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Development of Guides for Estimating the Ease of Compaction of World Soils

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ABSTRACT

Compaction of the soil by increasingly intensive cropping practices and large farm tillage and harvesting equipment is a world-wide problem. Increased compaction of the soil results in less plant root proliferation in the soil, lowers the rate of movement of water and air through soil, reduces the plant stand and consequently decreases yields. The objective of this study was to develop guidelines on the susceptibility of soils to compaction.

To achieve this objective laboratory uniaxial compression tests were conducted on soils from Israel, India, Sweden, Morocco, and the United States. These soils together with our previous data base totalled 87 soils representing 8 soil orders from Africa, Asia, North and South America and Europe. Based on the uniaxial compression data base, guidelines are developed to describe the susceptibility of thin sections of soils to compaction at various applied stresses and degree of saturation. Information needed to use these guidelines is the clay content. These guidelines point out that all soil compaction is not necessarily bad for plant growth. Also, further research is needed to define the parameters (including limits) of excessive compaction.

A soil compaction model is also developed to predict iso-stress and iso-bulk density profiles after a passage by an agricultural vehicle. The model was tested in the field on two soils in Minnesota, USA, and one soil in Israel. These verification tests showed that the compaction model predicted stress and bulk density profiles within 70 kPa and 0.23 Mg m^{-3} , respectively. The model pointed the need for additional experimentation to define (a) the relationship of concentration factor to soil type, water content, and initial bulk density; and (b) the relative magnitude of compressive-shear stresses during surface applied loads.

DEVELOPMENT OF GUIDES FOR ESTIMATING THE EASE OF COMPACTION
OF WORLD SOILS

S. C. Gupta, A. Hadas, W. B. Voorhees, D. Wolf, W. E. Larson and
E. C. Schneider

INTRODUCTION

Compaction of the soil has become a problem of world-wide concern because of (a) larger tractors, tillage and harvesting equipment, (b) increasingly intensive cropping practices, and (c) bringing of new lands into cultivation, particularly in the tropics.

Current research has shown that with larger tractors and wider wheels, compaction of the soil has increased at depths below the usual tilled zone (approximately 20 cm). This is of particular concern because it is difficult and costly to break-up the soil at these deeper depths.

Increased compaction of the soil results in less plant root proliferation in the soil, and lowers the rate of movement of water and air through the soil. Because of the root restriction the amount of water available to a crop is often decreased. Slower internal drainage results in poorer drain performance, longer periods of time when the soil is too wet for tillage following water application, and decreased crop production. Increased soil compaction also adds materially to the energy consumption by tractors for subsequent tillage.

Currently there is a scarcity of reliable information concerning soil compaction under field conditions that can be related either

theoretically or statistically with laboratory determined measurements of soil compaction.

Soils are often tilled when wet causing severe compaction. Yet there are no scientific methods applicable to agricultural soils that determine when a soil is too wet to till. Currently the decision must be made by the farm operator based on experience.

If scientific methods could be developed that predict the effect of applied mechanical stresses on soil compaction, it could lead to simpler methods suitable for farmer guidance. These methods need development for all soil conditions and water contents.

Soils vary widely in particle size distribution, mineral composition, and organic matter content. Hence to be universally applicable, a wide range of soils from temperate and tropical regions need examination.

Scientific and practical guidelines for the maximum pressure a specific soil can withstand over a wide range of water contents are needed. These guidelines, if applied, could increase crop yields, improve water use efficiency, and decrease the need for liquid fuels in tractors.

The objective of this study is to develop guidelines for determining the range of applied mechanical stresses and range in water contents that world soils can withstand from tillage equipment without undue compaction.

Specific objectives include:

- a. To enlarge the soil compression data base by running uniaxial confined compression tests on soils from Israel and other countries besides U.S.
- b. To study the effect of sample size on laboratory measured

compression characteristics of soils.

- c. To study the effect of aggregate size on laboratory measured compression characteristics of soils.
- d. To study the effect of corn residues on laboratory measured compression characteristics of soils.
- e. To field test a soil compaction model that predicts the distribution of applied stress and bulk density in a soil after a passage by an agricultural vehicle.
- f. To develop statistical relationships for predicting compression parameters from easily measured soil properties.
- g. To compare the prediction of soil bulk density profile from laboratory measured and estimated (statistical relationships) compression parameters.
- h. To provide nomographs of bulk density changes due to applied stress at various degree of saturation for world soils.
- i. To describe a procedure for estimating the range of applied stresses and a range of water contents that are not conducive to excessive compaction.

To achieve these objectives, a series of laboratory and field experiments were conducted.

Secondary objectives pursued under this project include:

- j. To determine the effects of residual soil compaction on soil structure and crop growth (establishment, development and yield).
- k. To develop a conceptual model for assessing the trade-off relations among soil compaction - trafficability and draft.

THE COMPRESSION PROCESS

If a nonaggregated dry soil consisting of particles randomly distributed is placed in a container, a certain bulk density, ρ , will be obtained (ρ_1 , Fig. 1). The loosely packed soil is an expression of the size distribution, shape and specific density of the particles. If increasing stress is applied to loosely packed soil, the bulk density will increase up to a maximum bulk density, ρ_F . If bulk density, ρ , is plotted vs $\log_{10}$ applied stress, σ_a , the relationship will be linear (Fig. 1) over much of the applied stress range. During stress application, the particles will be rearranged and brought closer together. The straight line is often called the virgin compression curve, VCC, and the slope of that line is called the compression index, C . If the soil has previously been subjected to a stress and a further stress is applied, the bulk density-stress relationship will increase along a line with a slight slope (secondary compression) until it joins with the VCC curve.

The linear portion of the VCC in Fig. 1 can be described by

$$\rho = \rho_k + C \log (\sigma_a / \sigma_k) \quad [1]$$

where ρ is the computed bulk density, ρ_k is the density at a known stress σ_k , σ_a is the applied normal stress, and C is the slope of the line.

If the VCC in Fig. 1 represents a dry soil, lines for soils at water contents less than saturation will be shifted to the left (e.g., a lower stress for a given bulk density) and basically parallel to the dry soil line. An example of this shift in compression curves is shown in Figure 2a. Larson et al. (1980) suggested that if the relationship in Eq. [1] is known for a given water content, or degree of saturation, S_k , curves

Figure 1. Theoretical soil compression curve.

Figure 2. Bulk density and pore water pressure of Waukegan silt loam as influenced by applied stress at five water contents.

for other water contents can be computed from the following relationship:

$$\rho = [\rho_k + \Delta_T (S_1 - S_k)] + C \log (\sigma_a / \sigma_k) \quad [2]$$

where Δ_T is the slope of the bulk density vs. degree of water saturation curve at σ_k , S_k is the degree of saturation corresponding to ρ_k and σ_k , and S_1 is the desired degree of saturation.

Larson and Gupta (1980) also showed that during the compression process, there is a change in the pore water pressure, U_w , of the sample. As σ_a increased, the U_w became more negative, reached a minimum, and then increased. The shape of the curve for each soil was similar, but the minimum pore pressure, U_m , was reached at a lower σ_a as the water content increased. An example of pore water pressure curves during compression are shown in Fig. 2b.

Larson and Gupta (1980) interpreted the changes in U_w during compression as related to change in soil structure. Their explanations were as follows:

During initial application of σ_a , the number of contacts of each aggregate increases, that is, each aggregate comes into contact with more surrounding aggregates. Each new contact produces a new meniscus which acts to pull water from within the aggregate and results in a lower pore water pressure. As additional mechanical stress is added and the contact area becomes greater, little change in U_w occurs (since few additional menisci are formed) until pores between the aggregates become small enough for the menisci to coalesce, i.e., the pores fill with water, and pore water pressure increases. As the pore water pressure approaches zero, aggregate strength decreases rapidly (Cruse and Larson, 1977) and application

of further σ_a shears them and destroys their identity. At lower water contents, smaller pores must be developed to cause the menisci to coalesce. Thus, U_m occurs at a higher σ_a as W decreases.

Larson and Gupta (1980) suggested that the stress at which pore water pressure is minimum represents the critical stress, σ_c , above which soil aggregates shear during the compression process. They also presented a procedure to calculate σ_c by normalizing the pore water pressure vs. applied stress curves.

SOIL COMPACTION MODEL

Harris (1971) discussed several models that describe soil compaction. All these models are empirically derived relationships between the bulk density or porosity or void ratio and the applied loads on finite soil columns. These relationships are either exponential or logarithmic functions. From laboratory confined compression tests, Larson et al. (1980) showed that (a) at a given water content, compression curves (bulk density vs. log applied stress) determined on agricultural soils are linear over the range of stress from about 0.1 to 1 MPa and (b) compression curves at different water contents for a given soil are approximately parallel over the range of initial pore water potential from -5 to -70 kPa. The relationship that described the linear portion of the compression curve is given in Eq. [2]. Equation [2] is similar to the models discussed by Harris (1971).

Gupta and Larson (1982) developed a soil compaction model based on compression relationship (Eq. [2]) and the Boussinesq equation as modified (Frohlich, 1934) by the introduction of a concentration factor to represent different kinds and conditions of soil. Details of

Boussinesq equations have been described by Soehne (1953). Briefly, equations that describe various stresses on an element of soil (Fig. 3a) as a result of concentrated point load, P , at point 0 in xy -plane are as follows:

$$\sigma_z = \frac{\nu P}{2\pi r^2} \cos^{\nu} \beta \quad [3]$$

$$\sigma_h = \frac{\nu P}{2\pi r^2} \cos^{(\nu-2)} \beta \sin^2 \beta \quad [4]$$

$$T = \frac{\nu P}{2\pi r^2} \cos^{(\nu-1)} \beta \sin \beta \quad [5]$$

where

σ_z = the vertical normal stress, kPa

σ_h = the horizontal normal stress in a radial direction, kPa

T = the shearing stress belonging to σ_z and σ_h , kPa

r = the radial distance in the soil profile from point 0, cm

β = the angle bisected by a vertical line from point 0 with a line to the center of gravity of the volume element under question

ν = the concentration factor

Soehne (1953) assumed that the contact area between tires and ground was elliptical in shape (Fig. 3b). The procedure for calculating main stress in the profile involved dividing the elliptical load surface into 25 load elements in whose center of gravity, a fraction of the surface load was applied as a concentrated load. Main stress at a point in the soil profile was then calculated from the summation of stresses (Eq. [3], [4], and [5]) from 25 load elements. Readers should refer to

Figure 3. (a) Stresses on a soil element caused by a point load, P. (b) A surface load broken up into 25 load elements. Open circles represent the center of gravity with a pressure distribution according to a parabola of 4th potency (Soehne, 1953).

Soehne (1953) article for equations and other details of this procedure. In Eq. [3], [4], and [5], the greater the value of v , the more concentrated are the stresses towards the load axis. Soehne (1953) suggested v equal to 4, 5, and 6 for hard, firm, and soft conditions of the soil, respectively. Soehne's description of firmness applies to a combination of both bulk density and water status of the soil. Gupta and Larson (1982) estimated that v values that gave the best prediction of iso-bulk density line under laboratory conditions (soil box) were small near the surface and increased with depth. Their findings were similar to the observations of Blackwell and Soane (1980). Based on a field experiment, Ram (1984) concluded that (a) the concentration factor varied from 3.28 to 5.84 for sandy and loamy soils in normal field conditions and this factor increased to 7.74 in low strength powdered silt loam soil and (b) the concentration factor increased with an increase in moisture content at a constant bulk density and decreased with an increase in bulk density of soil at the same moisture level.

Using a combination of two different size tires and two different loads, Taylor et al. (1978) concluded that Frohlich's equations (Eqs. [3] thru [5]) approximately described the soil pressure distribution in both a sandy soil and a clay soil with uniform density profiles. However, when a compacted layer was introduced in the density profile, this equation was no longer suitable. Blackwell and Soane (1981) also showed that after passage by an agricultural vehicle, Frohlich's equations required a different concentration factor with soil depth in order to match predicted bulk density profiles with measured values. Using the soil compaction model, Gupta and Larson (1982) predicted distribution of iso-stress and iso-bulk density lines after a passage of

a tractor with an applied stress of 380 kPa at the soil surface. However, no field verification was provided for the model.

SOILS AND METHODS

Laboratory Studies

During this study, samples for the laboratory compression tests came from Israel, Sweden, Morocco, India, and the United States. Uniaxial compression data base consist of 87 soils from South America, North America, Europe, Africa, Asia and Pacific locations (Table 1). Fifty four of the 87 soil samples have been earlier described by Larson et al (1980) and Larson and Gupta (1980). Soils for the laboratory compression tests were taken from the surface and subsurface horizons and represents 8 of 10 orders of soils (Soil Survey Staff, 1975). The samples were air dried and ground to pass a 2-mm sieve.

Standard Laboratory Compression Test

The apparatus used for determining one-dimensional compression curves is shown in Fig. 4. Stress was applied and changes in the length of the sample were measured with an Instron Universal Testing Machine (IUTM).^{3/} The press plate, sample holder, and piston were positioned without soil on the surface plate of the load cell of the IUTM and the

^{3/} Trade and company names are included for the benefit of the reader and do not imply endorsement by the USDA.

Table 1. Characteristics of the soils used in the compression studies.

Symbol	Order or suborder	Series	Depth cm	Horizon	Location	Dominant component in clay fraction
<u>Mollisols</u>						
M 1	Udic Haploborolls	Barnes	0-20	AP	MN, USA	Mt, HMi
M 2	Vertic Haplaquolls	Fargo	0-15	AP	MN, USA	Mt, HMi
M 3	Typic Argiaquolls	Bremer	0-20	A1	MN, USA	Mt, HMi
M 4	Aquic Hapludolls	Nicollet	0-20	AP	MN, USA	Mt, HMi
M 5	Typic Haplaquolls	Hangaard	12-17	A3G	MN, USA	Mt, HMi
M 6	Pachic Haplaquolls	-	16-27	A3	MN, USA	Mt, HMi
M 7	Typic Hapludolls	Monona		Ap	KS, USA	Mt, HMi
M 8	Aridic Argiustolls	Richfield		AP2	KS, USA	Mt, HMi
M 9	Pachic Haploborolls	-	0- 9	Ap	MN, USA	Mt, HMi
M10	Pachic Haploborolls	-	9-18	A1	MN, USA	Mt, HMi
M11	Typic Haploxerolls	Walla Walla			OR, USA	
M12	Typic Hapludolls	Hamble			England	
M13	Pachic Argiustolls	Abilene	0-15	Ap	TX, USA	
M14	Pachic Argiustolls	Abilene	15-30		TX, USA	
M15	Pachic Argiustolls	Abilene	30-60		TX, USA	
M16	Udic Haploborolls	Dolan	0-20	AP	MN, USA	
M17	Typic Haplaquolls	Webster	0-15	AP	MN, USA	
M18	Aquic Hapludolls	Nicollet	0-15	AP	MN, USA	
M19	Typic Hapludolls	Waukegan	0-20	AP	MN, USA	
SW1	Sweden 1				Sweden	
SW2	Sweden 2				Sweden	
W 1	Typic Haplaquolls	Webster	0-15	Ap	MN, USA	
<u>Inceptisols</u>						
I 1	Tropaquept	Algodonal		AP	Venezuela	VR
I 2	Typic Haplaquepts	Paulding	0-15	AP	Ohio, USA	HMt
I 3	Typic Hydrandepts	Hilo	0-12		Hawaii, USA	A
I 4	Typic Eutrandepts	Waimea	0-20		Hawaii, USA	A
I 5	Vertic Haplaquepts	Sharkey			USA	
<u>Spodosols</u>						
S 1	Typic Haplorthods	Adams		A2	N.Y., USA	VR
S 2	Typic Fragiorthods	Plaisted		A2	N.Y., USA	VR
<u>Vertisols</u>						
V 1	Udic Pellusterts	Houston Black		AP	TX, USA	Mt
V 2	Aquentic Chromuderts	Vaiden			AL, USA	
V 3	Typic Chromuderts	Houston		AP	AL, USA	
V 4	Typic Chromoxerts	6A	0- 9		Qedma ISR	Mt KK
V 5	Typic Chromoxerts	6B	9-58		Qedma ISR	Mt KK
V 6	Typic Chromusterts	-	0-15		India	
V 7	Typic Chromusterts	-	15-30		India	
V 8	Typic Chromoxerts	8			Gaushemuel ISR	Mt
V 9	Typic Pelloxerts	9			Yad Nathan ISR	Mt

Entisols

E 1	Typic Udorthents	Ida	0-20	Iowa, USA	Mt, HMi
E 2	Typic Quartzipsamments	Lakeland		FL, USA	
E 3	Typic Udifluvents	Congaree		SC, USA	
E 4	Typic Fluvaquents	Pockington		England	
E 5	Typic Fluvaquents	Pockington		England	
E 6	Xerofluvents		2	Gilat ISR	Mt Quartz
E 7	Typic Torriorthents	Waso		CA, USA	

Alfisols

A 1	Oxic Paleustalfs	Iwo	0-12	A1	Nigeria	KK
A 2	Oxic Paleustalfs	Iwo	20-24	B1	Nigeria	KK
A 3	Oxic Paleustalfs	Funtua	0-15	A1	Nigeria	KK
A 4	Aridic Haplustalfs	Dalhart		AP2	Kans, USA	HMt
A 5	Vertic Albaqualfs	Hurricane			USA	
A 6	Vertic Albaqualfs	Oktibbeha		A1,	USA	
A 7	Vertic Ochraqualfs	Stagno Gley DD			England	
A 8	Vertic Ochraqualfs	Stagno Gley DD			England	
A 9	Vertic Ochraqualfs	Stagno Gley PL			England	
A10	Vertic Ochraqualfs	Stagno Gley PL			England	
A11	Calcic Molic Haploxeralfs	3A	0-5		Avmin ISR	Mt KK IL
A12	Calcic Molic Haploxeralfs	3B	5-50		Avmin ISR	Mt KK IL
A13	Vertic Palexeralfs		5		Givati ISR	Mt IL
A14	Rhodoxeralfs		7		Golan ISR	Mt KK
A15	Haplustalfs	Red Soil			India	
A16	Haplustalfs	Red Soil			India	
A17	Calcic Molic Haploxeralf	4	0-45		Nahal Oz	Mt KK IL
A18	Udic Paleustalfs	Miles	0-15		TX, USA	
A19	Udic Paleustalfs	Miles	15-30		TX, USA	
A20	Udic Paleustalfs	Miles	30-60		TX, USA	

Ultisols

U 1	Typic Hapludults	Georgeville		A1	NC, USA	KK, VR-Cht
U 2	Arenic Paleudults	Wagram		A1	NC, USA	KK, VR-Cht
U 3	Arenic Tropustults	Caridad		A1	Venezuela	KK
U 4	Arenic Paleudults		0-10	A1	Brazil	KK
U 5	Arenic Paleudults		10-25	B1	Brazil	KK
U 6	Oxic Paleudults	Onne	0-15	A1	Nigeria	KK
U 7	Oxic Paleudults	Onne	15-30	A3-B1	Nigeria	KK
U 8	Typic Paleudults	Norfolk			NC, USA	
U 9	Rhodic Paleudults	Decatur		A1,	USA	
U10	Rhodic Paleudults	Decatur		A1,	USA	
U11	Typic Rhodudults	Hiwassee			NC, USA	
U12	Rhodic Paleudults	Davidson			GA, USA	
U13		Hamrai			Morocco	
U14		Rguiga			Morocco	

Oxisols

0 1	Eutrorthoxs	0-18	Al	Brazil	KK, FeO
0 2	Eutrorthoxs	30-80	Bl	Brazil	KK, FeO
0 3	Typic Haplustoxs	0-18	Al	Brazil	KK, FeO
0 4	Acrustoxs	0-18	Al	Brazil	KK, FeO
0 5	Acrustoxs	30-65	Bl	Brazil	KK, FeO
0 6	Haplorthoxs	0-24	Al	Brazil	KK, FeO
0 7	Haplorthoxs	24-57	Bl	Brazil	KK, FeO
R 1	Haplargids			Israel	Mt, KK, IL Polygorskite

, Figure 4. Apparatus used for uniaxial compression determination.

crosshead of the IUTM was brought to rest on the piston. The elevation of the crosshead was read from the positioning apparatus on the IUTM. The crosshead was then raised, the piston removed, and a 60-g soil sample placed in the sample holder (5.65 cm diam.). The piston was replaced in the sample holder, the crosshead was again brought down on the piston, and elevation and load readings were taken. Successive loads and movements of the crosshead were plotted directly on the X-Y plotter of the IUTM. Movement of the crosshead could be measured to an accuracy within 0.01 mm. Bulk density could then be calculated from the initial (without soil in the sample holder) and final (with soil at the desired stress) positions of the crosshead, the known diameter of the sample holder, and the known weight of the sample.

The sample rested on a porous ceramic plate which was connected to a ± 140 kPa capacity pressure transducer. Pore water pressure was recorded on a strip chart recorder. The air entry value of the ceramic plate was 100 kPa. In this system, the pore water pressure could be measured with only negligible transfer of water across the porous plate.

During a test, mechanical stress was applied until nearly constant soil volume and pore water pressure were achieved. Then, a new increment of stress was applied to the same sample and the process was repeated. The desired stress was achieved by appropriately setting the IUTM. To achieve the stress, the crosshead of the IUTM was brought to the proper position in < 1 min, then the stress was held constant for about 30 min. While the stress was constant the crosshead is free to move to maintain the stress. At the start of a test, the pore water pressure was negative. The test was stopped when the pore water pressure became zero or the limits of the load cell were reached. Air could escape around the piston. In a few cases of high clay soils and

high water contents the time-bulk density curve was extrapolated to estimate bulk density equilibrium. As the soils nears saturation, the equilibrium time increased sharply. We considered this a static loading procedure. With the procedure, the relationship among, stress, bulk density or void ratio, and negative pore water pressure could be obtained.

On most of the soil samples, compression curves were determined for four or five water contents ranging in pore water pressure from about -5 to -100 kPa at initial applied stresses of 10 to 20 kPa. The air dry soils were wet to the maximum desired water content (equivalent to about -1 kPa matric potential) with a fine water spray while rolling on a plastic sheet. The soils were then allowed to slowly dry to achieve lower water contents. The soils were allowed to equilibrate at each water content for several days before a test was made. Positive pore water pressure and negative pore water pressure less than about -70 kPa were not measured during the compression determinations but were inferred from other data. The compression index, C , was computed by regression techniques from the data points along the linear portion of the curve for each water content, and again using the points from the linear portion of the curves at all water contents. Compression parameters of 87 soil samples in this data base are given in Table 1, 2, and 3.

Effect of Sample Size on Compression Characteristics

Larson et al. (1980) arbitrarily selected 60 g of wet soil for standard laboratory compression tests. Because the height of the sample might affect the equilibrium bulk density and pore water pressure values

Table 2. Particle size, organic carbon, compression index, and compression parameters (ρ_k , Δ_T , S_k) at 100 kPa compression applied stress for various soils.

Symbol	Order or suborder	Sand, 2.0-0.05 mm	Silt, 0.05- 0.002 mm	Clay <0.002 mm	Organic Carbon	Compres- sion index	ρ_k	$\Delta_T \times 10^{-4}$	S_k
-----%-----									
Mollisols									
-----Mg m ⁻³ -----									
-----%-----									
M 1	Udic Haploborolls	44.8	31.8	23.5	2.52	0.49	1.28	40.0	-
M 2	Vertic Haploquolls	28.3	37.8	33.9	3.23	0.59	1.04	50.4	-
M 3	Typic Argiaquolls	10.8	47.9	41.5	3.49	0.48	1.00	-	-
M 4	Aquic Hapludolls	35.2	33.9	31.0	2.22	0.59	1.18	54.6	51.8
M 5	Typic Haplaquolls	57.7	25.9	16.5	1.60	0.49	1.50	89.0	51.7
M 6	Pachic Haploborolls	63.1	23.6	13.4	2.00	0.52	1.45	59.0	57.6
M 7	Typic Hapludolls	16.4	63.2	20.6	0.72	0.31	1.37	28.2	59.1
M 8	Aridic Argiustolls	42.9	35.2	22.0	1.02	0.42	1.50	48.8	56.9
M 9	Pachic Haploborolls	68.9	18.1	13.1	2.60	0.42	1.43	47.2	55.1
M 10	Pachic Haploborolls	65.3	21.3	13.6	1.90	0.42	1.48	-	-
M 11	Typic Haploxerolls	18.9	61.7	19.4	1.29	0.38	1.32	-	27.0
M 12	Typic Hapludolls	35.3	51.6	13.1	1.40	0.33	1.34	33.7	40.2
M 13	Pachic Argiustolls	53.7	26.9	19.4	0.32	0.47	1.53	53.5	56.6
M 14	Pachic Argiustolls	51.1	26.7	22.2	0.35	0.55	1.54	56.4	55.0
M 15	Pachic Argiustolls	45.7	20.6	33.7	0.38	0.57	1.38	70.4	62.7
M 16	Udic Haploborolls	39.1	38.3	22.6	1.82	0.47	1.30	35.7	51.3
M 17	Typic Haplaquolls	25.7	38.6	35.7	3.50	0.45	1.10	36.3	54.7
M 18	Aquic Hapludolls	31.9	37.2	30.9	1.51	0.53	1.31	51.3	64.4
M 19	Typic Hapludolls	18.7	58.3	23.0	2.70	0.46	1.31	45.1	55.2
SW 1		10.6	26.2	63.2	1.76	0.52	1.21	54.4	54.9
SW 2		47.0	34.8	18.2	2.61	0.39	1.34	31.7	65.7
Inceptisols									
I 1	Tropaquepts	30.9	37.2	32.1	1.90	0.55	1.26	45.6	-
I 2	Typic Haplaquepts	3.7	36.8	59.5	2.63	0.48	1.10	40.3	-
I 3	Typic Hydradepts	-	-	-	7.40	0.36	0.76	35.0	68.6
I 4	Typic Eutradepts	-	-	-	5.07	0.35	0.78	34.8	52.1
I 5	Vertic Haplaquepts	2.9	35.8	61.3	1.98	0.52	1.06	81.3	42.1

Spodosols

S 1	Typic Fragiorthods	92.7	4.5	3.0	1.11	0.25	1.17	37.4	16.0
S 2	Typic Fragiorthods	68.8	29.8	1.6	0.89	0.27	1.32	25.8	36.8
<u>Vertisols</u>									
V 1	Udic Pellusterts	6.4	29.9	63.8	5.49	0.56	1.15	47.9	68.2
V 2	Aqueantic Chromuderts	10.4	43.8	45.9	1.12	0.55	1.32	60.9	60.6
V 3	Typic Chromuderts	6.1	28.9	65.0	1.98	0.55	1.05	52.6	51.4
V 4	Chromuxerts	22.3	35.2	42.5	0.80	0.56	1.33	36.5	69.0
V 5	Chromuxerts	18.6	36.1	45.3	0.70	0.59	1.25	41.6	54.4
V 6	Chromusterts	9.0	44.7	46.3	0.90	0.59	1.34	35.1	57.0
V 7	Chromusterts	10.4	43.0	46.6	0.70	0.54	1.32	48.5	55.4
V 8	Chromoxererts	13.2	42.6	44.2	1.20	0.57	1.25	50.9	58.3
V 9	Pelloxerts	10.5	30.0	59.5	0.90	0.52	1.18	43.7	55.1

Entisols

E 1	Typic Udorthents	9.3	66.9	23.8	1.69	0.43	1.22	15.0	46.7
E 2	Typic Quartzipsaments	83.6	10.7	5.7	0.30	0.18	1.48	41.3	14.0
E 3	Typic Udifluvents	21.9	46.2	31.9	1.26	0.43	1.35	41.2	61.7
E 4	Typic Fluvaquents	72.6	17.1	10.3	1.99	0.20	1.37	-	47.1
E 5	Typic Fluvaquents	26.7	40.8	32.6	2.14	0.54	1.30	42.3	64.6
E 6	Xerofluvents	39.5	38.7	21.8	0.70	0.52	1.46	58.8	49.5
E 7	Typic Torriorthents	76.6	13.5	9.9	0.23	0.35	1.61	14.9	53.5

Alfisols

A 1	Oxic Paleustalfs	68.8	12.2	19.2	1.28	0.40	1.48	-	52.3
A 2	Oxic Paleustalfs	58.6	9.0	32.6	0.45	0.46	1.37	73.0	44.5
A 3	Oxic Paleustalfs	39.6	46.6	13.9	0.70	0.31 ⁺	1.44	38.0	51.2
A 4	Aridic Haplustalfs	34.3	39.8	26.1	0.72	0.44	1.38	44.1	59.6
A 5	Vertic Albaqualfs	6.9	24.2	68.9	2.06	0.56	0.95	45.8	44.4
A 6	Vertic Hapludalfs	19.5	52.8	27.7	0.85	0.47	1.44	60.4	47.3
A 7	Vertic Ochraqualfs	10.2	63.9	25.9	1.91	0.46	1.29	-	64.1
A 8	Vertic Ochraqualfs	10.8	63.0	26.2	1.81	0.44	1.31	32.0	66.0
A 9	Vertic Ochraqualfs	8.3	63.4	28.3	1.95	0.47	1.27	-	63.6
Al0	Vertic Ochraqualfs	8.3	61.8	29.9	1.86	0.49	1.27	-	60.4
Al1	Haploxeralfs	49.1	35.0	15.9	1.30	0.36	1.42	44.4	64.3
Al2	Haploxeralfs	49.5	33.6	16.9	0.90	0.42	1.50	37.1	56.3
Al3	Vertic Palexeralfs	25.4	32.5	42.1	0.60	0.61	1.27	42.9	53.6
Al4	Rhodoxeralfs	7.6	20.2	72.2	0.90	0.52	1.04	48.9	51.9

A15	Haplusalfs	43.0	21.8	35.2	1.60	0.44	1.23	40.2	49.8
A16	Haplusalfs	45.4	21.0	33.6	1.50	0.43	1.27	47.6	53.8
A17	Calcic Molic Haploxeralf	40.2	38.3	21.5	0.50	0.52	1.48	44.1	59.5
A18	Udic Paleustalfs	77.1	12.3	10.6	0.14	0.32	1.55	14.1	42.2
A19	Udic Paleustalfs	73.5	13.4	13.1	0.15	0.39	1.56	51.6	45.8
A20	Udic Paleustalfs	62.7	14.4	22.9	0.26	0.61	1.50	59.7	57.0

Ultisols

U 1	Typic Hapludults	10.4	39.2	50.5	1.04	0.46	1.25	-	58.2
U 2	Arenic Paleudults	81.8	15.9	2.4	0.72	0.22	1.50	79.0	17.9
U 3	Tropustults	80.4	13.1	6.7	0.59	0.25	1.35	-	-
U 4	Paleudults	19.4	29.0	51.8	2.35	0.50	1.17	-	67.0
U 5	Paleudults	6.9	26.6	66.7	1.21	0.48	1.14	54.30	70.0
U 6	Oxic Paleudults	77.2	6.2	16.8	1.12	0.31	1.40	-	33.7
U 7	Oxic Paleudults	71.9	5.6	22.7	0.70	0.40	1.40	59.0	41.5
U 8	Typic Paleudults	70.3	16.5	13.2	0.26	0.30	1.52	59.2	19.9
U 9	Rhodic Paleudults	27.2	27.5	45.3	0.66	0.44	1.34	48.7	55.3
U10	Rhodic Paleudults	28.0	42.0	30.0	0.49	0.52	1.47	57.7	50.0
U11	Typic Rhodudults	71.7	9.6	18.7	0.61	0.32	1.47	97.3	24.3
U12	Rhodic Paleudults	27.5	27.5	45.1	0.71	0.47	1.30	86.6	46.3
U13		27.9	34.6	37.5	3.17	0.56	1.36	53.3	52.1
U14		17.1	55.3	27.6	3.38	0.54	1.40	51.0	55.8

Oxisols

O 1	Eutrothoxs	14.5	24.3	61.3	2.02	0.56	1.22	-	67.5
O 2	Eutrothoxs	9.7	15.7	74.7	0.92	0.50	1.06	-	54.7
O 3	Typic Haplustoxs	36.4	30.7	33.1	2.25	0.45	1.00	59.2	35.5
O 4	Acrostoxs	18.0	15.5	66.7	2.45	0.44	0.95	-	44.2
O 5	Acrostoxs	14.5	20.2	65.5	1.34	0.45	1.00	-	66.8
O 6	Haplorthoxs	61.6	0.8	35.7	1.04	0.48	1.34	63.6	51.6
O 7	Haplorthoxs	54.1	3.1	42.9	0.55	0.48	1.35	-	55.7
R 1	Haplogruids	36.4	43.4	20.2	0.40	0.53	1.58	51.8	72.2

Table 3. Degree of Saturation at minimum pore water pressure, θ_m ; normalized stress at normalized minimum pore water pressure, σ_n at $u_n = 1$; and standard error of estimation of σ_n at $u_n = 1$ for 87 soil samples.

Soil Order designation of sample	Order or suborder	θ_m	σ_n at $u_n = 1$	SE of σ_n at $u_n = 1$
<u>Mollisols</u>				
M 1	Udic Haploborolls	0.449	0.725	0.052
M 2	Vertic Haplaquolls	0.578	0.847	0.026
M 3	Typic Argiaquolls	0.529	0.765	0.027
M 4	Aquic Hapludolls	0.479	0.768	0.043
M 5	Typic Haplaquolls	0.383	0.663	0.073
M 6	Pachic Haploborolls	0.434	0.697	0.053
M 7	Typic Hapludolls	0.623	0.757	0.074
M 8	Aridic Arguistolls	0.561	0.742	0.076
M 9	Pachic Haploborolls	0.370	0.626	0.039
M 10	Pachic Haploborolls	0.510	0.701	0.003
M 11	Typic Haploxerolls	0.611	0.759	0.028
M 12	Typic Hapludolls	0.484	0.701	0.042
M 13	Pachic Agiustolls	0.513	0.733	0.054
M 14	Pachic Agiustolls	0.502	0.770	0.258
M 15	Pachic Agiustolls	0.505	0.757	0.147
M 16	Udic Haploborolls	0.500	0.607	0.327
M 17	Typic Haplaquolls	0.540	0.718	0.101
M 18	Aquic Hapludolls	0.500		
M 19	Typic Hapludolls	0.489	0.716	0.216
SW 1	Sweden 1	0.580	0.770	0.119
SW 2	Sweden 1	0.470	0.699	0.306
W 1	Typic Haplaquolls	0.471	0.690	0.088
<u>Inceptisols</u>				
I 1	Tropaquepts	0.496	0.806	0.041
I 2	Typic Haplaquepts	0.616	0.825	0.034
I 3	Typic Hydrandepts	0.602	0.766	0.120
I 4	Typic Eutrandepts	0.625	0.734	0.019
I 5	Vertic Hapluquepts	0.566	0.780	0.075
<u>Spodosols</u>				
S 1	Typic Fragiorthods	0.389	0.583	0.025
S2	Typic Fragiorthods	0.490	0.673	0.027
<u>Vertisols</u>				
V 1	Udic Pellusterts	0.644	0.827	0.077
V 2	Aqueptic Chromuderts	0.580	0.785	0.105
V 3	Typic Chromuderts	0.583	0.719	0.127

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V 4	Typic Chromoxerts	0.578	0.793	0.098
V 5	Typic Chromoxerts	0.506	0.788	0.312
V 6	Typic Chromuterts	0.572	0.744	0.119
V 7	Typic Chromuterts	0.564	0.788	0.175
V 8	Typic Chromoxerts	0.652	0.802	0.138
V 9	Typic Pelloxerts	0.570	0.757	0.150

Entisols

E 1	Typic Udorthents	0.521	0.730	0.024
E 2	Typic Quartzipsamments	0.309	0.501	0.050
E 3	Typic Udifluvents	0.512	0.769	0.307
E 4	Typic Fluvaquents	0.502	0.650	0.048
E 5	Typic Fluvaquents	0.555	0.767	0.156
E 6	Xerofluvents	0.577	0.789	0.084
E 7	Typic Torriorthents	0.549	0.741	0.057

Alfisols

A 1	Oxic PaleustalFs	0.545	0.783	0.008
A 2	Oxic PaleustalFs	0.566	0.795	0.068
A 3	Oxic PaleustalFs	0.497	0.686	0.051
A 4	Aridic HaplustalFs	0.589	0.740	0.099
A 5	Vertic AlbaqualFs	0.600	0.808	0.281
A 6	Vertic HapludalFs	0.538	0.761	0.116
A 7	Vertic OchraqualFs	0.594	0.749	0.124
A 8	Vertic OchraqualFs	0.633	0.787	0.097
A 9	Vertic OchraqualFs	0.582	0.767	0.097
A 10	Vertic OchraqualFs	0.577	0.793	0.079
A 11	Calcic Mollic HaploxeralFs	0.592	0.690	0.284
A 12	Calcic Mollic HaploxeralFs	0.597	0.749	0.085
A 13	Vertic PalexeralFs	0.543	0.769	0.151
A 14	Vertic RhodoxeralFs	0.691	0.827	0.125
A 15	Vertic HaplusalFs	0.595	0.763	0.107
A 16	Vertic HaplusalFs	0.570	0.762	0.067
A 17	Calcic Mollic HaploxeralF	0.611	0.775	0.078
A 18	Udic PaleustalFs	0.433	0.648	0.052
A 19	Udic PaleustalFs	0.488	0.709	0.071
A 20	Udic PaleustalFs	0.430	0.810	0.285

Ultisols

U 1	Typic Hapludults	0.693	0.869	0.012
U 2	Arenic Paleudults	0.269	0.574	0.039
U 3	Tropustults	0.417	0.567	0.013
U 4	Paleudults	0.589	0.732	0.062
U 5	Paleudults	0.612	0.746	0.100
U 6	Oxic Paleudults	0.404	0.592	0.070
U 7	Oxic Paleudults	0.468	0.673	0.067
U 8	Typic Paleudults	0.335	0.623	0.082
U 9	Rhodic Paleudults	0.602	0.775	0.120
U 10	Rhodic Paleudults	0.577	0.780	0.085
U 11	Typic Rhodudults	0.444	0.760	0.040
U 12	Rhodic Paleudults	0.543		

U 13	0.537	0.774	0.105
U 14	0.608	0.785	0.086

Oxisols

01	Eutrothoxs	0.678	0.788	0.066
02	Eutrothoxs	0.607	0.758	0.034
03	Typic Haplustoxs	0.652	0.803	0.209
04	Acrustoxs	0.578	0.729	0.057
05	Acrustoxs	0.576	0.718	0.031
06	Haplorthoxs	0.506	0.737	0.072
07	Haplorthoxs	0.499	0.711	0.018
R1	Haplargids	0.540	0.751	0.066

at a given applied stress, an experiment was undertaken to study the effect of sample size on compression characteristics. Compression curves were determined using 40, 60, 80, 100, and 120 g of moist Webster clay loam soil. For a constant cross sectional area of the sample holder, various amounts of wet soil corresponded to different sample height.

Effect of Aggregate Size on Compression Characteristics

Because of the difficulty of obtaining in-situ soil cores and then transporting these undisturbed samples to the laboratory for compression tests, Larson et al (1980) pretreated all samples similarly before compression test. Disturbed samples were ground, passed through 2 mm sieve, and wetted to a given moisture content. Since in the field most medium to heavy textured soils are aggregated, an experiment was conducted to study the effect of aggregate size on compression characteristics.

Laboratory compression tests were run on two aggregate fractions of the Webster clay loam soil. The aggregate fractions were 3.36 - 5.66 and 5.66 - 12.7 mm. Loosely packed air dry aggregates were saturated overnight on the pressure plate and desorbed to -10 KPa matric potential in the pressure plate apparatus. Lower water contents were achieved by drying the wet aggregates. At each water content compression tests were run on aggregate in its natural form, and also when broken into smaller sizes with a spatula (ground). In each test, 60 g of wet soil was used.

Effect of Crop Residues on Compression Characteristics

As crop residues are readily available on the farm, the objective of this experiment was to study if crop residues could be used to reduce or prevent excessive soil compaction. In this experiment, corn residues

were chopped and separated into three fractions (0.25 - 0.51, 1.0 - 2.0 and 3.36 - 5.66 mm). Compression curves were obtained on moist soil mixed with various size fractions of corn residues at the rate of 0.0, 0.5, 1.0 and 2.0 g per 60 g of moist soil. Since pore water pressure was slow to equilibrate when air dry residues were mixed with the moist soil, no attempt was made to monitor changes in soil pore water pressure during the compression tests. Effect of crop residues on compression characteristics was determined on Zimmerman sand, Sargent silt loam, and Webster clay loam soils.

Field Studies

United States

Stress distributions in soil in response to a static load can be calculated from Soehne's equation, or derivations of it. However, an isotropic mass must be assumed. Under field conditions, this isotropic condition is rarely found because of vertical texture, water, and bulk density variations, especially between the tilled layer and the subsoil. Therefore, "artificial" soil profiles were constructed at Morris and Rosemount, MN, using the surface 20 cm of Dolan loam (M16) and Waukegan silt loam soils (M19), respectively. Loose, tilled soil was piled above-ground to form a profile about 1 meter deep, 6 meters wide, and 18 meters long. The sides of the profile are supported by wood planks. Earthen ramps were built on both ends to facilitate later driving of a tractor up onto the profile. After over-wintering, one pass by a tractor was made across the profile during summer. Tractor type, axle loads, and the contact areas of the tires used in these field studies are given in Table 4.

Measurements of bulk density, penetration resistance, water contents

Table 4. Total load, highest load per axle, tire width and contact area of tractors used in field validation studies.

Location	Soil Type	Tractor Type	Model	Total Load	Highest Load/axle	Tire Width	Tire Contact Area
<u>USA</u>				-----kg-----		m	m ²
Morris, MN	Dolan Loam	International Harvester (2 + 2)	3788	7741	4180†	0.250	0.326
Rosemount, MN	Waukegan Silt Loam	John Deere	4640	8903	6129††	0.260	0.399
<u>ISRAEL</u>							
Nahal Oz	Nahal Oz Silt Loam	Ford	6610	3900	2080††	-	0.080
Nahal Oz	Nahal Oz Silt Loam	John Deere	4490	10176	5696†	-	0.178
Nahal Oz	Nahal Oz Silt Loam	Case	1370	3776	1990††	-	0.092

† Front axle.

†† Rear axle.

and soil sinkage were made at four to five successive locations laterally away from the middle of the wheel track, and replicated 5 times along the tractor track.

At Rosemount location, seven miniature Sensotec^{3/} strain gauge pressure transducers were also used to monitor the pressure distribution during the passage by tractor wheels. Transducers were inserted from the side of the bin to a given position and depth. Holes were made by pushing a cylindrical auger into the side of the soil bin. Transducers were mounted on a rod and pushed into the soil. Holes were then filled with an expanding type of insulation foam spray. It took 12-24 hours for the foam to set in. During the second run, some of the transducer surfaces were covered with the foam. Data from these transducers were discarded.

Two runs were made at each location. However, data from second run at Morris, MN could not be completed due to rain. Objectives of two runs per bin was to study the effect of water content on pressure and bulk density profile after a passage by a tractor wheel. The Rosemount, MN soil bin was irrigated before the first run.

Bulk density and water content measurements were made on soil cores (3.5 cm diameter) taken with a Giddings probe mounted on the back of a tractor or a pickup truck. Penetration resistance was measured with a hand held penetrometer (cone angle = 60° and cone diameter = 1.9 cm). For sinkage measurement, a microrelief meter with total of 39 pins at 2 cm spacing was used.

Particle size determinations were performed by direct sieving of the sand fraction and by the pipette method for silt and clay. Sodium hexametaphosphate was used as the dispersing agent. Particle size was

not determined on the two Andepts because of uncertainty of how to disperse the samples.

Israel

Field experiment was located on a silty loam soil (A17) near Nahal Oz. Particle size distribution varied from 18-20% clay, 27-30% silt with remainder for fine sand. Organic matter of the soil varied from 0.3 to 0.4%. Water content corresponded to 0.18, and 0.08 gg^{-1} at soil matric potential of -33 and -1500 kPa. Hygroscopic water content was about 0.03 gg^{-1} . Calcium carbonate was mostly present (0.13 gg^{-1}) in the silt fraction.

Soil compaction experiment was conducted on a 3.2 ha field which had been under a potato crop before this experiment. After the potato harvest, the soil was chisel plowed three times to a depth of 50-55 cm. Chisel plow had three tines, each equipped with small winglets at a depth of 35-40 cm. After deep chisel plowing, cultivators having 7 tines per bed were operated to an approximate depth of 30 cm. Final cultivation included the rototilling of the top 20 cm. Field was then irrigated by a single line perpendicular to the soil compaction beds.

Soil compaction runs were made by driving a tractor across a cultivated bed. Characteristics of the three tractors used in this experiment are given in Table 4. Other treatments included two speeds and number of passes (1 and 3).

Bulk density, gravimetric moisture content, shape of the bed and penetration resistance were measured before and after the compaction run. Shape of the bed was measured with a microrelief meter. Bulk density and gravimetric water content profiles were measured on the undisturbed cores taken at three positions (5, 12, and 15 m) from the

line source. All measurements except penetration resistance was replicated twice. Penetrations resistance was replicated five times.

Disturbed samples taken from the same experimental field were also subject to compaction tests (Proctor density, consolidation) at various water contents in the laboratory.

RESULTS AND DISCUSSION

Laboratory Studies

Effect of Sample Size on Compression characteristics

Figure 5 shows the effect of sample size on the ρ_b vs. σ_a and porewater pressure, U_a , vs. σ_a relationships of Webster clay loam soil at two moisture contents. These water contents represent the extremes of the moisture contents used in this experiments. At a given stress, ρ_b are slightly lower and U_a are slightly higher when 120 g of soil sample is used in the uniaxial compression test. These differences are more noticeable at drier moisture contents. For other sample sizes, ρ_b vs. σ_a and U_a vs σ_a curves are approximately same. Compression parameters from these curves and curves at other water contents (not shown) are summarized in Table 5. At a given water content, compression parameters are approximately same for all sample sizes except 120 g treatment. This may be due to lack of enough time (30-45 min) for large sample (120 g) to reach compression and pore water pressure equilibrium with the applied stress. In spite of lower pore water pressure curves for 120 g treatment, θ_m and σ_n at $U_n = 1$ were approximately same for all sample size (Table 5). This indicates that parameters defining critical stress above which soil aggregate shear is not influenced by sample size.

Figure 5. Effect of sample size on compression and pore water pressure curves during a uniaxial confined compression test.

Table 5. Compression parameters of Webster clay loam soil as influenced by sample size at four water contents.

Water Content	Sample Size	C	ρ_k	θ_m	σ_n at $U_n = 1$
$g\ g^{-1}$	g		$Mg\ m^{-3}$	$g\ g^{-1}$	
0.34	40	0.488	1.23	0.572	0.724
	60	0.460	1.22	0.573	0.724
	80	0.453	1.21	0.582	0.736
	100	0.464	1.19	0.581	0.734
	120	0.426	1.15	0.600	0.733
0.31	40	0.502	1.19	0.552	0.754
	60	0.471	1.17	0.561	0.726
	80	0.462	1.14	0.602	0.788
	100	0.434	1.13	0.561	0.723
	120	0.429	1.12	0.616	0.722
0.29	40	0.496	1.12	0.530	0.734
	60	0.480	1.13	0.581	0.760
	80	0.453	1.12	0.619	0.782
	100	0.456	1.11	0.586	0.746
	120	0.429	1.11	0.609	0.763
0.21	40	0.455	1.07	0.533	0.758
	60	0.407	1.08	0.539	0.707
	80	4.401	1.07	0.562	0.719
	100	0.394	1.04	0.525	0.705
	120	0.357	1.06	0.546	0.688

Effect of Aggregate Size on Compression Characteristics

Figure 6 gives the comparison of ρ_b vs σ_a and U_a vs σ_a curves for two aggregate fractions (3.36 - 5.66 and 5.66 - 12.7 mm) in its natural condition as well as when broken into smaller sizes. Compression parameters of these and curves at other water contents are given in Table 6. Figure 6 and Table 6 show that characteristics (C, ρ_k) of VCC (straight line) were approximately same for both aggregate sizes in their natural condition and when broken into smaller sizes with a spatula before the compression test. There is a slight difference in the secondary compression (curved line) behavior between aggregates in their natural and broken condition. Bulk density during secondary compression were slightly lower when aggregates are larger whether in their natural or artificially broken state before compression test. This is expected because secondary compression is more dependent on packing due to arrangement of aggregates than packing due to applied stress.

Pore water pressure curves showed much greater difference between large and small aggregates and between natural and broken aggregates, at lower water contents. However, θ_m and σ_n at $U_n = 1$ (Table 6) defining critical stress above which soil aggregate shear were approximately same for two aggregate sizes and two aggregate conditions before compression test. These results show that pretreatment of the soil sample before compression does not alter the strength of natural structural units in soils.

Effect of Crop Residue on Compression Characteristics

Changes in compression of Webster clay loam, Sargent silt loam, and Zimmerman sand when mixed with 0, 0.5, 1.0, and 2.0 g of 1-2 mm corn

Figure 6. Effect of aggregate size and precompression condition on compression and pore water pressure curves during uniaxial confined compression test.

Table 6. Compression parameters of Webster clay loam aggregates in the natural and broken form at five water contents.

Water Content	Aggregate Size	Treatment†	C	ρ_k	S_k	θ_m	$\frac{\sigma_n}{U_n}$ at $U_n = 1$
$g\ g^{-1}$	mm			$Mg\ m^{-3}$	%	$g\ g^{-1}$	
0.33	5.66-12.7	N	0.463	1.27	79.1	0.553	0.698
		B	0.430	1.28	80.7	0.488	0.690
0.32	3.36-5.66	N	0.491	1.27	77.4	0.585	0.728
		B	0.482	1.29	79.7	0.563	0.724
0.28	5.66-12.7	N	0.491	1.19	60.8	0.458	0.698
		B	0.461	1.21	62.4	0.505	0.712
0.28	3.36-5.66	N	0.532	1.24	65.3	0.461	0.694
		B	0.466	1.24	65.7	0.544	0.720
0.24	5.66-12.7	N	0.473	1.12	46.8	0.531	0.730
		B	0.436	1.17	50.1	0.568	0.738
0.24	3.36-5.66	N	0.469	1.19	51.9	0.555	0.732
		B	0.427	1.20	52.6	0.635	0.725
0.19	5.66-12.7	N	0.484	1.10	35.9	0.514	0.743
		B	0.437	1.16	39.4	0.456	0.702
0.15	5.66-12.7	N	0.416	1.08	27.5	0.443	0.705
		B	0.408	1.10	28.3	0.410	0.684
0.16	3.36-5.66	N	0.443	1.10	29.4	0.465	0.741
		B	0.411	1.14	31.2	0.479	0.665

† N = Natural form.

B = Broken into smaller aggregates.

residue with 60 g of wet soil are shown in Fig. 7. Compression curves shift to the right with an increase in the amount of residue. In other words, bulk density decreases with the addition of residue at a given applied stress. However, Fig. 7 shows that Virgin Compression Curves of residue mixed Webster clay loam and Sargent silt loam soils were parallel to the VCC of respective soil without residue. Residue addition to Zimmerman slightly increased the slope (C) of the VCC.

Compression index and ρ_k of Webster clay loam, Sargent silt loam and Zimmerman sand when mixed with 0, 0.5, 1.0, and 2.0 g per 60 g of wet soil for three different fractions of corn residues are plotted in Fig. 8 and 9. As stated above, C of Webster clay loam and Sargent silt loam soils did not change with the amount of corn residue. However, C values increased slightly with an increase in the size of corn residue. In other words, compressibility of these soils increases when larger size fraction of corn residue are mixed with the soil. Compression index of Zimmerman sand increased with an increase in the addition of corn residues. However, for a given amount of corn residues, there is no difference in the compression index of Zimmerman sand for various residue fractions.

Bulk density at an applied stress of 100 kPa decreases with an increase in the amount and size of the corn residue (Fig. 9). For the range of water contents studied in this experiment, the decrease in ρ_k due to addition of corn residue is greater for Sargent silt loam followed by Zimmerman sand and Webster clay loam. Except for Zimmerman sand, ρ_k was lower when soils were mixed with 3.36-5.66 mm followed by 1.0-2.0 mm and 0.25-0.50 mm size corn residues. Also for Sargent silt loam and Webster clay loam soils, the decrease in ρ_k on residue addition

Figure 7. Effect of corn residue (1.0 - 2.0 mm) addition on compression curves of Webster clay loam, Sargent silt loam and Zimmerman sand.

Figure 8. Influence of various amount and sizes of corn residue on compression index of three different textured soils.

Figure 9. Influence of various amounts and sizes of corn residue on bulk density corresponding to an applied stress of 100 kPa in three different textured soils.

was much larger at higher moisture content. Data in Fig. 9 indicates that ρ_k depends upon the size of residue fractions along with particle and aggregate size distributions of soils. To understand the interaction between residue fraction, particle size and aggregate size of soil, further experimentation is needed.

Figure 10 gives the compression curves of two particle size fractions of corn, soybean, wheat and barley residues. For a given size fraction, compression curves were approximately same for all type of residues. Soybean, wheat, and barley residues were stems and did not include any leaf residues. Corn residues included both stem and leaves. Compression curves of 0.25-0.5 mm fraction of all types of residue and 3.36-5.66 mm corn residues were similar to 1.0-2.0 mm fraction data plotted in Fig. 10. Higher bulk density of 3.36-5.66 mm of corn residues as compared to soybean, barley and wheat is due to presence of leaves. Leaves and stem residues together will be more susceptible to compression than individual residue type.

Ultimate goal of residue incorporation is not to increase the compressibility of soils and at the same time lower the bulk density at any applied stress. The advantage of this goal would be that larger tillage machinery could be used on wet soils without crossing the limits of soil matrix-air-water relationship that are optimum for root growth, and water and air movement. Results from this experiment indicate that corn residue addition will be more beneficial in Sargent silt loam, followed by Zimmerman sand and Webster clay loam.

Compression index and ρ_k of compaction prone soils (Webster clay loam) does not materially change with the addition of up to 2 g of corn residue per 60 g of wet soil. A much higher amount of corn residue may

Figure 10. Compression curves of corn, soybeans, wheat and barley residues.

be needed before any significant effect is noticed in lowering the susceptibility of Webster clay loam soils to compaction.

Generally, a 100 bushel corn yield corresponds to 6272 kg/ha of corn residue. If these residues are uniformly mixed in the top 15 cm of soil, this will correspond to 0.13 to 0.15 g of corn residue per 60 g of wet soil. Similarly, if these residues are incorporated in the top 15 cm of the wheel track area (1/4 of the total area), this will correspond to 0.51 to 0.62 g per 60 g of wet soil. Both these rates of residue incorporation along with Figs. 8 and 9 show that corn residues available on the farm will have little value in reducing susceptibility of soils to compaction, if the corn residues are uniformly mixed in the top 15 cm of the soil over the whole field or in the wheel tracks. Because of the elastic nature and bulkiness of corn residues (Fig. 10), concentrating residues in the wheel track at the soil surface may be more effective than mixing them with surface soil to reduce compaction. Field studies are needed to check this concept.

Field Testing of the Soil Compaction Model

Morris, MN USA

Table 7 gives the water content profiles at five locations (replications) along the path of the tractor in a soil bin at Morris, MN. The soil used in the bin was Dolan Loam (M16). Water content at each depth and replication is an average of five readings. Gravimetric water content varied from 0.212 to 0.269 g g⁻¹. Average water content for all five replications could be grouped into three groups: (a) 0.223, (b) 0.247, and (c) 0.258 g g⁻¹.

Table 8 gives the measured bulk densities profile at five locations perpendicular to the path of the tractor. Bulk density at each depth

Table 7. Water content profiles at five locations (replications) along the path of the tractor in a soil bin at Morris, MN.

Depth cm	Replications				
	I	II	III	IV	V
	water content, g g ⁻¹				
0 - 10	0.216	0.240	0.241	0.242	0.231
10-20	0.214	0.252	0.246	0.256	0.240
20-30	0.233	0.262	0.241	0.237	0.245
30-40	0.212	0.260	0.237	0.237	0.250
40-50	0.230	0.269	0.245	0.257	0.256
50-60	0.231	0.264	0.249	0.261	0.247
Mean $\pm$ SD	0.223 $\pm$.019	0.258 $\pm$.013	0.243 $\pm$.010	0.249 $\pm$.014	0.247 $\pm$.012

SD = standard deviation.

Table 8. Measured bulk density profiles and soil surface sinkage at five locations perpendicular to the path of the tractor in soil bin at Morris, MN.

Depth cm	-----Distance from the center of wheel track, cm-----				
	0	15	30	45	60
	$\rho_b, \text{Mg m}^{-3}$				
0-10	1.23 $\pm$.10†	1.17 $\pm$.07	1.01 $\pm$.10	1.04 $\pm$.05	1.03 $\pm$.07
10-20	1.23 $\pm$.06	1.17 $\pm$.06	1.09 $\pm$.04	1.01 $\pm$.13	1.03 $\pm$.05
20-30	1.16 $\pm$.06	1.14 $\pm$.07	1.17 $\pm$.06	1.13 $\pm$.06	1.10 $\pm$.06
30-40	1.09 $\pm$.13	1.12 $\pm$.12	1.12 $\pm$.08	1.12 $\pm$.07	1.12 $\pm$.08
40-50	1.01 $\pm$.09	1.01 $\pm$.05	1.06 $\pm$.06	1.07 $\pm$.11	1.13 $\pm$.10
50-60	1.20 $\pm$.06	1.11 $\pm$.05	1.13 $\pm$.04	1.08 $\pm$.05	1.09 $\pm$.02
	-----Sinkage, cm-----				
	8.7	4.6	0	0	0

† Mean $\pm$ SD.

and location is an average of five measurements corresponding to five replications. Bulk densities are higher under the wheel track followed by 15 and 30 cm away from the center of wheel track. Bulk densities at 45 and 60 cm from the center of wheel track are approximately same. Projection of bulk density profile (Fig. 11) from the soil compaction model showed that there is little effect of surface loads on soil elements in the profile at 45 and 60 cm away from the center of the wheel track. Thus, bulk densities at 60 cm away from the center of wheel track were assumed to be the initial bulk densities of the soil profile in the bin.

Figure 12 is the plot of microrelief meter readings across the wheel track. Each microrelief reading in Fig. 12 is an average of five readings corresponding to each of the five replications. Figure 12 shows the center of wheel track at 40 cm distance. Bulk density and water content measurements were made on the right hand side of the center of the wheel track. Using Fig. 12, sinkage of soil surface was calculated for all five locations perpendicular to wheel track. Sinkage at 0 and 15 cm away from the center of wheel track corresponded to 8.7 and 4.6 cm (Table 8). There was no sinkage of soil surface at 30, 45, and 60 cm away from the center of wheel track. Sinkage of soil surface over the whole wheel track corresponds to 0.03 m^2 . This is equivalent to a uniform sinkage of 6.0 cm under the tractor wheel.

Figure 11 are plots of predicted iso-bulk density lines from the soil compaction model at three water contents. A value of 3 for concentration factor (ν) in Boussinesq equation was used for this simulation. This is in close approximation to the values that matched the predicted and the measured bulk density (Gupta and Larson, 1980)

Figure 11. Predicted iso-bulk density lines after a pass by an International Harvester 3788 tractor on the surface of an artificial profile of Dolan loam at Morris, MN.

Figure 12. Microrelief height across the wheel track at the soil surface of an artificial profile of Dolan loam at Morris, MN.

profiles under controlled conditions. Figure 11 shows that iso-bulk density lines penetrated deeper at higher moisture contents.

Figure 13 gives the comparison between measured and predicted bulk densities at 0, 15, and 30 cm distance from the center of wheel track. Predicted bulk densities corresponding to three locations and various depths were read from Fig. 11. An adjustment of surface sinkage was made while reading predicted densities from Fig. 11. If the predicted bulk density was less than the initial bulk densities, then the predicted bulk densities were assumed same as the initial bulk densities. In other words, soil compaction model assumes that change in bulk density occurs along the VCC and not along the secondary compression curve.

Maximum change in the measured bulk density from the initial value corresponded to 0.2 Mg m^{-3} at 0-10 cm depth under the wheel track. With increase in depth and away from the center of wheel track, the differences between measured bulk density before and after the passage of tractor decreased. Maximum difference in predicted bulk density between each subsequent water content was equal to 0.04 Mg m^{-3} . In general, predicted bulk densities were slightly higher than the measured values. Maximum difference between measured and predicted ($W = 0.247$) bulk density was equal to 0.13 Mg m^{-3} at 0-10 depth and 15 cm away from the center of wheel track.

Table 9 shows the measured penetrometer resistance profiles at five lateral distances from the center of the wheel track. Each value at each depth is an average of five replications. Like bulk density, the highest penetration resistance was measured in the center of the wheel track and at a depth of 0-5 cm. Penetration resistance generally

Table 9. Measured penetrometer resistance at five locations perpendicular to the path of the tractor in soil bin at Morris, MN.

Depth	Distance from the center of the wheel track, cm				
	0	15	30	45	60
cm	penetrometer resistance, kPa				
0-5	1030 $\pm$ 110†	790 $\pm$ 40	140 $\pm$ 70	310 $\pm$ 60	330 $\pm$ 160
5-10	940 $\pm$ 190	810 $\pm$ 90	310 $\pm$ 40	380 $\pm$ 180	310 $\pm$ 80
10-15	840 $\pm$ 170	780 $\pm$ 110	390 $\pm$ 50	400 $\pm$ 200	310 $\pm$ 80
15-20	740 $\pm$ 80	710 $\pm$ 40	450 $\pm$ 90	320 $\pm$ 60	300 $\pm$ 80
20-25	690 $\pm$ 90	650 $\pm$ 90	430 $\pm$ 60	300 $\pm$ 50	280 $\pm$ 80
25-30	620 $\pm$ 70	590 $\pm$ 70	430 $\pm$ 50	370 $\pm$ 90	280 $\pm$ 60
30-35	590 $\pm$ 60	600 $\pm$ 90	540 $\pm$ 140	480 $\pm$ 210	350 $\pm$ 110
35-40	590 $\pm$ 90	640 $\pm$ 110	560 $\pm$ 240	470 $\pm$ 140	340 $\pm$ 100
40-45	520 $\pm$ 80	550 $\pm$ 100	420 $\pm$ 30	440 $\pm$ 80	380 $\pm$ 160
45-50	540 $\pm$ 80	550 $\pm$ 70	450 $\pm$ 60	460 $\pm$ 90	540 $\pm$ 200
50-55	570 $\pm$ 140	540 $\pm$ 40	540 $\pm$ 180	560 $\pm$ 290	580 $\pm$ 240
55-60	630 $\pm$ 70	560 $\pm$ 140	580 $\pm$ 190	530 $\pm$ 180	550 $\pm$ 90
60-65	650 $\pm$ 240	540 $\pm$ 120	660 $\pm$ 60	500 $\pm$ 140	540 $\pm$ 220
65-70	630 $\pm$ 90	670 $\pm$ 180	700 $\pm$ 140	500 $\pm$ 130	580 $\pm$ 140

† Mean $\pm$ standard deviation.

Figure 13. Comparison between measured and predicted bulk densities of Dolan loam after a pass by an International Harvester 3788 tractor at Morris, MN.

decreased with increasing depth and increasing lateral distance from the center of the wheel track. There was essentially no change beyond 30 cm from the center of the track. The relatively low value (140 kPa) measured within the surface 5 cm at a lateral distance of 30 cm from the center of the track is probably due to a slight outward and upward displacement of soil at the edge of the wheel track.

Figure 14 shows iso-penetrometer resistance lines drawn from data in Table 9 with the depth readings adjusted according to the surface elevations shown in Fig. 12. These iso-lines are qualitatively similar to the predicted iso-bulk density lines shown in Fig. 11. Iso-lines for penetration resistances less than 60 kPa do not show a completed characteristic bulb shape. This probably is due to the abrupt lower boundary of the artificial profile at a depth of about 100 cm. Similar deflected iso-stress lines have been predicted under a tire running over soil underlain by concrete (Cohron, 1971).

Rosemount, MN USA

Table 10 and 11 give the average water content distribution for run #1 and #2 at five locations along the wheel track. Except for top 10 cm of the profile, water content distribution was uniform for all locations. Average water for all locations and depths corresponds to 0.270 and 0.264 g g⁻¹ for run #1 and #2, respectively.

Figure 15 shows the microrelief readings in the wheel track after a passage by the tractor on artificial profile of Waukegan loam (M19) at Rosemount, MN. Soil surface over the wheel track was relatively level for run #1. For run #2 the soil surface near the wheel track had a slope of 4.8%. For both runs, center of wheel track was 40 cm distance on the microrelief meter. Total sinkage was slightly higher for run #1

Table 10. Water content profiles at five locations (replications) along the path of tractor for run #1 in a soil bin at Rosemount, MN.

Depth cm	-----Replications-----				
	I	II	III	IV	V
	water content, g g ⁻¹				
0-10	0.245	0.238	0.244	0.245	0.239
10-20	0.268	0.271	0.266	0.275	0.266
20-30	0.275	0.287	0.273	0.278	0.296
30-40	0.256	0.278	0.288	0.275	0.260
40-50	0.263	0.278	0.295	0.280	0.289
50-60	0.261	0.270	0.293	0.285	0.281
Mean $\pm$	0.262 $\pm$.014	0.270 $\pm$.022	0.276 $\pm$.019	0.272 $\pm$.016	0.272 $\pm$.025

SD = standard deviation

Table 11. Water content profiles at five locations (replications) along the path of tractor for run #2 in a soil bin at Rosemount, MN.

Depth cm	-----Replications-----				
	I	II	III	IV	V
	water content, g g ⁻¹				
0-10	0.233	0.241	0.257	0.236	0.257
10-20	0.254	0.258	0.272	0.260	0.267
20-30	0.259	0.261	0.276	0.280	0.264
30-40	0.275	0.266	0.277	0.277	0.257
40-50	0.274	0.271	0.256	0.269	0.261
50-60	0.280	0.280	0.265	0.274	0.267
Mean	0.262 $\pm$.018	0.263 $\pm$.018	0.267 $\pm$.017	0.266 $\pm$.019	0.262 $\pm$.019

SD = standard deviation

Figure 14. Measured iso-penetrometer resistance lines after one pass by an International Harvester 3788 tractor on the surface of an artificial profile of Dolan loam at Morris, MN.

Figure 15. Microrelief heights across the wheel track at the soil surface of an artificial profile of Waukegan silt loam at Rosemount, MN

(0.07m^2) as compared to run #2 (0.06m^2). This may be expected because of slightly higher water content during run #1. Average sinkage corresponds to 13.4 and 11.6 cm for runs #1 and #2, respectively. Bulk density and water content measurements were made on the right side of the wheel track for run #1 and left side of the wheel track for run #2 (Figure 15).

Figure 16 shows the comparison between measured and predicted mechanical stress at three positions perpendicular to wheel track in an artificially built soil profile of Waukegan silt loam. Predicted mechanical stress were read from iso-pressure lines (Fig. 17) predicted from the soil compaction model. A value of $\nu = 3$ was also selected for these simulations. Because foam covered three of the transducers during run #2, data from only four transducers is included in this report. Comparison shows that measured values were higher for both runs at all positions and depths. Difference between measured and predicted values varied from 10 to 50 and 30 to 70 kPa for run #1 and 2, respectively. Difference between measured and predicted mechanical stress near the surface were much higher in run #2 than run #1. In general, the differences between measured mechanical stress between run #1 and #2 are probably due to the spatial variability of the soil in the bin and to the difficulty of placing transducers horizontally in the profile. During the excavation of transducers after the passage of tractor, we found several problems with the position of transducers in run #2.

Measured bulk densities in Waukegan silt loam after a passage by a tractor are given in Table 12 and 13 for run #1 and #2, respectively. There is little change in measured bulk densities at 35 and 50 cm away from the wheel track. We assumed that bulk densities at 50 cm away from

Table 12. Measured bulk density profiles and soil surface sinkage at five locations perpendicular to the path of the tractor for run #1 in a soil bin at Rosemount, MN.

Depth cm	-----Distance from the center of wheel track, cm-----				
	0	10	25	35	50
	$\rho_b, \text{Mg m}^{-3}$				
0-10	1.35 $\pm$.03†	1.29 $\pm$.04	1.26 $\pm$.12	1.09 $\pm$.06	1.06 $\pm$.06
10-20	1.36 $\pm$.05	1.38 $\pm$.04	1.28 $\pm$.02	1.15 $\pm$.06	1.20 $\pm$.14
20-30	1.31 $\pm$.06	1.33 $\pm$.04	1.31 $\pm$.04	1.10 $\pm$.07	1.18 $\pm$.25
30-40	1.37 $\pm$.10	1.33 $\pm$.07	1.31 $\pm$.02	1.31 $\pm$.07	1.26 $\pm$.03
40-50	1.31 $\pm$.05	1.37 $\pm$.09	1.36 $\pm$.08	1.26 $\pm$.08	1.25 $\pm$.05
50-60	1.30 $\pm$.10	1.34 $\pm$.06	1.29 $\pm$.13	1.32 $\pm$.06	1.22 $\pm$.10
	----- sinkage, cm -----				
	17	15	10.5	0	0

† mean $\pm$ standard deviation

Table 13. Measured bulk density profiles and soil surface sinkage at five locations perpendicular to the path of the tractor for run #2 in a soil bin at Rosemount, MN.

Depth	-----Distance from the center of wheel track, cm-----				
	0	10	25	35	50
cm	$\rho_b, \text{Mg m}^{-3}$				
0-10	$1.43 \pm .06^\dagger$	$1.34 \pm .05$	$1.22 \pm .08$	$1.16 \pm .05$	$1.17 \pm .08$
10-20	$1.40 \pm .03$	$1.41 \pm .02$	$1.36 \pm .04$	$1.22 \pm .10$	$1.11 \pm .06$
20-30	$1.40 \pm .04$	$1.38 \pm .03$	$1.25 \pm .09$	$1.25 \pm .09$	$1.20 \pm .08$
30-40	$1.33 \pm .08$	$1.35 \pm .03$	$1.27 \pm .14$	$1.26 \pm .07$	$1.19 \pm .11$
40-50	$1.31 \pm .03$	$1.27 \pm .10$	$1.31 \pm .05$	$1.31 \pm .10$	$1.32 \pm .12$
50-60	$1.36 \pm .12$	$1.30 \pm .10$	$1.23 \pm .16$	$1.34 \pm .10$	$1.34 \pm .13$
	-----sinkage, cm-----				
	15.5	13.3	6.0	0	0

† mean $\pm$ standard deviation

Figure 16. Comparison between predicted and measured mechanical stresses in an artificial soil profile of Waukegan silt loam during the passage of a John Deere 4640 tractor on the soil surface.

Figure 17. Predicted iso-stress lines in an artificial soil profile of Waukegan silt loam during the passage of a John Deere 4640 tractor on the soil surface.

the center of wheel track corresponds to the initial values. Initial bulk density increased with soil depth in the bin. Also, initial bulk densities were slightly higher for run #2 at 40-50 cm depths. For run #2, measured bulk densities are highest at 0-10 cm depth under the center of wheel track and decrease with soil depth and distance away from the center of wheel track. For run #1, bulk densities are slightly higher at 10 cm away from the center of wheel track compared to the center of wheel tracks at same depths. This slight difference in bulk density profiles at 0 and 10 cm away from the center of wheel may be the reflection of spatial variability in the soil bin. Maximum change in measured bulk density before and after the passage of 3065 kg load corresponds to 0.3 Mg m^{-3} .

Figures 18 and 19 show the comparison between measured and predicted bulk density profiles at four positions perpendicular to the wheel track. Predicted bulk densities were read from the iso-bulk density lines (Fig. 20) predicted from the soil compaction model. Since soil cores for bulk density were taken with reference to the surface of the wheel track, an adjustment in the depth was made for soil sinkage (Fig. 15, Tables 12 and 13) while reading the predicted bulk density from the iso-bulk density diagrams. If predicted bulk density was less than the initial value, we assumed that predicted bulk density was equal to the initial values. In other words, soil compaction model assumes that change in bulk density occur along the VCC and not along the secondary curve. In general, measured bulk densities are slightly higher than the predicted values. Maximum difference between measured and predicted bulk densities corresponds to 0.12 Mg m^{-3} in both runs.

Table 14 shows the measured penetrometer resistance profiles for run

Table 14. Measured penetrometer resistance at five locations perpendicular to the path of the tractor in soil bin at Rosemount, MN, Run #1.

Depth	Distance from the center of wheel track, cm				
	0	10	25	35	50
cm	penetrometer resistance, kPa				
0-5	1160 $\pm$ 90†	880 $\pm$ 240	270 $\pm$ 140	290 $\pm$ 80	340 $\pm$ 80
5-10	660 $\pm$ 80	720 $\pm$ 60	380 $\pm$ 110	310 $\pm$ 50	320 $\pm$ 40
10-15	620 $\pm$ 110	670 $\pm$ 120	440 $\pm$ 90	340 $\pm$ 130	350 $\pm$ 60
15-20	500 $\pm$ 70	600 $\pm$ 50	480 $\pm$ 80	350 $\pm$ 130	390 $\pm$ 80
20-25	460 $\pm$ 60	580 $\pm$ 100	420 $\pm$ 70	370 $\pm$ 60	300 $\pm$ 60
25-30	480 $\pm$ 70	600 $\pm$ 130	410 $\pm$ 80	360 $\pm$ 40	330 $\pm$ 90
30-35	530 $\pm$ 90	590 $\pm$ 130	480 $\pm$ 60	390 $\pm$ 60	380 $\pm$ 90
35-40	490 $\pm$ 70	630 $\pm$ 120	440 $\pm$ 60	440 $\pm$ 90	390 $\pm$ 130
40-45	510 $\pm$ 80	570 $\pm$ 150	490 $\pm$ 110	420 $\pm$ 70	420 $\pm$ 80
45-50	530 $\pm$ 130	700 $\pm$ 270	510 $\pm$ 120	430 $\pm$ 60	430 $\pm$ 100
50-55	550 $\pm$ 80	720 $\pm$ 300	550 $\pm$ 170	580 $\pm$ 190	430 $\pm$ 60
55-60	540 $\pm$ 60	740 $\pm$ 220	590 $\pm$ 160	590 $\pm$ 170	470 $\pm$ 100

† mean $\pm$ standard deviation.

Figure 18. Comparison between measured and predicted bulk densities of Waukegan silt loam after a pass by a John Deere 4640 tractor at Rosemount, MN.

Figure 19. Comparison between measured and predicted bulk densities of Waukegan silt loam after a pass by a John Deere 4640 tractor at Rosemount, MN.

Figure 20. Predicted iso-bulk density lines after a pass by a John Deere 4640 tractor on the surface of an artificial profile of Waukegan silt loam at Rosemount, MN.

#1 at various lateral distances from the center of the wheel track. Each value at each depth is an average of five replications. Run #2 showed similar results as run #1. The data is similar to that from the Morris site (Table 9) in that the highest penetration resistance was directly below the wheel, and resistance decreased with depth and lateral distance from the center of the wheel track. There were significant differences, however. Figure 21 shows iso-penetration resistance lines derived from the data in Table 14, and adjusted according to the surface elevations shown in Fig. 15. The iso-lines show a generally flattened pattern compared to the typical bulbular patterns predicted for iso-stress lines (Fig. 17), and the measured iso-penetration resistance lines for the Morris site (Fig. 14).

Some of the measured differences between the Morris and Rosemount site may be due to the different type of tractors used. The Morris site used a 4-wheel drive tractor with equal front and rear tire size, while the Rosemount runs used a 2-wheel drive tractor with front wheels considerably smaller than the rear wheels. At both sites, all measurements were made after passage of the rear wheel. Thus, the two sites differed in the "pre-treatment" loading by the front wheels. It is not known how this would affect final results.

For both the Morris and Rosemount sites, measured penetration resistances were about an order of magnitude higher than the predicted iso-stress. Qualitatively, the measured iso-penetration resistance lines are sufficiently similar to the predicted iso-stress lines to suggest that the compaction model may, with proper modification, be suitable for predicting penetration resistance and root growth in addition to bulk density and mechanical stress.

Figure 21. Measured iso-penetrometer resistance lines after one pass by a John Deere 4640 tractor on the surface of an artificial profile of Waukegan silt loam at Rosemount, MN.

Nahal Oz, Israel

Gravimetric water content variation in the plot area at the time of compaction could be categorized into three groups, i.e., 0.19-0.20, 0.16-0.17, and $\sim 0.125 \text{ g g}^{-1}$. Accordingly, computer simulation of bulk density profile after compaction were run at three water contents.

Figure 22 shows the iso-penetration resistance lines after one pass by two type of tractors (Ford 6610 and John Deere 4490) at two different speeds. Iso-penetration resistance lines are an average of five replications. Standard deviation of the iso-penetration resistance values varied from 15 to 20 % over the water content range of 0.13 to 0.20 g g^{-1} . This reflects the field variability including the presence of soil clods of relatively large sizes as compared to the size of soil probe.

Iso-penetration resistance lines look like an oblong ellipsoid which would suggest a ν value of 5 to 6. For computer simulation of stress and bulk density profiles (Appendix A, Figs. 1 to 10) we chose a $\nu = 6$. The use of $\nu = 6$ also signifies an existence of vertical shear. Description of shear processes is not complete in the existing soil compaction model. Improvement are needed in the model to include vertical shear and other localized stresses in soil during a passage by farm equipment.

Figures 1 to 10 (Appendix A) show the comparison between measured and predicted soil bulk density profile by three tractor types at two speeds and at three soil moisture contents. Results of all the runs were grouped into three categories of water contents and comparisons were made on 1:1 plot (Figs. 23 to 25). At water contents of 0.19 - 0.20 g g^{-1} , predicted bulk densities were higher than the measured values. Whereas at water contents of 0.16 - 0.17 and 0.12 - 0.13 g g^{-1} ,

Figure 22. Rut imprints and iso-penetration resistance lines after one pass by John Deere 4490 and Ford 6610 tractors at two speeds.

Figure 23. Comparison between measured and predicted bulk density of Nahal Oz silt loam ($W = 0.19, -0.20 \text{ g g}^{-1}$) after one or three passes by three types of tractor at two speeds.

Figure 24. Comparison between measured and predicted bulk density of Nahal Oz silt loam ($W = 0.16 - 0.17 \text{ g g}^{-1}$) after one or three passes by three types of tractors at two speeds.

Figure 25. Comparison between measured and predicted bulk density of Nahal Oz silt loam ($w = 0.12 - 0.13 \text{ g g}^{-1}$) after one or three passes by three types of tractors at two speeds.

predicted bulk densities were lower than the measured values. Following discussion corresponds to each category of the water content.

a. $\underline{W \sim 0.19-0.20 \text{ g g}^{-1}}$

Figure 23 shows that the predicted bulk densities are higher than the measured values under the wheels. On the other hand, computed bulk densities were lower than the measured values at same distances away from the center of the wheel. There are two possible explanations for these differences: 1) ν value changes with depth and laterally away from the center of wheel and 2) some soil compaction was caused by the soil subsidence or shear actions as a result of vibrations during the passage of wheels. Preliminary checks of changing ν in the model did not affect the computed bulk densities under the wheels or some distance away from the center of wheels.

b. $\underline{W \sim 0.16-0.17 \text{ g g}^{-1}}$

Figure 24 shows that the predicted bulk density are lower than the measured values. The scatter of data around 1:1 line in Fig. 24 is somewhat smaller than the scatter in Fig. 23 corresponding to $W \sim 0.19 - 0.20 \text{ g g}^{-1}$. Additionally most of the scatter is in the midranges of bulk densities which also corresponds to the edge of the ruts. Figure 24 suggests that the soil compaction model underpredicts the bulk density at medium or low ground pressures.

c. $\underline{W \sim 0.125\% \text{ g g}^{-1}}$

Figure 25 shows that predicted bulk densities are slightly lower than the measured values both at the mid and low ranges of bulk densities. This scatter is similar to Fig. 23 for $W \sim 0.19-0.20 \text{ g g}^{-1}$.

Differences between measured and predicted bulk densities in Figs. 23 to 25 could be explained as follows:

1. Higher measured bulk densities at low ranges of predicted bulk densities indicate some additional compaction by rearrangement of soil particles or clods. This rearrangement probably occurred from the vibrations of the vehicle during its passage over the seedbed.

2. Compression behavior of field aggregated soil is different than the laboratory measurement on small sieved sample. Table 15 shows the effect of aggregate size on ρ_k and C values at three ranges of water content. Data shows that ρ_k decreases with an increase in the aggregate size and C value change both with water content and aggregate size. Differences in C values are within range measured by Larson et al (1980) and are consistent with their assumption that C values are approximately same between soil matric potential of -10 to -60 kPa. Sensitivity analysis of the model showed that predicted bulk densities are highly dependent on the accuracy of ρ_k as compared to C value.

3. Additional factor that may explain the scatter between measured and predicted bulk density values, is the core sampling procedure for bulk density measurement. Since plot area was deep tilled before the compaction runs, large clods were present in the soil profile at the time of compaction. Small core sample are not effective for measuring bulk density in a cloddy field. This limitation can be overcome by constructing above ground soil bin for compaction run. Soil could be pulverized before piling it in the bins.

Generally, the agreement between predicted and measured bulk densities is rather good. However, improvements are needed to include shear processes and soil subsidence due to vibration in the soil compaction model.

In summary, field test of the soil compaction showed that model slightly under or over predicts the effect of load on mechanical stresses and bulk density profiles. However, variability with depth and between runs was larger than the differences between measured and predicted values. Additional experiment on other soil types and water contents are needed to further field test and improve the model predictions. Imbedding large number of strain gauge transducers in the soil profile will be highly desirable to test the mechanical stress predictions.

Relationship of Compression Parameters to Particle Size Distribution

Soil compaction model described earlier predicts the changes in bulk density profile due to applied load, if the compression characteristics of a soil are known. The objective of this section is to present statistical relationships of compression parameters to easily measured properties (particle size distribution) of soils. The relationships described below are developed from the basic data of 86 samples (excluding M19) as described in Table 1, 2, and 3.

Estimation of ρ_k

Figure 26 shows the relationship between bulk density (ρ_{ks}) at $\sigma_a = 100$ kPa and $S = 50\%$ vs. the percent clay. Since measured ρ_k corresponded to a different degree of saturation for different soils, all values of ρ_{ks} used in the regression equation were standardized to a reference degree of saturation (50%) by interpolation between the measured values. The regression equation is:

$$\rho_{ks} = 1.571 - 7.506 \times 10^{-3} (\%CLAY) - 6.379 \times 10^{-6} (\%CLAY)^2 \quad [6]$$

at $S = 50\%$

$$R = 0.82$$

Figure 26. Relationship of ρ_b at $\sigma_k = 100 \text{ kPa}$ and $S_k = 50\%$ vs. percent clay.

Relationships similar to equation [6] were also developed for other degree of saturation and applied loads of 1000, 500, 200, 150, 100, 75, and 50 kPa. Regression and correlation coefficients of these equations are given in Table 16.

Estimation of Δ_T

Stepwise regression analysis gave the best correlation coefficient of Δ_T with percent silt for the fine-textured soils (Fig. 27) and Δ_T with percent clay for the coarse-textured soils (Fig. 28). Regression equations that described these relationships are:

$$\Delta_T = 5.367 \times 10^{-3} + 2.755 \times 10^{-5}(\%CLAY) - 1.039 \times 10^{-6}(\%SILT)^2 \quad [7]$$

$$R = 0.46$$

for the fine-textured soils and

$$\Delta_T = 3.016 \times 10^{-3} + 2.060 \times 10^{-4}(\%CLAY) - 2.147 \times 10^{-6}(\%CLAY)^2 \quad [8]$$

$$R = 0.56$$

for the coarse-textured soils.

Soils included in the coarse-textured group in Fig. 28 were sand, loamy sand, sandy loam, sandy clay loam, and sandy clay. All others were in the fine-textured group.

Estimation of C

Larson et al. (1980) showed that compression index, C, increases up to a clay content of about 33% and then levels off. Regression equations that described the relationships between C and percent clay are:

$$C = 2.085 \times 10^{-1} + 1.441 \times 10^{-2}(\%CLAY) - 1.494 \times 10^{-4}(\%CLAY)^2 \quad [9]$$

$$R = 0.79$$

Table 16. Regression and correlation coefficient of the relationship of bulk density (ρ) vs. clay content at various degree of saturation (S) and applied stresses (σ_a).

-----Regression coefficient †-----					
S	a	b x 10 ³	c x 10 ⁵	R	SE††
$\sigma_a = 1000 \text{ kPa}$					
30	1.715	3.832	-11.838	.67	.118
40	1.759	4.219	-12.192	.66	.121
50	1.799	4.711	-12.626	.63	.128
60	1.837	5.370	-13.285	.60	.136
70	1.881	5.746	-13.586	.56	.147
80	1.921	6.285	-14.035	.53	.158
90	1.964	6.684	-14.395	.49	.171
$\sigma_a = 500 \text{ kPa}$					
30	1.650	-0.101	-7.918	.75	.107
40	1.687	0.672	-8.724	.73	.111
50	1.729	1.100	-9.083	.70	.119
60	1.772	1.521	-9.458	.67	.127
70	1.811	2.132	-10.005	.63	.138
80	1.854	2.522	-10.357	.58	.150
90	1.894	3.053	-10.846	.55	.163
$\sigma_a = 200 \text{ kPa}$					
30	1.555	-4.775	-3.364	.82	.099
40	1.599	-4.383	-3.697	.80	.103
50	1.638	-3.787	-4.249	.77	.110
60	1.681	-3.399	-4.591	.74	.119
70	1.723	-3.001	-4.899	.71	.130
80	1.761	-2.261	-5.688	.66	.143
90	1.803	-1.866	-5.978	.62	.157
$\sigma_a = 150 \text{ kPa}$					
30	1.529	-6.381	-1.812	.83	.098
40	1.569	-5.841	-2.299	.82	.101
50	1.610	-5.311	-2.793	.80	.108
60	1.651	-4.802	-3.238	.76	.117
70	1.692	-3.678	-4.329	.73	.129
80	1.733	-3.908	-3.979	.69	.141
90	1.774	-3.325	-4.581	.65	.155

$\sigma_a = 100 \text{ kPa}$

30	1.487	-8.443	0.206	.85	.097
40	1.531	-8.056	-0.116	.84	.100
50	1.571	-7.506	-0.638	.82	.107
60	1.609	-6.888	-1.214	.79	.117
70	1.651	-6.473	-1.509	.75	.127
80	1.694	-6.048	-1.894	.71	.140
90	1.734	-5.450	-2.463	.67	.153

 $\sigma_a = 75 \text{ kPa}$

30	1.458	-9.923	1.676	.86	.096
40	1.501	-9.495	1.293	.85	.101
50	1.542	-9.006	0.853	.83	.107
60	1.583	-8.487	0.362	.80	.116
70	1.622	-7.935	-0.133	.77	.127
80	1.666	-7.533	-0.516	.74	.139
90	1.708	-7.138	-0.796	.69	.153

 $\sigma_a = 50 \text{ kPa}$

30	1.421	-12.275	3.985	.87	.099
40	1.459	-11.653	3.436	.86	.102
50	1.501	-11.166	2.997	.84	.108
60	1.545	-10.772	2.617	.82	.117
70	1.582	-10.067	1.967	.79	.128
80	1.624	-9.664	1.637	.76	.139
90	1.666	-9.216	1.255	.72	.153

$$\dagger \quad \rho = a + b(\% \text{CLAY}) + c(\% \text{CLAY}^2)$$

†† SE = Standard error of regression.

Figure 27. Relationship between Δ_T and percent silt for fine-textured soils.

Figure 28. Relationship between Δ_T and percent clay for coarse-textured soils. Soils included in the coarse-textured group were sand, sandy loam, sandy clay loam, and sandy clay.

for the temperate region soils with expanding type clays (Fig. 29) and

$$C = 2.148 \times 10^{-1} + 1.203 \times 10^{-2}(\%CLAY) - 1.161 \times 10^{-4}(\%CLAY)^2 \quad [10]$$

$$R = 0.76$$

for the tropical and semi-tropical region soils with non-expanding type clays (Fig. 30). Equations [9] and [10] contain the data of additional soils and are thus slightly different than those of Larson et al.

(1980). Maximum C value was 0.59 for soils with predominantly expanding type clays and 0.61 for soils containing predominantly non-expanding type clays.

Estimation of σ_n

Critical stress above which soil aggregates shear could be estimated from the applied stress needed to saturate the soil (σ_s) and normalized stress at minimum pore water pressure, σ_n :

$$\log \sigma_c = \sigma_n \cdot \log \sigma_s \quad [11]$$

Figure 31 presents the relationship between σ_n at $U_n = 1$ and the clay content of the soil. The regression equation is:

$$\sigma_n = 5.806 \times 10^{-1} + 8.653 \times 10^{-3}(\%CLAY) - 8.752 \times 10^{-5}(\%CLAY)^2 \quad [12]$$

$$R = 0.74$$

Estimation of θ_m

Figure 32 gives the relationship between degree of saturation at minimum pore water pressure, θ_m , and clay content of the soil. The regression equation is:

$$\theta_m = 3.853 \times 10^{-1} + 7.090 \times 10^{-3}(\%CLAY) - 5.671 \times 10^{-4}(\%CLAY)^2 \quad [13]$$

$$R = 0.67$$

Relationships presented in this section are similar to the relationships described by Larson et al. (1980), Larson and Gupta (1980), and Gupta and Larson (1982). Larson et al. (1980) and Larson

Figure 29. Relationships between compression index and percent clay for Mollisols, Spodosols, Entisols, Inceptisols, and Vertisols.

Figure 30. Relationship between compression index and percent clay for Alfisols, Ultisols and Oxisols.

Figure 31. Normalized stress (σ_n) at $U_n = 1$ vs. percent clay.

Figure 32. Degree of water saturation at minimum pore water pressure, θ_m vs. percent clay.

Gupta (1980) stated that C , θ_m , and σ_n increased with clay content up to about 33% clay and then leveled off. This suggested that above 33% clay, clay fraction dominates the aggregates and pore structure. However, clay type does not seem to be a factor in determining basic pore structure.

Comparison of predicted bulk density profiles using measured and
estimated compression parameters

Figure 33 shows a comparison of predicted bulk density profiles for Waukegan silt loam using the measured and predicted compression parameters. Water content and load during simulation correspond to 0.27 g g^{-1} and 3065 kg , respectively. Bulk density profiles were simulated for $v = 3$ and 4 . Compression parameters were estimated using the particle size analysis of Waukegan silt loam in Figs. 26 thru 32. Broken and solid lines correspond to the use of measured and predicted compression parameters in the compaction model. Comparison of similar iso-bulk density lines in Fig. 33 shows that predicted bulk density at a given depth is higher when estimated compression parameters are used in the compaction model as compared to measured values. In other words, given iso-bulk density lines penetrated deeper when estimated compression parameters were used in the compaction model as compared to measured values. Difference in the depth of penetration of similar iso-line varied between 27 to 37 cm.

A comparison of the measured and estimated compression parameters (Fig. 33, inset Table) indicated that ρ_k and Δ_T are over and under estimated, respectively, from Figs. 26 and 27. The errors in ρ_k and Δ_T result in larger (inset Table) value of ρ_1 from particle size analysis as compared to measured values. Since iso-pressure lines are same for

$W = 0.270 \text{ g g}^{-1}$, Load = 3065 kg

	ρ_k	S_k	C	Δ_T	ρ_1
Measured -----	1.31	55.2	.46	.00451	1.45
Estimated -----	1.39	50.0	.45	.00344	1.60

Figure 33. Comparison of predicted bulk density profiles for Waukegan silt loam using the measured and estimated compression parameters.

both simulation, difference (0.15 Mg m^{-3}) in ρ_1 values from estimated and measured compression parameters is being carried in the predicted iso-bulk density profiles. Further sensitivity analysis showed that predicted bulk density profile from particle size analysis are more sensitive to the errors in ρ_k than Δ_T .

Equation in Fig. 26 shows a standard error of 0.107 Mg m^{-3} in the regression equation. Sensitivity analysis in the above paragraph shows that the standard error of 0.107 Mg m^{-3} in the regression is too large for accurately predicting the iso-bulk density lines in Waukegan silt loam from particle size analysis. Regression equation with lower standard error are needed to describe the relationship of ρ_{ks} vs. particle size fraction. Alternatively, to improve prediction of bulk density profile, one would need to provide a measured value of ρ_k in the soil compaction model.

GUIDES TO ESTIMATE COMPACTION OF WORLD SOILS

Ease of soil compaction implies the rate at which soil compresses with applied load at a given degree of saturation. In other words, ease of soil compaction is a property of the soil and is analogous to the compression index described in earlier sections. Figures 29 and 30 give the relationships of compression index to clay content for soil with expanding and non-expanding clay types, respectively. As stated earlier, these figures show that compression index increases with an increase in clay content up to 33% clay and then level off. Higher values of compression index also mean higher compactability of a soil. However, soils with higher compression index may not necessarily be bad for root and plant growth. In other words, soils with larger compression index mean larger change in soil matrix-water-air

relationships for a given applied load. It is possible that these soils could have less than limiting soil matrix-water-air relationship (lower ρ_b) even after a load has been applied. Hence, it is more appropriate to categorize world soils with respect to soil compaction and not ease of soil compaction. Thus, soil compaction in this report implies comparison of soil matrix-water-air relationships at various applied loads to the limiting values for root and top growth. Definition of compression index, compactability and soil compaction have been described by Bradford and Gupta (1984).

Changes in soil matrix-water-air relationships due to applied load can be shown by plotting ρ_b or porosity vs. degree of saturation at various applied stresses. Figure 34 describes such relationships at various clay contents. These relationships were obtained from the regression equations given in Table 16. By superimposing the values of variables that limit root and top growth, we can estimate the range of applied stresses and degree of saturation above which plant growth will be restricted.

Some of the factors that might limit root and top growth described by Gupta and Larson (1982) are: a) air filled porosities critical for gaseous diffusion, b) stress above which soil aggregates shear, and c) soil resistance above which root growth is negligible. Other factor that may be important for plant growth is the hydraulic properties or drainage characteristics as influenced by applied load. There is not enough information in the literature defining the drainage characteristics or soil resistance that limit root growth. Daddow and Warrington (1983) compiled a list of publications where soil resistance to root growth relationships are described. Using this data base,

Figure 34. Changes in bulk density vs. degree of water saturation diagrams with clay content. AFP line corresponds to 10% air filled porosity.

Figure 34.

Daddow and Warrington (1983) defined the bulk densities that limit root growth at field capacity water content over the textural triangle.

Recently, Gerard, Sexton and Shaw (1982) defined root growth vs. soil strength and critical soil strength vs. clay content relationships for two soil types. Gupta and Larson (1984) also presented penetration resistance vs. bulk density at several water contents for two soils. However, much larger data base is needed to generalize maximum soil strength or critical ρ_b above which root growth is impaired.

Ten percent air filled porosity has been used as a critical value below which gaseous exchange with the atmosphere may restrict biological activities such as root respiration (Gupta and Larson, 1982). This, however, depends upon the type of plant and the level of microbial activity in the soil. If the particle density of a soil is known, bulk density corresponding to 10% air filled porosities can be estimated for a given degree of saturation. The relationship is:

$$\rho_c = (1.0 - \frac{0.1}{(1-S)}) \rho_a \quad [14]$$

where ρ_a is the particle density. In this study, we assumed a particle density of 2.65 Mg m^{-3} . Values of ρ_c from Eq. [14] are plotted in Fig. 34. Thus, for a given applied stress, we can define if the bulk density after compaction, for a soil with known clay content will be greater than the ρ_c at a given degree of saturation. For example, soil with 0% clay content should not be subjected to applied loads of 1000, 500, 200, 150, 100, 75 and 50 kPa at degree of saturation greater than 65, 68, 72, 73, 75, 75, and 77%, respectively. The air-filled porosity of soil with 0% clay will be less than 10% if the above restriction is violated. If

critical values of other limiting variables are available, these could be superimposed on Fig. 34, and limit of loads or degree of saturation could be defined where limiting variables will not be restrictive to root and top growth. Example of this procedure are as follows: Figure 35 and 36 are the bulk density vs. degree of saturation relationships for Miles sandy loam (A 18, A 19, A 20) and Abilene sandy loam soils (M 13, M14, M15), respectively. These relationships were calculated using the particle size analysis of these soils in Table 2 and the regression coefficient of ρ_1 vs. clay content in Table 16. Also, superimposed in Figs. 35 and 36 are the limit of bulk density corresponding to (a) soil resistance when root growth stops, CPR, (b) critical stresses above which soil aggregate shear, CS, and (c) diffusion is nearly zero (airfilled porosity is equal to 10%), AFP. Penetration resistance and bulk densities when root growth is nearly zero for these soils were calculated from regression equations in Table 2 and Fig. 3 and 4 of Gerard, Sexton and Shaw (1982). Stresses above which soil aggregate shear were calculated using the procedure described by Larson and Gupta (1980). These critical stresses were converted to critical bulk density values at which aggregate shear using the compression equation [2]. Shaded area in Figs. 35 and 36 delineate the range of stresses and degree of saturation which is not conducive to excessive compaction. Comparison of Figs. 35 and 36 shows that for a given soil depth, Abilene soil has a narrow working range of water saturation and stresses and thus greater susceptibility to compaction as compared to Miles sandy loam. In general, Figs. 35 and 36 suggest that higher the clay content of a soil, narrower the range of water saturation and stresses at which soil can support traffic without being excessively compacted.

Figure 35. Bulk density vs. degree of water saturation diagrams for three layers of the Miles sandy loam with superimposed criteria of (1) 10% air-filled porosity, AFP; (2) stress critical for shearing soil aggregates, CS; and (3) critical penetration resistance, CPR.

Figure 36. Bulk density vs. degree of water saturation diagrams of three layers of the Abilene sandy loam with superimposed criteria of (1) 10% air-filled porosity, AFP; (2) stress critical for shearing soil aggregates, CS; and (3) critical penetration resistance, CPR.

Additionally, water flow in clay soil will be another factor that may further delineate the susceptibility of these soils to excessive compaction.

Since Fig. 34 is developed from the data base of uniaxial compression test, optimum stresses at corresponding degree of saturation applies to thin soil sections. However, these observations could be extended to soil elements in a soil profile through the use of Frolich's modified Boussinesq equation.

Figure 37 shows the iso-stress lines for various surface loads and soil-tire contact area, of commonly used tractors as simulated from the modified Boussinesq equation. Iso-stress lines corresponding to $v = 3$ and 4 are only given. Table 17 gives the tractor load and tire characteristics used in simulating the iso-stress lines. We assumed that 60% of the total tractor load was on the rear axle and the contact area in the wet soil was 1.75 times the area on the hard surface. Predicted stresses at various depths in Fig. 37 could be used in Fig. 34 to define the bulk density profile after a passage of a tractor with a given load. These bulk density profile could then be delineated into zones of limiting conditions. An example of this has been given by Gupta and Larson (1982). Additionally, Figs. 34 and 37 could also be used to define surface load that is not conducive to excessive compaction for the total profile. An example where lower depths may be more important is a case with higher clay content and higher degree of saturation.

Table 17. Tractor load and wheel characteristics used in simulating mechanical stresses in soils.

Total Load	Load on † Single Rear Wheel	Tire Width	-----Contact Area, m ² -----	
			Hard Surface	Wet Soil ††
kg	kg	m		
3632	1090	0.315	0.101	0.176
4540	1362	0.345	0.126	0.220
5448	1634	0.378	0.132	0.230
6356	1907	0.394	0.154	0.270
7264	2179	0.429	0.150	0.262
8172	2452	0.467	0.168	0.295
9080	2724	0.528	0.161	0.282

† Load on the rear axle was assumed to be 60% of the total load.

†† Contact area in wet soil was 1.75 times the area on Hard Surface.

Load = 1090 kg
Hard Surface
Contact Area = 0.101 m²

Load = 1090 kg
Wet Soil
Contact Area = 0.176 m²

Figure 37. Predicted iso-stress lines for various surface loads and soil-tire contact areas. Surface loads and contact areas used in the simulation correspond to commonly used tractors.

Load = 1362 kg
Hard Surface
Contact Area = 0.126 m²

Load = 1362 kg
Wet Soil
Contact Area = 0.220 m²

Figure 37.

Load = 1634 kg
Hard Surface
Contact Area = 0.132 m²

Load = 1634 kg
Wet Soil
Contact Area = 0.230 m²

Figure 37.

Load = 1907 kg
Hard Surface
Contact Area = 0.154 m²

Load = 1907 kg
Wet Soil
Contact Area = 0.270 m²

Figure 37.

Load = 2179 kg
Hard Surface
Contact Area = 0.150 m²

Load = 2179 kg
Wet Soil
Contact Area = 0.262 m²

Figure 37.

Load = 2452 kg
 Hard Surface
 Contact Area = 0.168 m²

Load = 2452 kg
 Wet Soil
 Contact Area = 0.295 m²

Figure 37.

Load = 2724 kg
Hard Surface
Contact Area = 0.161 m²

Load = 2724 kg
Wet Soil
Contact Area = 0.282 m²

Figure 37.

SUMMARY

Compaction of the soil has become a problem of world-wide concern because of (a) larger tractors, tillage, and harvesting equipment, (b) increasingly intensive tillage practices, and (c) bringing of new lands into cultivation, particularly in the tropics. Increased compaction of the soil results in less plant root proliferation in the soil, lowers the rate of movement of water and air through the soil, reduces the plant stand and consequently decreases yields. It also results in increased energy input in tillage and increased water runoff and soil erosion.

Soils differ in their susceptibility to compaction, and the soils susceptibility varies with water content. Hence the weight of tractors, the size of the tractor wheels, and the inflation pressure need to be varied for different soils so that undue compaction does not occur. This report discusses a soil compaction model that predicts the distribution of applied stresses and bulk densities after a passage by an agricultural vehicle. The model is based on Frolich's modification of Boussinesq equations and the laboratory measured uniaxial compression characteristics. Field testing of the soil compaction model on Waukegan silt loam showed that model underpredicted the effect of load on mechanical stresses and bulk density profiles in this soil. Difference between measured and predicted stresses and bulk densities varied between 10 to 70 kPa and 0 to 0.12 Mg m^{-3} , respectively. Field testing of the model on Dolan loam showed that model overpredicted the bulk density profile by a maximum value of 0.13 Mg m^{-3} . Field validation of the same model on Nahal-Oz silty loam soil (Israel) showed that the

model overestimates the bulk density by a maximum value of 0.23 Mg m^{-3} and the deviations were soil moisture, surface contact pressure and tractor speed depended. The model pointed the need for additional experimentation to define (a) the relationships of v values to soil type, water content, and initial bulk density; and (b) the relative magnitude of compressive-shear stresses during surface applied loads.

Using the compression data base, statistical relationships of compression parameters to soil constituents are developed. These relationships along with the soil compaction model provide a mean to predict iso-bulk density profile after a wheel traffic for soils with unknown compression characteristics. Sensitivity analysis of the compaction model showed that predicted iso-bulk density profiles are sensitive to the errors in the estimated value of bulk density at reference degree of water saturation and reference applied stress, ρ_k .

Based on the uniaxial compression data base, a series of nomographs delineating the potential of a thin section of soil to compaction at various applied loads and degree of saturation were developed. By superimposing limits of gaseous diffusion on these nomographs, excessive loads with corresponding degree of saturation were delineated for world soils. Input needed to use these nomographs is the clay content of soil. It is also suggested that the limiting values of other variable (root growth, hydraulic conductivity) that may define excessive compaction should be superimposed on these nomographs. This would further delineate excessive loads with corresponding degree of saturation that may limit root growth and water flow. Currently, data base defining the limiting values of these variables is not available and further experiments are needed to define these limits. Application

of this procedure is demonstrated by delineating the susceptibility of various layers of Miles and Abilene sandy loam soils to compaction.

Simulated values of the iso-stress profiles after a passage by several commonly used tractors are also included. Procedure is discussed to use predicted iso-stress values in the uniaxial compression equation to predict iso-bulk density profiles for world soils.

The report also discusses the effect of sample size, aggregate size and corn residue on compression characteristics. There was little influence of sample size and aggregate fraction on the compression parameters. Compression tests on soils mixed with various amount and size of corn residue showed that residue addition will be most beneficial in alleviating compaction on silt loam followed by sand and loam soils. However, amount of corn residues (100 bu yield) available on the farm will have little value in reducing susceptibility of soils to compaction, if corn residues are uniformly mixed in the top 15 cm of the soil over the whole field or in the wheel tracks. Because of the elastic nature and bulkiness of corn residues, banding residues in the wheel track at the surface may be more effective in reducing compaction of soils than incorporation of residue in the top 15 cm of soil. Field studies are needed to check this concept.

Draft manuscripts on research studies involving residual effects of soil compaction on soil strength, roughness of seedbed, crop stand and cotton yield is also included in the Appendix of this report. These manuscripts also discuss the trade-off between required draft and soil compaction during field operation on moist soil.

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DEFINITION OF SYMBOLS

- C = Compression index (slope of ρ_b vs. $\log \sigma_a$ curves)
 P = Load at a point, Kg
 R = Correlation coefficient
 S = Degree of saturation, %
 SE = Standard error of regression
 SD = Standard deviation
 S_l = Desired degree of saturation at σ_k , %
 S_K = Degree of saturation at $\sigma_a = 100$ kPa
 U_m = Minimum porewater pressure, kPa
 U_w = Porewater pressure, kPa
 W = Gravimetric water content, $g\ g^{-1}$
 r = Radial distance in the soil profile from point 0, cm
 σ_a = Applied compressive stress, kPa
 σ_c = Critical stress or σ_a corresponding to U_m , kPa
 σ_h = Horizontal normal stress in radial direction, kPa
 σ_n = Normalized stress, $\log \sigma_a / \log \sigma_s$, at U_m
 σ_s = Applied stress at saturation, kPa
 σ_z = Vertical normal stress, kPa
 β = Angle bisected by a vertical line from point 0 with a line to the center of gravity of the volume element under question
 τ = Shearing stress belonging to σ_z and σ_h , kPa
 θ_m = Degree of saturation at minimum porewater pressure
 v = Concentration factor
 Δ_T = Slope of ρ_k vs. S curve
 ρ = Computed bulk density, $Mg\ m^{-3}$
 ρ_a = Soil particle density, $Mg\ m^{-3}$

ρ_b = Generic symbol for bulk density, Mg m^{-3}

ρ_c = Bulk density corresponding to 10% air-filled porosity

ρ_k = Bulk density at an applied stress of 100 kPa and reference degree of saturation, Mg m^{-3}

ρ_l = Bulk density at an applied stress of 100 kPa and S_l degree of saturation, Mg m^{-3}

ρ_{ks} = Bulk density at an applied stress of 100 kPa and 50% degree of saturation, Mg m^{-3}

LIST OF PUBLICATIONS

1. Gupta, S. C. and W. E. Larson. 1982. Predicting soil mechanical behavior during tillage. Chapter 10 In Symposium proceedings "Predicting Tillage Effects on Soil Physical Properties and Processes". American Society of Agronomy Special publication #44, Ed. P. Unger, et al. 151-178.
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1. Gupta, S. C., A. Hadas, W. B. Voorhees, D. Wolf, W. E. Larson, and E. C. Schneider. 1985. Field testing of a soil compaction model. International Conference on soil dynamics, June 17-19, 1985, Auburn, AL.
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FUTURE RESEARCH NEEDS

- A. Additional field testing of the soil compaction model.
- B. Guide to select v values for given set of initial bulk density, water content and soil type.
- C. Quantify the soil and crop parameters (root penetration, bulk density, hydraulic properties, gaseous exchange) that define excessive compaction.
- D. Improvement in the regression relationship of bulk density at reference applied stress to particle size analysis.
- E. Testing and improvement of guidelines on maximal soil surface pressure and range of water content that are not conducive to excessive compaction.
- F. Identify soil structural (bulk density, tortuosity, resistance to penetration, hydraulic properties, gaseous exchange) changes due to artificially and/or naturally caused stresses within the soil profile.
- G. Define the relative importance of shear and compressive stresses during field soil compaction.

DESCRIPTION OF COOPERATION

The research was cooperatively planned at a meeting in Minnesota before data gathering was initiated. Research expertise and experience was shared in the planning process. As information was developed, frequent telephone conversations, written correspondence, and personal exchanges (at professional society meetings) allowed both Israel and American teams to keep fully informed of progress. Modifications in procedures and tentative conclusions were discussed and decisions made. The American team took the lead in laboratory analysis and computer model development. The Israel team confirmed the adequacy of laboratory and field procedures and assumed the lead in field applications.

Draft copies of sections of the final report were prepared by the two teams and reviewed in detail at a meeting in Israel. Interpretation of the data was stressed. Final editing of the report was accomplished following the meeting.

Of prime value in this project was the sharing of expertise and experiences among the Israel and American investigators. The knowledge and experience in the behavior of soils strongly complimented the laboratory determinations. Because soil behavior varies widely depending upon geographical characteristics, the knowledge of temperate region soils by the Americans and of Mediterranean soils by the Israelis was invaluable. This was of particular value in the selection and sampling of world soils, as well as the interpretation of the results.

BENEFITS TO AGRICULTURE

Compaction of the soil by increasingly intensive cropping practices and larger farm tillage and harvesting equipment is a world-wide problem. Compaction of the soil decreases the rate at which water can enter and move through the soil allowing less water to be stored and more water runoff. The erosion resulting from runoff is the chief cause of world soil degradation. Compaction also results in mechanical restriction and lower oxygen levels for root growth which results in lower crop yields.

The research in this report shows that soils vary greatly in their susceptibility to compaction. It is the first study that provides a world-wide basis from which the degree of susceptibility to compaction can be quantified. If the susceptibility to compaction is known, cropping, tillage and harvesting practices can be prescribed to growers which will prevent undue compaction. On those soils where compaction has already taken place, practices can be developed to alleviate the problem. Perhaps the most important benefit is that practices can be recommended on compaction-prone soils which will prevent soil degradation from erosion. The pay-off from the research in this report can be applied world-wide, and will be of major benefit in tropical and semi-tropical regions.

Figure 1. Predicted iso-bulk density lines as compared to measured values after one pass by a John Deere 4490 tractor at two different speeds on a Nahal Oz silt loam soil ($W = 0.19 - 0.20 \text{ g g}^{-1}$).

Figure 2. Predicted iso-bulk density lines as compared to measured values after three passes by a John Deere 4490 tractor at two different speeds on a Nahal Oz silt loam soil ($W = 0.19 - 0.20 \text{ g g}^{-1}$).

Figure 3. Predicted iso-bulk density lines as compared to measured values after one pass by a Ford 6610 tractor at two different speeds on a Nahal Oz silt loam soil ($W = 0.19 - 0.20 \text{ g g}^{-1}$).

Figure 4. Predicted iso-bulk density lines as compared to measured values after three passes by a Ford 6610 tractor at two different speeds on a Nahal Oz silt loam soil ($W = 0.19 - 0.20 \text{ g g}^{-1}$).

Figure 5. Predicted iso-bulk density lines as compared to measured values after one pass by a Case 1370 tractor (dual rear) at two different speeds on a Nahal Oz silt loam soil ($W = 0.19 - 0.20 \text{ g g}^{-1}$).

Figure 6. Predicted iso-bulk density lines as compared to measured values after three passes by a John Deere 4490 tractor at one speed on a Nahal Oz silt loam soil ($W = 0.16 - 0.17 \text{ g g}^{-1}$).

Figure 7. Predicted iso-bulk density lines as compared to measured values after one pass by a Ford 6610 tractor at two different speeds on a Nahal Oz silt loam soil ($W = 0.16 - 0.17 \text{ g g}^{-1}$).

Figure 8. Predicted iso-bulk density lines as compared to measured values after three passes by a Ford 6610 tractor at two different speeds on a Nahal Oz silt loam soil ($W = 0.16 - 0.17 \text{ g g}^{-1}$).

Figure 9. Predicted iso-bulk density lines as compared to measured values after one pass by a Case 1370 tractor (dual rear) at two different speeds on a Nahal Oz silt loam soil ($W = 0.16 - 0.17 \text{ g g}^{-1}$).

Figure 10. Predicted iso-bulk density lines as compared to measured values after one pass by a Ford 6610 tractor at two different speeds on a Nahal Oz silt loam soil ($W = 0.12 - 0.13 \text{ g g}^{-1}$).