did not cause further increase in soil density.

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Date May 7, 1981

COMPACTION BY LOGGING EQUIPMENT OF SIX SOILS IN NORTHWESTERN MONTANA AS AFFECTED BY SOIL WATER CONTENT, EQUIPMENT TYPE, AND NUMBER OF PASSES

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

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TABLE OF CONTENTS

	Page
VITA	ii
ACKNOWLEDGMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vii
LIST OF FIGURES	xii
ABSTRACT	xiii
INTRODUCTION	1
Study Objectives	1
General Description of Study Area Parent Materials	2
LITERATURE REVIEW	3
General Principles of Compaction	3
Effects of Soil Moisture on Compaction	5
Effects of Particle Size Distribution on Soil Compaction	10
Compactive Effect of Crawler Tracks and Rubber-Tired Vehicles	13
Soil Compaction by Logging Equipment	21
Rubber-Tired Vehicles	21
Track Vehicles	22
Duration	23
The Effect of Soil Compaction on Plant Growth	25
Soil Water	25
Soil Air	26
Soil Strength	26
Compaction Effects on Tree Growth	27

Table of Contents (Con't)

	Page
MATERIALS AND METHODS	31
Study Area and Site Selection	31
Experimental Methods	31
Parent Material Map	44
Statistics	45
RESULTS	46
Site Characteristics	46
Dry Treatment Results	55
Surface Horizon--Track Vehicle	57
Surface Horizon--Rubber-Tired Vehicle	57
Second Horizon--Track Vehicle	57
Second Horizon--Rubber-Tired Vehicle	57
Third Horizon--Both Vehicles	63
Results by Individual Sites	63
Effect of Equipment and Number of Passes	66
Summary of Dry Treatment Results	82
Wet Treatment Results	84
Surface Horizon--Track Vehicle	84
Surface Horizon--Rubber-Tired Vehicle	86
Second and Third Horizons--Both Vehicles	86
Results by Individual Sites	92
Effects of One Versus Eight Passes	92
Effects of Track Versus Rubber-Tired Vehicle	94
Summary of Wet Treatment Results	94
Wet Versus Dry Treatments	98
Proctor Test Results	99
DISCUSSION	101
Equipment Impact	101

Table of Contents (Con't)

	Page
Moisture Content	102
Effects on Susceptibility to Compaction	102
Effects on Magnitude of Compaction	102
Effect of Repeated Passes	104
Depth of Compaction	106
Proctor Test Data	108
Management Implications	110
Susceptibility of Soils to Compaction	110
Soils with High Susceptibility (Class 1)	113
Soils with Moderate Susceptibility (Class 2)	114
Soils with Low Susceptibility (Class 3)	115
Parent Material Map	115
Reducing Compaction Hazard	118
CONCLUSION	120
APPENDICES	122
APPENDIX I: SOIL PROFILE DESCRIPTIONS	123
APPENDIX II: PROCTOR CURVES	132
APPENDIX III: INDIVIDUAL SOIL CLOD DATA	164
APPENDIX IV: FLOW CHART FOR STATISTICAL ANALYSES	189
LITERATURE CITED	191

LIST OF TABLES

Table Page

1. Summary of some previous compaction studies (Froehlich, 1978). 19

2. Specifications for the D6D tractor and the 518 Rubber-tired skidder. 35

3. Parent materials and soil classifications for each site. . . . 47

4. Parent material, horizon designations, horizon boundaries, textures, coarse fragment contents, and bulk densities of horizons sampled in site AQT 48

5. Parent material, horizon designations, horizon boundaries, textures, coarse fragment contents, and bulk density at dry and wet treatment of horizon sampled in site AQR 49

6. Parent material, horizon designations, horizon boundaries, textures, coarse fragment contents, and bulk densities of horizons sampled in site MIX 50

7. Parent material, horizon designations, horizon boundaries, textures, coarse fragment contents, and bulk densities of horizons sampled in site LAC 51

8. Parent material, horizon designations, horizon boundaries, textures, coarse fragment contents, and bulk densities of horizons sampled in site AAR 52

9. Parent material, horizon designations, horizon boundaries, textures, coarse fragment contents, and bulk densities of horizons sampled in site ALT 53

10. Soil moisture content of all horizons at time of dry and wet treatments 56

11. Dry treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of surface horizon bulk densities (g/cm^3) in the control and track-vehicle skid trails of all sites, with the ANOV p value and the LSD value for these data 58

List of Tables (Cont'd)

Table Page

12. Dry treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of surface horizon bulk densities (g/cm^3) in the control and rubber-tired vehicle skid trails of all sites, with the ANOV p value for these data. 60

13. Dry treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of second depth horizon bulk densities (g/cm^3) in the control and track-vehicle skid trails of all sites, with the ANOV p value and the LSD value for these data 61

14. Dry treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of second depth horizon bulk densities (g/cm^3) in the control and rubber-tired vehicle skid trails of all sites, with the ANOV p value for these data 62

15. Dry treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of third depth horizon bulk densities (g/cm^3) in the control and track-vehicle skid trails of all sites, with the ANOV p value for these data. 64

16. Dry treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of third depth horizon bulk densities (g/cm^3) in the control and rubber-tired vehicle skid trails of all sites, with the ANOV p value for these data 65

17. Means ($\bar{x}$), standard deviations (s) and sample sizes (n) for all horizon bulk densities (g/cm^3), in the track and rubber-tired vehicle skid trails for both the dry and the wet treatments in site AQT 67

18. Means ($\bar{x}$), standard deviations (s) and sample sizes (n) for all horizon bulk densities (g/cm^3), in the track and rubber-tired vehicle skid trails for both the dry and the wet treatments in site AQR 68

List of Tables (Cont'd)

Table | Page

19. Means ($\bar{x}$), standard deviations (s) and sample sizes (n) for all horizon bulk densities (g/cm^3), in the track and rubber-tired vehicle skid trails for both the dry and the wet treatments in site MIX 69

20. Means ($\bar{x}$), standard deviations (s) and sample sizes (n) for all horizon bulk densities (g/cm^3), in the track and rubber-tired vehicle skid trails for both the dry and the wet treatments in site LAC 70

21. Means ($\bar{x}$), standard deviations (s) and sample sizes (n) for all horizon bulk densities (g/cm^3), in the track and rubber-tired vehicle skid trails for both the dry and the wet treatments in site AAR 71

22. Means ($\bar{x}$), standard deviations (s) and sample sizes (n) for all horizon bulk densities (g/cm^3), in the track and rubber-tired vehicle skid trails for both the dry and the wet treatments in site ALT 72

23. Dry treatment means of the surface horizon bulk densities (g/cm^3) of the control area and the track-vehicle one- and two- pass skid trails for all sites, with the ANOV p value and LSD value for these data 73

24. Dry treatment means of the surface horizon bulk densities (g/cm^3) of the control area and rubber-tired skidder one- and two-pass skid trails for all sites, with the ANOV p value for these data 74

25. Dry treatment means of the surface horizon bulk densities (g/cm^3) of the four-pass trails versus the surface horizon bulk densities of the eight-pass trails, with the ANOV p value for these data 76

26. Dry treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of the surface horizon bulk densities (g/cm^3) of the combined track vehicle control, one- and two-pass trails versus the combined track vehicle four- and eight-pass trails, with the ANOV p value and the LSD value for these data 77

List of Tables (Cont'd)

Table | Page

27. Dry treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of the surface horizon bulk densities (g/cm^3) of the combined rubber-tired vehicle control, one- and two-pass trails versus the combined rubber-tired vehicle four- and eight-pass trails, with the ANOV p value for these data 78

28. Dry treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of the second depth horizon bulk densities (g/cm^3) of the combined track vehicle control, one- and two-pass trails versus the combined track vehicle four-and eight-pass trails, with the ANOV p value for these data 79

29. Dry treatment means of the surface horizon densities (g/cm^3) of the track vehicle four- and eight-pass trails versus the rubber-tired vehicle four- and eight-pass trails, with the ANOV p value and the LSD value for these data 81

30. Absolute and percent increases of surface horizon densities in sites AQT, MIX and ALT after the dry treatment 83

31. Wet treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of surface horizon bulk densities (g/cm^3) in the control and track-vehicle skid trails of all sites, with the ANOV p value and the LSD value for these data 85

32. Wet treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of surface horizon bulk densities (g/cm^3) in the control and rubber-tired vehicle skid trails of all sites, with the ANOV p value and the LSD value for these data 87

33. Wet treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of second depth horizon bulk densities (g/cm^3) in the control and track vehicle skid trails of all sites, with the ANOV p value for these data. 88

List of Tables (Cont'd)

Table | Page

34. Wet treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of second depth horizon bulk densities (g/cm^3) in the control and rubber-tired vehicle skid trails of all sites, with the ANOV p value for these data 89

35. Wet treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of third depth horizon bulk densities (g/cm^3) in the control and track-vehicle skid trails of all sites, with the ANOV p value for these data 90

36. Wet treatment means ($\bar{x}$), standard deviations (s) and sample sizes (n) of third depth horizon bulk densities (g/cm^3) in the control and rubber-tired vehicle skid trails of all sites, with the ANOV p value for these data 91

37. Wet treatment means of the surface horizon bulk densities (g/cm^3) of the one-pass skid trails versus the surface horizon bulk densities of the eight-pass skid trails (maximum treatment in site ALT), with the ANOV p value and the LSD value for these data 93

38. Wet treatment means of the surface horizon bulk densities (g/cm^3) of the track vehicle one- and eight-pass skid trails (maximum treatment in site ALT) versus the rubber-tired vehicle one- and eight-pass skid trails, with the ANOV p value and the LSD value for these data. 96

39. Absolute and percent increases of surface horizon densities in all sites after the wet treatment 97

40. Proctor test data for all sites including optimum moisture content, maximum bulk density, coarse fragment content of test sample, and optimum moisture content and maximum bulk density corrected for coarse fragments. 100

41. Criterion for ranking susceptibility of soils to compaction. 112

42. Legend for mapping units 117

LIST OF FIGURES

Figure		Page
1.	Typical Proctor curve (Proctor, 1933)	8
2.	Stresses at point X due to uniform pressure q on a strip of width B and semi-infinite length (Craig, 1974)	14
3.	Contours of equal vertical stress under a uniform pressure q on a strip of width B and semi-infinite length (Craig, 1974)	15
4.	Relationship between soil density increases and seedling height growth (Froehlich, 1976)	30
5.	Map showing location of study area	32
6.	Map showing locations (section, township, and range) of individual study plots	33
7.	Plot layout for site AQT	37
8.	Plot layout for site AQR	38
9.	Plot layout for site MIX	39
10.	Plot layout for site LAC	40
11.	Plot layout for site AAR	41
12.	Plot layout for site ALT	42
13.	Parent material map	116

ABSTRACT

The objective of this study was to determine whether soil compaction occurred in the upper three mineral horizons of soils trampled by a track-type tractor and a rubber-tired skidder. Tree felling and skidding were performed by loggers and closely resembled an actual logging operation. The soils sampled were formed in: 1) volcanic ash over quartzite till, 2) volcanic ash over quartzite residuum, 3) mixed volcanic ash and lake sediments over mixed glacial till, lake sediments and alluvium, 4) lacustrine deposits, 5) volcanic ash over calcareous argillite residuum, 6) volcanic ash over limestone till. The soils were trampled from one to eight times by each machine at both relatively wet and dry soil moisture conditions.

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INTRODUCTION

Soil compaction is the compression of a soil system resulting from surficially applied loads. Kuennen et al. (1979), found that soil compaction may occur during timber harvesting operations in northwestern Montana. When compaction occurs, it may significantly reduce subsequent timber growth and yields (Foil and Ralston, 1967; Froehlich, 1976). This study was initiated by the Plant and Soil Science Department at Montana State University in cooperation with Champion Timberlands to determine the susceptibility of soils in the Pleasant Valley management district, located in northwestern Montana, to compaction by timber harvesting equipment.

Study Objectives

The objectives of this study were to:

1) Identify and map the major soil types in the northern portion of the Pleasant Valley management district of Champion Timberlands based on soil parent material.
2) Measure the bulk density of these soils after they have been trampled by a Caterpillar D6D track-type tractor and a Caterpillar 518 rubber-tired skidder at relatively wet and dry soil moisture conditions.

General Description of Study Area Parent Materials

There are four dominant rock types in the study area which can be divided into two groups based on the presence or absence of calcium carbonate. These are calcareous argillite and limestone, and noncalcareous argillite and quartzite.

During the most recent (Wisconsin) glacial stage, the Cordilleran ice sheet probably covered the entire area reaching elevations ranging from 1615 to 2225 m (Johns, 1970). Concurrently, alpine glaciers originating on higher peaks travelled down mountain valleys and merged with the continental ice sheet. The retreat of the glaciers left the mid-elevation positions covered with local glacial till, while the lower elevation positions were covered with mixed Cordilleran and local glacial till, as well as glacio-fluvial and lacustrine deposits. Higher elevation positions were characterized by bare rock surfaces with some thin patches of local glacial till and, in some locations, undisturbed soil material.

Subsequent to the Wisconsin glacial stage, volcanic ash from at least three Cascade Range volcanos blanketed the region. The ash thickness is not uniform, but varies depending on such factors as slope, aspect and post-depositional erosion (Ottersburg, 1977).

LITERATURE REVIEW

General Principles of Compaction

Compaction is the increase in soil bulk density resulting from applied loads or pressure. The compaction process involves an external pressure being applied to the soil, a resistance of the soil to the stress, and soil compression as the resistance is overcome. Compaction occurs when soil particles are rearranged, decreasing the volume of soil pores.

Soil is a complex material, and several attempts have been made to explain how external stresses act to move soil particles. The resistance of a soil to movement of its particles is defined as its shear strength and is a function of interparticle friction and cohesion. The most commonly used model to explain shear strength is based on the Mohr-Coulomb failure criterion. Coulomb first expressed shear strength (T_f) as a function of normal stress and quantified it in the following equation:

$$T_f = C + \sigma_f \tan \phi \tag{1}$$

where C represents the cohesive forces present, σ_f is a function of the applied normal stress, and $\tan \phi$ is the coefficient of friction with ϕ being the angle of friction.

The Mohr-Coulomb model defines soil as a rigid, brittle material that will fail suddenly when a critical stress level is reached. This model may be applicable to the typically dense soils used by engineers, but is inappropriate for compaction of less dense field soils by heavy equipment. A more appropriate model would be one in which soil is described as a compressive, frictional, work-hardening, and plastic material (Reece, 1977). The frictional component means that soil strength will increase with greater stresses, work hardening means the soil will become stronger as it compacts.

Effects of Soil Moisture on Compaction

Proctor (1933) stated that "the effect of the moisture content of a soil upon the density to which it may be compacted is the most important principle of soil compaction." The resistance of a soil to compaction is a function of the frictional forces at the interparticle contact areas, and the cohesive forces that hold soil particles together. Soil cohesion is determined by the type of cementing agents present and the strength of the interparticle moisture bonds. Of these properties, it is the strength of the moisture bonds which is most likely to vary within any one soil (Mirreh and Ketcheson, 1972).

Because of their polarity, water molecules attach themselves to soil particles and other water molecules by adsorption or hydrogen bonding. At low moisture contents, soil water surrounds each particle as a thin film. Where soil particles come into contact, the surface tension of the joined films produces a capillary force which holds the particles together. The total cohesive force produced by the water films can be expressed as the sum of the individual forces exerted at each point of contact. As water content increases, the thickness of the water film around soil particles increases which has the effect of lowering the cohesive forces in the soil.

Towner (1961) showed that soil water suction is quantitatively equivalent to an externally applied isotropic pressure in a saturated soil. His results showed that soil strength increased with increasing water suction.

Williams and Shaykewich (1970) applied this concept to unsaturated soils using Terzaghi's principle of effective stress. Effective stress (σ') is that stress which is transmitted through the soil skeleton and is a function of total normal stress (σ) and pore water pressure (μ). In a saturated soil, this relationship can be expressed as follows:

$$\sigma' = \sigma - \mu \qquad (2)$$

When matric potential (Ψm) is expressed in units of stress, it is equivalent to negative pore water pressure and thus equation 2 can be rewritten as

$$\sigma' = \sigma + |\Psi m| \qquad (3)$$

In unsaturated soils equation 3 can be written as

$$\sigma' = \sigma + \chi|\Psi m| \qquad (4)$$

where χ equals the proportion of the matric potential which contributes to effective stress. The value of χ for a saturated soil is 1, and decreases with decreasing matric potential.

Using the principle of effective stress, the Mohr-Coulomb equation (1) can be rewritten as

$$T_f = C' + [\sigma + \chi|\Psi m|]\tan \sigma' \qquad (5)$$

where C′ and σ′ are effective stress parameters of cohesion and angle of friction, and $[\sigma + \chi|\Psi m|]$ is the effective stress normal to the plane of failure. Williams and Shaykewich (1970) found shear strength to increase exponentially with decreasing matric potential.

Proctor (1933) found that the moisture content of a soil subjected to a given compactive event plays a major role in determining the density that will be reached. Furthermore, there is a specific moisture content at which maximum compaction will occur when soil is compacted in a confined system (Fig. 1).

Several things should be noted about Proctor curves. Compaction decreases on the right or wet side of the optimum moisture content because of the inability of the system to expel excess water. The pore water pressure in a nearly saturated soil is great enough to support the compactive force without further decrease in soil volume. On the dry side of optimum, the shear strength of the soil is increased due to the thinness of the water films. The decrease in compaction correlates with the increase in shear strength as soil moisture decreases.

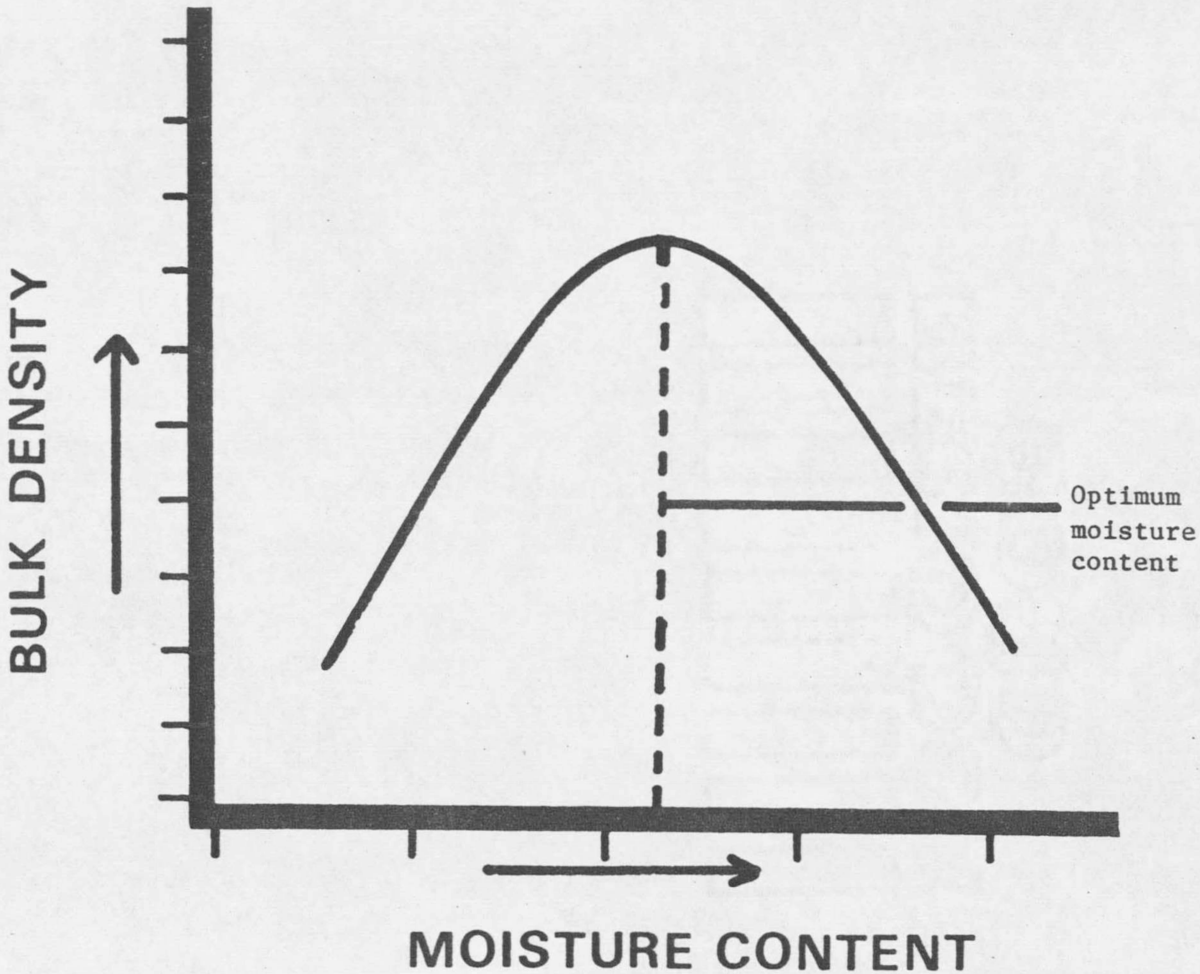

Fig. 1. Typical Proctor curve (Proctor, 1933).

The optimum soil moisture for compaction of a given soil varies with different compactive efforts. As the compactive effort increases, the optimum moisture content decreases (Proctor 1933).

Effects of Particle Size Distribution on Soil Compaction

The particle size distribution of a soil system plays a major role in determining the ease with which compaction will occur and the final density that will be attained. Most work has been done studying the effects of varying proportions of the soil fines (less than 2 mm), however some researchers believe that the presence of coarse fragments may also strongly influence the compaction process.

Bodman and Constantin (1965) studied the packing behavior of soils where the particle size was homogenous versus soils where particle size was heterogenous. They found that soils of mixed particle sizes packed to a more dense arrangement than soils of a uniform particle size. This was due to the finer particles filling in the pores created between the larger particles. Increasing the percentage of fine sand in a silt-clay soil increased the maximum obtainable density of the system. The maximum bulk density decreased when the amount of sand added was greater than 80 percent because there was an insufficient amount of finer particles present to fill the pore space between the sand particles. Adding coarse rather than fine sand yielded similar results, but the maximum densities achieved were greater (Bodman and Constantin, 1965).

The coarse sand in the above experiment may simulate the effect of coarse fragments on compaction. A soil with a large percentage of coarse fragments would compact under the forces of an externally applied load, however, the pore space between coarse fragments may be so great that compaction of the fine earth fraction may not occur (Li, 1956).

In some cases, the coarse fragment content may be such a dominant member of the soil skeleton, that a surface load can be dispersed almost totally through the coarse fragments with minimal compactive force being applied to the fines. Soils high in coarse fragment content may be compacted, but the effect on the fine earth fraction may not be as great as in soils relatively free of coarse fragments (Lowman et al., 1978).

Particle size distribution also affects the optimum moisture content for compaction. Finer particles, because of their greater surface area per unit mass, require more water to increase the matric potential sufficiently for particle rearrangement to occur than do coarser particles (Proctor, 1933). Thus, soils with more fine particles will have a greater shear strength and resistance to particle rearrangement than a coarse soil when both are at the same moisture content.

The importance of soil texture in soil compaction is further exemplified by the differing physical properties of clay versus nonclay sized particles. Interaction between nonclay particles occurs mainly as friction at interparticle contacts. The number and strength of these contacts is determined primarily by the arrangement of the particles which is in turn determined by particle size distribution and the shape of the particles. Soils with particles of varying sizes and shapes produce the most interparticle contacts and thus are the most resistant soils to particle movement. The influence of electrical forces between larger particles is absent or negligible relative to the frictional forces (Harris, 1971).

Clay particles, however, interact through physiochemical forces of attraction and repulsion. Cohesive forces between clay particles are affected greatly by soil water content. Increasing water content acts to increase the diffuse double layer surrounding individual clay particles which reduces the attractive forces between them. The result is relatively easy rearrangement of clay particles into a more dense, parallel arrangement when subjected to a compactive force (Harris, 1971). Soil texture is therefore one of the principle characteristics which defines the magnitude of the cohesive and frictional forces in a soil.

Compactive Effect of Crawler Tracks and Rubber-Tired Vehicles

The distribution of compactive forces within a soil is primarily determined by pressure patterns applied to the soil surface (Chancellor, 1971). The stresses acting on any point (X) below a strip of uniform pressure (such as might be exerted by a track or tire) are a function of the depth to point (X) and the lateral distance from the center of the compactive force (Fig. 2) (Craig, 1974). In figure 2, where q is the pressure applied and B is the width of the track or tire, the vertical stress (σz) and the horizontal stress (σx) can be defined as follows (Craig, 1974):

$$\sigma z = {}^{q}/\pi \ (\alpha + \sin\alpha \ \cos 2\beta) \qquad (6)$$

$$\sigma x = {}^{q}/\pi \ (\alpha - \sin\alpha \ \cos 2\beta) \qquad (7)$$

Solving equation (6) for various points in the soil, it is possible to develop contours of equal vertical stress under an applied load. These contours are shown in figure 3 for a strip of width B and exerting pressure q. The greatest pressure is exerted directly beneath the center of the strip.

The average pressure exerted to the ground through a rubber tire is generally considered to be the inflation pressure of the tire. Chancellor (1971) cites three cases where this may not be true. First, the stiff walls of some tires may transmit some force directly to the ground causing pressures at the edges of the tires to be greater