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**Development of Guides on the Susceptibility of Soils
to Excessive Compaction**

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W. Larson, P.P. Sharma

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ABSTRACT

Excessive compaction lowers the rate of movement of water and air through soil, decreases plant root proliferation, reduces plant population and consequently decreases crop yields. The objective of this study was to develop a method of characterizing and classifying soil according to their susceptibility to excessive compaction.

To achieve this objective laboratory and field experiments were conducted to study changes in soil physical and root growth properties at various applied stresses and soil wetness conditions at the time of compaction. The soils in the United States study included three coarse-textured and four fine-textured soils from areas where soil compaction is known to be a major problem. The Israel study included nine soils, six of which are known to be compaction prone. Measurements included air permeability, saturated hydraulic conductivity, water retention characteristics, diffusion coefficient, penetration resistance, and corn seedling root growth rate. Based on this data base, two sets of criterion were defined to delineate stresses that cause excessive compaction. First set of criterion assumes a stress is excessive if it completely stops root extension, root respiration or microbial activity. Second set of criterion assumes a stress is excessive if it results in less than optimal conditions for root growth and aerobic microbial activity. An additional criteria included stresses that cause degradation of soil aggregates. These criterion of excessive compaction combined with prediction of iso-stress and iso-bulk density lines for a given surface applied stress provide means to quantify soil's susceptibility to excessive compaction.

In the United States study, the application of the procedure is demonstrated by comparing the susceptibility of three soils from Minnesota, Ohio, and Nebraska. A procedure is also presented for defining maximum loads that are not conducive to excessive compaction for a given soil type and soil wetness conditions. Since the wetness and the applied stress for a given soil type varies due to weather condition and the type of farm equipment, respectively, a strong emphasis is placed in presenting the susceptibility of soil to excessive compaction on a probability basis. The probability of soil wetness is predicted from a Soil Water Balance Model using long term weather records. The Israel study covered the field validation of soil compaction effects on soil water transport properties, soil resistance to cone penetration and root elongation.

DEVELOPMENT OF GUIDES ON THE SUSCEPTIBILITY OF SOILS TO EXCESSIVE COMPACTION

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

INTRODUCTION

Compaction of soil is a problem of worldwide concern because of (1) larger tractors, tillage, and harvesting equipment; (2) increases in intensive cropping practice; and (3) new lands being brought into cultivation, particularly in the tropics. According to McKibben (1971), between 1948 and 1968 the average weight of tractors increased from 2.7 to 4.5 tons. At present, the average is 6.8 tons, with larger units weighing more than 22.4 tons.

With larger, heavier field equipment and wider wheels, compaction of soil has increased at depths below the usual tilled zone of approximately 20 cm (Soehne, 1976; Voorhees et al., 1978) and are further aggravating field soil compaction (Monnier and Goss, 1987; Hakansson et al., 1988). This is of particular concern because it is difficult and costly to loosen the soil at these greater depths. Gill (1971) estimated an annual loss of \$1.18 billion in the United States from soil compaction. This loss results from decreased yields and increased energy costs during field tillage.

Excessive compaction of soil reduces plant root proliferation and lowers the rate of movement of water and air through the soil (Bowen, 1981; Unger et al., 1981; Wolf and Hadas, 1984). Because of the root restriction, the amount of water and nutrients available to a crop are often decreased. Slower internal drainage impedes water redistribution and drain performance, prolongs the time when the soil is too wet for tillage, and decreases crop production.

Limited information is available in the literature about variables and levels that could be used to define excessively compacted soils. Most often, bulk density has been used as an indicator of excessive compaction. In reality, primary indicator of excessive compaction is not the bulk density but those soil physical properties which directly control flow mechanisms or soil mechanical behavior (Gupta et al., 1989a). Gupta et al., (1985,1989a) and Gupta and Allmaras (1987)

suggested using following parameters and their corresponding processes to characterize excessive soil compaction.

- air permeability / gaseous exchange
- diffusion coefficient / gaseous exchange
- hydraulic conductivity / water flow
- pore size distribution and water retention / water flow
- soil penetration resistance / root growth
- soil strength / erosion processes

Currently limited information exists on the effects of compaction on above mentioned soil physical properties and processes. If data bases could be developed on the variables defining excessive compaction, then existing computer models could be used to (1) quantify the effect of applied mechanical stress on soil compaction and (2) separate beneficial from harmful compaction (Gupta and Allmaras, 1989). Output from these models can be summarized to provide simple guidelines for extension specialists and farmers on the susceptibility of soils to excessive compaction. These guidelines should be in terms of (1) maximum pressures a specific soil can withstand for a range of water contents, (2) range of applied pressures and water contents that are not conducive to excessive compaction, (3) soil types and areas in a geographical region that are susceptible to excessive compaction, (4) dominant soil and plant limiting conditions in a given area.

Furthermore, computer models can evaluate management systems that may prevent or alleviate excessive compaction.

OBJECTIVES

A general objective of this research was to develop a procedure for delineating the susceptibility of soils to excessive compaction. Specific objectives were :

- (1) To develop relationships of hydraulic conductivity and air permeability as influenced by soil wetness and applied stress.
- (2) To define relationships of soil resistance to steel probe penetration, bulk density, water

content, root development.

(3) To develop a method of characterizing and classifying the susceptibility of soils to excessive compaction.

LITERATURE REVIEW

Detail literature review on compaction effects on soil physical properties, mechanical behavior of soil during compaction and models to assess the susceptibility of soils to excessive compaction has been given by Gupta et al. (1989a), Gupta et al. (1989b) and Gupta and Allmaras (1987), respectively. The following is a brief outline of criterion and the threshold values used by the authors of this report in their previous studies to define excessive soil compaction.

Excessive Soil Compaction

Gupta and Larson (1982) suggested three variables to define soil and plant limiting conditions arising from soil compaction. These included (1) the air-filled porosity critical for gaseous diffusion, (2) stresses critical for shearing soil aggregates, and (3) soil resistance critical for root growth. Gupta and Larson (1982) assumed 10% air-filled porosity as a critical value below which gaseous exchange with the atmosphere may restrict biological activities. The limit of 10% air-filled porosity was based on the data of Grable and Siemer (1968) that showed that at 10-12% air-filled porosity, diffusivity of oxygen and the rate of corn root elongation was nearly zero.

Critical stresses for shearing soil aggregates was based on the hypothesis of Larson and Gupta (1980) that pore water pressure reverses its direction when the majority of soil aggregates shear during compaction. These authors showed that at minimum pore water pressure, the degree of saturation and the applied stress were unique for each soil. Furthermore, the degree of saturation and the applied stress at the minimum pore water pressure increased with an increase in clay content of the soil.

Soil resistance critical for root growth was based on the relationship of cotton (Gossypium

hirsutum L.) root penetration to penetrometer resistance (Taylor et al., 1966). The relationship showed that at a penetrometer resistance of 2 MPa, the penetration of cotton root through 0.025 m core was zero.

MATERIALS AND METHODS

Laboratory Tests

Bulk samples of surface soils were acquired from seven different locations in the U.S. (Table 1). These soils are representative of areas where soil compaction is a major problem. Samples were air dried, ground and passed through a 2 mm sieve. Particle- size (Table 2) was determined by direct sieving for the sand fraction and by the International pipette method for the silt and clay fractions (Gee and Bauder, 1986). Organic matter content was measured using the wet combustion method (Nelson and Sommers, 1982).

Laboratory tests involved measuring air permeability, diffusion, hydraulic conductivity, water retention, penetration resistance and root growth on soil cores that have been compressed at four applied stresses and were at four initial water contents. The procedure for core preparation involved saturating overnight a loosely packed large (2 to 3 kg) sample of air dried soil on a pressure plate and then desorbing the saturated soil in a pressure plate apparatus to a known matric potential. The equilibrating potential were -33 , -100, -500, -1500 kPa.

Three cylinders (7.6-cm dia. by 7.6 cm high) were taped together, and a known weight of the moist soil was compressed at both ends using an Instron Universal Testing Machine. Soil was compressed to a given mechanical applied load at a rate of 1 cm/hr. Applied mechanical load treatments were 0.225, 0.450, 0.900, and 1.800 kN. These loads translated to applied mechanical stresses of 49.3, 98.7, 197.4, and 394.7 kPa for a 7.6 cm dia. core. The middle core separated from the end cores using a thin wire was used for soil physical measurements. Gupta et al. (1979) showed that cores compressed using the above procedure had minimal variation in soil packing along the length of the core. Bulk densities of the middle core were calculated from the mass of the

Table 1. Soil type, soil family and location of seven soils used in the Soil Compaction Study.

Soil Type	Soil Family	State	Contact Person/Location
Blount	Fine, Illitic, Mesic Aeric Ochraqualfs	Ohio	Dr. Norman R. Fausey USDA-ARS, Columbus, OH
Cecil	Clayey, Kaolinitic, Thermic Typic Hapludult	Alabama	Dr. J.H. Taylor USDA-ARS, Auburn, AL
Holtville	Clayey over loamy Montmorillonitic (Calcareous), Hyperthermic Typic Torrifluvent	California	Dr. Alan Mitchell USDA-ARS, Brawley, CA
Miles	Fine-loamy, Mixed, Thermic Udic Paleustalf	Texas	Dr. C.J. Gerard Texas Expt. Sta., Vernon, TX
Norfolk	Fine-loamy, Siliceous, Thermic Typic Paleudult	South Carolina	Dr. Warren J. Buscher USDA-ARS, Florence, SC
Sharpsburg	Fine, Montmorillonitic Mesic typic Argiudoll	Nebraska	Dr. Alice Jones Univ. of NE, Lincoln, NE
Webster	Fine-loamy, Mixed, Mesic Typic Haplaquoll	Minnesota	Dr. Gyles Randall Univ of MN, Waseca, MN

Table 2a. Sand, silt, clay and O.C. content of seven soils used in the Soil Compaction Study.

Soil Type	Sand -----	Silt -----	Clay -----	OC -----	Texture
Blount	15.9	56.2	27.9	2.7	SICL
Cecil	78.5	16.7	4.8	0.6	LS
Holtville	11.7	41.6	46.7	1.0	SIC
Miles	82.5	11.5	6.0	0.2	LS
Norfolk	75.4	20.4	4.2	0.7	LFS
Sharpsburg	6.4	56.6	37.0	2.1	SICL
Webster	41.3	30.3	28.4	2.9	CL

Table 2b. Detailed particle size analysis of seven soils used in the Soil Compaction Study.

Soil Type	Diameter, mm										
	2-1	1-0.5	.5-.42	.25-.42	.1-.25	.074-.1	.05-.074	.03-.05	.002-.03	<.002	
Blount	0.1	1.0	0.7	2.4	5.6	2.6	3.5	12.5	43.7	27.9	
Cecil	5.7	12.0	10.9	17.6	19.2	7.4	5.7	7.4	9.3	4.8	
Holt- ville	0.0	0.1	0.1	0.1	1.4	2.7	7.3	10.8	30.8	46.7	
Miles	0.1	3.6	4.4	20.1	35.3	9.0	10.0	9.8	1.7	6.0	
Norfolk	0.5	1.9	1.1	2.7	36.4	23.6	9.2	10.0	10.4	4.2	
Sharps- burg	0.0	0.0	0.1	0.2	0.4	0.3	5.4	35.5	21.1	37.0	
Webster	1.1	3.8	2.1	7.8	17.5	4.9	4.1	10.7	19.6	28.4	

wet soil in the core, soil water content and the core volume.

Air permeability : The first measurement was the permeability of the soil core to air flow. Air permeability was measured using the constant volume technique of Kirkham (1946). The procedure involved setting the compressed core in a metal assembly (Fig. 1) and tightening the butterfly nuts so that no leakage of air occurred at the rubber stopper and the O-ring seal connecting the air tank with the core. The tank was filled with small amount of air from the wall-mounted air pressure line and allowed to equilibrate for a few minutes. The tank volume corresponded to 113.6 liters. On an average the initial tank pressure corresponded to about 25 to 30 cm air pressure. After equilibration of the tank pressure, the valves were open and the fall in the manometer reading (y) was recorded as a function of time. Air permeability was calculated from Eq. [1] using the slope (S) of the $\ln y$ vs. time curve.

$$K_a = \frac{L V S N}{A P} \quad [1]$$

where K_a is the air permeability of soil to air, cm^2 ; L is the length of soil column; V is the volume of tank; N is the viscosity of air at the room temperature; A is the cross sectional area of the sample; and P is the atmospheric pressure.

Saturated hydraulic conductivity : After the air permeability measurement, the soil core was placed in a tank of water and saturated over night. Saturated hydraulic conductivity was then measured from the flow rates using the constant head technique (Klute and Dirksen, 1986). For cores where the flow rates were small, saturated hydraulic conductivity was measured with the falling head technique (Klute and Dirksen, 1986).

Water retention characteristics : After the hydraulic conductivity measurement, saturated cores were carefully transferred to wet pressure plates and saturated overnight again. The saturated cores were then desorbed to a given potential in the pressure plate apparatus. The desorption potentials corresponded to -5 , -10 , and -100 kPa. Water contents at -500 and -1500 kPa were

Figure 1. Experimental setup for air permeability measurements.

estimated from the measured water retention of loosely packed large samples of soil used for core preparation. This estimation procedure assumed that the water content by weight at -500 and -1500 kPa of packed and loose samples were nearly same.

Diffusion coefficient : Diffusion coefficients were measured by Xu (1990) on the freshly prepared soil cores using the procedure of Rloston (1986). The experimental set-up (Fig. 2) consisted of a plexiglass chamber connected to a pump and covered with a sliding lid. The pump facilitated the uniform mixing of gases in the chamber. The lid was tightly held to the chamber with clamps. Initially, the chamber was filled with an inert gas (argon) and an initial sample of gases in the chamber was analyzed for the concentration of argon, oxygen and nitrogen. After the filling of chamber with argon, the lid was slid so that one face of the soil core was exposed to the argon gas in the chamber. A rubber O-ring and grease on the sliding lid prevented the direct mixing of gases with outside air. Starting at time zero, gases in the chamber were analyzed for oxygen, nitrogen and argon at regular intervals using gas chromatography. It is presumed that the changes in the concentration of chamber argon is due to diffusion of oxygen and nitrogen through soil pores. Diffusion coefficient (D) was calculated using an iterative scheme on the first ten terms of the solution (Eq. [2]) of the diffusion equation (Xu ,1990).

$$\frac{C_L - C_S}{C_0 - C_S} = \sum_{n=1}^{\infty} \frac{2 h \exp (-D \alpha_n^2 t / E_g)}{L (\alpha_n^2 + h^2)} \quad [2]$$

where C_S , C_L is the concentration of nitrogen in the atmosphere and chamber, respectively; C_0 is the nitrogen concentration in the chamber at time zero; $h=Eg/aEc$, Ec is the air content of the chamber ($1.0 \text{ m}^3 \text{ air/ m}^3 \text{ chamber}$), a is the volume of the chamber per unit area of the soil column; α_n with $n=1,2,3...$ are the positive roots of $(\alpha_n L)\tan(\alpha_n L) = hL$; d = diffusion coefficient; t is time; and L is the length of the column. The correct value of D was the one yielding the smallest total sum of squared deviation between the measured and the calculated nitrogen concentrations in the chamber at various times. Additional details of the procedure are given in Xu (1990).

Figure 2. Experimental setup for measuring gas diffusion coefficient in soil.

Penetration resistance : A separate sets of cores were prepared for penetration resistance measurements. Resistance of the soil to penetration of a steel probe was measured by forcing the probe (diameter=0.376 cm , $\alpha=30^\circ$) through the packed soil cores. The rate of penetration (3.0 cm / hr) was controlled by the movement of the crossbar in the Instron Universal Testing Machine. Details of the procedure have been given by Voorhees et al. (1975).

Root elongation : Root elongation rates were measured by planting pre-germinated corn (Zea mays, Pioneer 3790) seedlings into the soil cores. The seeds were pre-germinated between the moist towels at a constant temperature of 25 °C until the radicle was about 1 cm in length. The initial root length was recorded and the radicle of one seedling per core was placed in the preformed hole corresponding to the initial root length and diameter. The seedling was held in place on the top of the soil core with a rubber band. The cores were loosely wrapped in plastic bags to retard evaporation, and then placed in a darkened chamber at a temperature of 25 °C. After a suitable growth period (not exceeding 72 hours), the soil core was gently broken apart, the root extracted and the final root length measured. Root growth rates in mm/hr were then calculated and correlated with various soil physical properties measured on identically prepared soil cores.

RESULTS AND DISCUSSION

Based on the similarity in the behavior of soils to applied stress, the results and discussion of all seven soils is grouped into two groups: (a) coarse-textured soils and (b) fine-textured soils. A brief summary of the results describing the similarity among soils of each group is described at the start of each section. The effects of soil matric potential at the time of compaction, in the following discussion are in terms of the differences in soil wetness.

Coarse-Textured Soils

The soils under this group are Cecil, Miles, and Norfolk loamy sands. Briefly bulk density

increased whereas differences in the other mechanical properties like porosity, void ratio, and air-filled porosity decreased with an increase in applied stress. The effect of soil wetness at the time of compaction on soil mechanical properties was minimal. Water retention characteristics of each soil were nearly similar irrespective of applied stress and soil wetness at the time of compaction. Both air permeabilities and saturated hydraulic conductivities decreased with an increase in applied stress. Air permeabilities and saturated hydraulic conductivity linearly increased with an increase in air filled porosity and total porosity, respectively. Effect of soil wetness at the time of compaction on both air permeabilities and saturated hydraulic conductivities was negligible. Resistance of soils to cone penetrometer increased with an increase in applied stress, with an increase in bulk density and with a decrease in soil wetness. Penetration resistance of all three soils at four applied stresses and four soil matric potentials was less than 2 MPa, a value identified in the literature as a critical limit above which the root growth stops. Root growth of corn seedling decreased with an increase in applied stress, bulk density or penetration resistance. Root growth decreased with a decrease in soil matric potential. At soil matric potential of -500 and -1500 kPa, root growth was always less than 0.1 cm hr^{-1} for all applied stresses.

Following discussion relates to the data of each individual soils in the coarse textured group.

Cecil loamy sand: The effect of applied stress on bulk density, porosity, void ratio and the air porosity for Cecil loamy sand at four soil matric potentials is plotted in Fig. 3. At any given applied stress, the effect of soil wetness (varying soil matric potential) on bulk density, porosity and void ratio is minimal. Only at the higher applied stress (395 kPa) there was a slight increase in the bulk density (thus a slight decrease in porosity and void ratio) with an increase in soil matric potential. At a given applied stress, the air filled porosity decreases with an increase in soil matric potential. The decrease in air-filled porosity is much greater between soil matric potentials of -33 and -100 kPa as compared to -100 and -500 and -500 and -1500 kPa.

Figure 4 shows the effect of applied stress and the soil matric potential at the time of compaction on water retention characteristics. For a given soil matric potential at the time of applied stress, the effect of applied stress on water retention characteristics for Cecil loamy sand is negligible. This is

Figure 3. Effect of applied stress on bulk density, porosity, void ratio and air porosity of Cecil loamy sand at four soil matric potentials.

Figure 4. Effect of applied stress (σ_a) and soil matric potential at the time of compaction (Ψ_c) on water retention characteristics of Cecil loamy sand.

expected because the differences in soil wetness between four matric potentials (-33, -100, -500, -1500 kPa) at the time of compaction are small ($\theta = 0.08$ to 0.04 cm cm^{-1}).

The effect of applied stress on air permeability at four soil matric potentials is shown in Fig. 5a for Cecil loamy sand. In general, the air permeability decreases both with an increase in applied stress and with a decrease in soil matric potential at the time of compaction. At any given applied stress, the air permeability is slightly higher for soils compacted at a soil matric potential of -33 kPa. As expected, the air permeability increases with an increase in air porosity (Fig. 5b). Similarly, at any given air-filled porosity, the air permeability is slightly higher for soils compacted at -33 kPa. Relative to the errors involved in this measurement, the differences in air permeability due to applied stress and soil matric potential at the time of compaction are small.

In Fig. 6a is shown the effect of applied stress and soil matric potential at the time of compaction on saturated hydraulic conductivity. In general, saturated hydraulic conductivity decreases with an increase in applied stress. At a given applied stress, there is no definite effect of soil matric potential at the time of compaction on saturated hydraulic conductivity. Figure 6b shows that saturated hydraulic conductivity of Cecil loamy sand is uniquely related to total porosity irrespective of applied stress and the soil matric potential at the time of compaction. Saturated hydraulic conductivity increases with an increase in total porosity.

Resistance to cone penetrometer as a function of applied stress and soil matric potential at the time of compaction for Cecil loamy sand is shown in Fig. 7a. As expected, penetration resistance increases both with an increase in applied stress and a decrease in soil matric potential. The increase in soil resistance to cone penetration is much higher due to applied stress than due to soil matric potential at the time of compaction. The maximum penetration resistance of Cecil loamy sand at all four soil matric potentials and four applied stresses is less than the critical penetration resistance of 2 MPa (Taylor et al., 1966) and >7 MPa (Gerard et al., 1982) when root growth stops. Figure 7b shows the relationship between penetration resistance and bulk density. Again the penetration resistance increases with an increase in bulk density and with a decrease in soil matric potential at the time of compaction.

Figure 5. Effect of applied stress on air permeability of Cecil loamy sand at four soil matric potentials, Ψ , (Fig. 5a) and relationship between air permeability of Cecil loamy sand and air porosity at four soil matric potentials (Fig. 5b).

Figure 6. Effect of applied stress on saturated hydraulic conductivity of Cecil loamy sand at four matric potentials, Ψ , (Fig. 6a) and relationship between saturated hydraulic conductivity of Cecil loamy sand and total porosity at four soil matric potentials (Fig. 6b).

Figure 7. Effect of applied stress on resistance of Cecil loamy sand to the penetration of steel probe at four soil matric potentials, Ψ , (Fig. 7a) and relationship between penetration resistance of Cecil loamy sand and bulk density at four soil matric potentials (Fig. 7b).

In Fig. 8 are shown the root growth of corn seedling as a function of applied stress (Fig. 8a), bulk density (Fig. 8b), and penetration resistance (Fig. 8c) at four soil matric potentials at the time of compaction. As expected, at a given soil matric potential, the root growth is maximum at low applied stress, low bulk density, or low penetration resistance. Also, at any given applied stress, bulk density or penetration resistance, the root growth decreases with a decrease in soil matric potential at the time of compaction. At lower soil matric potentials (-500 and -1500 kPa), the root growth is low and nearly constant (0.02 to 0.05 cm hr^{-1}). Considering 0.1 cm hr^{-1} as a minimum rate of root growth, applied stress causing excessive compaction correspond to stresses greater than 180 kPa at soil matric potential of -33 kPa, greater than 70 kPa at soil matric potential of -100 kPa, and greater than 49 kPa at soil matric potentials of -500 and -1500 kPa. Although there is no limit of minimum root growth rates at which the crops will survive in the field, it was assumed that laboratory measured root growth rates of 0.1 cm hr^{-1} and below will be difficult to sustain for long periods in the field. In other words, laboratory measured root growth rates of less than 0.1 cm hr^{-1} is used as another criteria of excessive compaction.

Miles loamy sand: The variation in physical characteristics of Miles sandy loam as influenced by applied stress and soil matric potential at the time of compaction are similar to that of Cecil loamy sand. Bulk density increases with an increase in applied stress, however, the effect of soil wetness at the time of compaction has little influence on bulk density (Fig. 9a). Similarly, porosity (Fig. 9b), void ratio (Fig. 9c) and air porosity (Fig. 9d) decrease with an increase in applied stress but again the effect of soil matric potential at a given applied stress is minimal on changes in porosity and void ratio.

Like Cecil loamy sand, the effect of applied stress and soil matric potential at the time of compaction is also negligible on soil water retention characteristics of Miles loamy sand (Fig. 10). Air permeability decreases with an increase in applied stress but there is no difference in air permeability due to variation in soil wetness at the time of compaction (Fig. 11a). In general, air permeability increases with an increase in air-filled porosity and there is some difference in air permeabilities due to a variation in soil wetness for a given air-filled porosity (Fig. 11b). Saturated

Figure 8. Relationship between corn seedling root growth and applied stress (Fig. 8a), bulk density (Fig. 8b), and penetration resistance (Fig. 8c) of Cecil loamy sand at four soil matric potentials, Ψ .

Figure 9. Effect of applied stress on bulk density, porosity, void ratio and air porosity of MILES loamy sand at four soil matric potentials.

Figure 10. Effect of applied stress (σ_a) and soil matric potential at the time of compaction (Ψ_c) on water retention characteristics of Miles loamy sand.

Figure 11. Effect of applied stress on air permeability of Miles loamy sand at four soil matric potentials, Ψ , (Fig. 11a) and relationship between air permeability of Miles loamy sand and air porosity at four soil matric potentials (Fig. 11b).

hydraulic conductivity decreases with an increase in applied stress (Fig. 12a). At a given applied stress, saturated hydraulic conductivity of Miles loamy sand compacted at a soil matric potential of -33 kPa is slightly higher than the corresponding values at -100, -500, and -1500 kPa. As expected, saturated hydraulic conductivity of Miles sandy loam also increases with an increase in total porosity (Fig. 12b). At any applied stress, the difference in saturated hydraulic conductivity between cores compacted at a soil matric potential of -100, -500, -1500 kPa are minimal but the saturated hydraulic conductivity of soil compacted at -33 kPa is slightly higher than the corresponding values at other soil matric potentials.

Diffusion coefficient for Miles loamy sand decreases with an increase in applied stress, however, the differences in soil diffusion coefficient due to applied stress or due to a variation in soil matric potentials at the time of compaction (Fig. 13a) are relatively small (0.1). Diffusion coefficient of Miles loamy sand increases with an increase in air-filled porosity and is nearly similar for various soil matric potential at the time of compaction (Fig. 13b).

Resistance of Miles sandy loam to cone penetrometer increases with an increase in applied stress but the differences due to soil matric potential at the time of compaction are relatively small (Fig. 14a). Penetration resistance increases with an increase in bulk density but the differences due to soil matric potential at the time of compaction are nearly absent (Fig. 14b). Resistance of Miles sandy loam to cone penetrometer is less than the critical limit of 2 MPa for all combination of four applied stresses and four soil matric potentials at the time of compaction.

At any soil matric potential, root growth decreases slightly with an increase in applied stress, bulk density and penetration resistance (Fig. 15). Also, at any applied stress, bulk density or penetration resistance, root growth increases with an increase in soil matric potential at the time of compaction. Considering a critical root growth rate of 0.1 cm hr^{-1} , the applied stresses that will cause excessive compaction correspond to stresses greater than 395, 130, 49, and 49 kPa at soil matric potentials of -33, -100, -500 and -1500 kPa, respectively.

Norfolk loamy sand: The effect of applied stress on soil physical properties of Norfolk loamy

Figure 12. Effect of applied stress on saturated hydraulic conductivity of Miles loamy sand at four matric potentials, Ψ , (Fig. 12a) and relationship between saturated hydraulic conductivity of Miles loamy sand and total porosity at four soil matric potentials (Fig. 12b).

Figure 13. Effect of applied stress on diffusion coefficient of Miles loamy sand at four soil matric potentials, Ψ , (Fig. 13a) and the relationship between diffusion coefficient and air porosity of Miles loamy sand at four soil matric potentials (Fig. 13b).

Figure 14. Effect of applied stress on resistance of Miles loamy sand to the penetration of steel probe at four soil matric potentials, Ψ , (Fig. 14a) and the relationship between penetration resistance of Miles loamy sand and bulk density at four soil matric potentials (Fig. 14b).

Figure 15. Relationship between corn seedling root growth and applied stress (Fig. 15a), bulk density (Fig. 15b), and penetration resistance (Fig. 15c) of Miles loamy sand at four soil matric potentials, Ψ .

sand is similar to that of Cecil and Miles Loamy sands. At a given soil matric potential, bulk density (Fig. 16a) increases whereas porosity (Fig. 16b), void ratio (Fig. 16c), and air porosity (Fig. 16d) decreases with an increase in applied stress. The effect of soil matric potential at the time of compaction on soil mechanical parameters is relatively small. At a given applied stress, the bulk densities, porosities, void ratios, and air-filled porosities of Norfolk loamy sand between soil matric potentials of -33 and -1500 kPa and between soil matric potentials of -100 and -500 kPa are nearly similar. This suggested that the soil wetness between soil matric potentials of -100 and -500 kPa results in the maximum soil compaction.

Soil water retention characteristics of Norfolk loamy sand are nearly same irrespective of applied stress and the soil wetness at the time of compaction (Fig. 17). Air permeability decreases with an increase in applied stress but the effects of soil wetness at the time of compaction on air permeability are minimal (Fig. 18). The air permeability at applied stress of 197 kPa and soil matric potential of -500 is slightly higher. This data point could be an anomaly in our measurements and additional measurements will be made to check this data point. Similar to other coarse textured soils, the air permeability of Norfolk loamy sand also decreases with an increase in air-filled porosity (Fig. 18b).

Saturated hydraulic conductivity of Norfolk loamy sand decreases with an increase in applied stress but the effects of soil wetness at the time of compaction on saturated hydraulic conductivity are minimal (Fig. 19a). Saturated hydraulic conductivity decreases with an increase in total porosity and is uniquely related irrespective of applied stress and soil wetness at the time of compaction (Fig. 19b).

Resistance of Norfolk loamy sand to cone penetrometer increases with an increase in applied stress and a decrease in soil matric potential (Fig. 20a). The differences in penetration resistance due to applied stress are much greater than due to a variation in soil wetness. Penetration resistance as a function of bulk density and soil matric potential (Fig. 20b) is nearly similar to that of Fig. 20a. For all four applied stresses and four soil matric potentials at the time of compaction, penetration resistance was less than the critical limit of 2 MPa when root growth stops. As expected root

Figure 16. Effect of applied stress on bulk density, porosity, void ratio and air porosity of Norfolk loamy sand at four soil matric potentials.

Figure 17. Effect of applied stress (σ_a) and soil matric potential at the time of compaction (Ψ_c) on water retention characteristics of Norfolk loamy sand.

Figure 18. Effect of applied stress on air permeability of Norfolk loamy sand at four soil matric potentials, Ψ , (Fig. 18a) and relationship between air permeability of Norfolk loamy sand and air porosity at four soil matric potentials (Fig. 18b).

Figure 19. Effect of applied stress on saturated hydraulic conductivity of Norfolk loamy sand at four matric potentials, Ψ , (Fig. 19a) and relationship between saturated hydraulic conductivity of Norfolk loamy sand and total porosity at four soil matric potentials (Fig. 19b).

Figure 20. Effect of applied stress on resistance of Norfolk loamy sand to the penetration of steel probe at four soil matric potentials, Ψ , (Fig. 20a) and the relationship between penetration resistance of Norfolk loamy sand and bulk density at four soil matric potentials (Fig. 20b).

growth decreases with an increase in applied stress (Fig. 21a), bulk density (Fig. 21b), and penetration resistance (Fig. 21c). At a given applied stress, root growth is higher for soil matric potential of -33 kPa and decreases with a decrease in soil matric potential. Considering 0.1 cm hr^{-1} as a critical rate of root growth, the excessive applied stresses are greater than 180, 105, 49 and 49 kPa at soil matric potential of -33, -100, -500 and -1500 kPa, respectively.

Fine-Textured Soils

The soils in this group are Blount silty clay loam, Holtville silty clay, Sharpsburg silty clay loam, and Webster clay loam. The trends in the mechanical and physical properties of these soils with respect to applied stress were similar to those of coarse-textured soils but the magnitude of the effect was much greater. Briefly, the bulk density increased and the other mechanical properties decreased with an increased in applied stress. At a given applied stress, the effect of soil matric potential at the time of compaction on mechanical properties varied with soil type. For example, Webster and Blount soils with about 28 percent clay had a very small effect of soil wetness on soil mechanical properties whereas Sharpsburg and Holtville with 37 and 47 percent clay, respectively, the effect of soil wetness on soil mechanical properties was much greater. At a given soil wetness at the time of compaction, water retention increased with an increase in applied stress, however, the effect of soil wetness varied with soil type and the matric potential at the time of compaction. In general, increasing the applied stress from 49 kPa to 395 kPa increased the water retention by about 10 to 15 percent.

Both air permeability and saturated hydraulic conductivity decreased with an increase in applied stress but the effect of soil wetness at the time of compaction varied with soil type. Except at low values of air-filled porosity and total porosity, both air permeability and saturated hydraulic conductivity of each soil were uniquely related to air-filled porosity and total porosity, respectively. Diffusion coefficient measured on Blount and Sharpsburg soils decreased with an increase in applied stress and soil wetness. Diffusion coefficient increased with an increase in air-filled porosity and was also uniquely related to air-filled porosity irrespective of applied stress and soil matric potential at the time of compaction.

Figure 21. Relationship between corn seedling root growth and applied stress (Fig. 21a), bulk density (Fig. 21b), and penetration resistance (Fig. 21c) of Norfolk loamy sand at four soil matric potentials, Ψ .

Resistance of all four fine textured soils to steel probe penetration increased with an increase in applied stress and bulk density, however, the effect of soil wetness at the time of compaction was small on low clay content soils (Webster and Blount). Except for applied stress of 395 kPa at a soil matric potential of -33, -100, -500 kPa, penetration resistance was always less than 2 MPa, a value above which root growth stops. Root growth decreased with an increase in applied stress, bulk density, penetration resistance and soil matric potential. Root growth rate was always less than 0.1 cm hr^{-1} when the applied stress was 395 kPa and the soil matric potential was less than -500 kPa. Root growth rate of Holtville was less than 0.1 cm hr^{-1} for all applied stresses and soil matric potentials.

The following discussion details the effect of applied stress and soil matric potential on individual fine textured soils used in this study.

Blount silty clay loam: Bulk density (Fig. 22a) increases whereas the other soil mechanical properties like porosity (Fig. 22b), void ratio (Fig. 22c), and air-filled porosity (Fig. 22d) decreases with an increase in applied stress. At any given applied stress, the effect of soil wetness on soil mechanical properties is negligible for soil matric potential of -100, -500, and -1500 kPa. At soil matric potential of -33 kPa, bulk density is higher, and porosity and void ratio are lower than the corresponding values at other soil matric potentials when the applied stress is less than 197 kPa. At any given applied stress, air porosity increases with an decrease in soil matric potential.

At any given soil matric potential, volumetric water content increases with an increase in applied stress, however, at a given applied stress, soil wetness at the time of compaction has a minimal effect on soil water retention (Fig. 23). In some instances, the water contents at -500 and -1500 kPa are slightly higher than the water content at -100 kPa. The reason for this difference is two set of differing data bases. The water retention at -500 and -1500 kPa was measured in loosely packed samples whereas the water retention at soil matric potentials $> -100 \text{ kPa}$ is measured on cores that have been compressed at a known applied stress.

Figure 22. Effect of applied stress on bulk density, porosity, void ratio and air porosity of Blount silty clay loam at four soil matric potentials.

Figure 23. Effect of applied stress (σ_a) and soil matric potential at the time of compaction (Ψ_c) on water retention characteristics of Blount silty clay loam.

In general, the air permeability decreases with an increase in applied stress and a decrease in soil wetness (Fig. 24a). On an average, air permeability decreases by about six fold when the applied stress increases from 49 to 395 kPa. The decrease in air permeability due to increase in soil matric potential is much less (two to three fold). Although the air permeability of Blount soil compacted at a soil matric potential of -500 kPa is higher than that of the soil compacted at -1500 kPa, the differences are within the range of errors encountered in this measurement. Air permeability is uniquely related to air porosity irrespective of applied stress and soil wetness (Fig. 24b). Air permeability increases with an increase in air porosity.

Saturated hydraulic conductivity also decreases with an increase in applied stress, however, there is no definite trend with soil matric potential at the time of compaction (Fig 25a). Saturated hydraulic conductivity is also uniquely related to total porosity irrespective of applied stress or soil wetness at the time of compaction (Fig. 25b).

In general, diffusion coefficient decreases with an increase in applied stress and soil wetness (Fig. 26a). Also, the diffusion coefficient is uniquely related to air-filled porosity and increases with an increase in air-filled porosity (Fig. 26b).

Resistance of Blount silty clay to cone penetrometer increases with an increase in applied stress but the rate of increase was less than those of coarse textured soils (Fig. 27a). The effects of soil matric potential on penetration resistance are relatively small but can not be generalized across all applied stresses. Penetration resistance also increases with an increase in bulk density and can be described with a single relationship up to a bulk density of 1.3 Mg m^{-3} , for all four applied stresses and four levels of soil wetness (Fig. 27b). Penetration resistance at a combination of four applied stresses and four soil wetness levels is well below 2 MPa value considered to limit the root growth.

Root growth decreases with an increase in applied stress, bulk density and penetration resistance but the trends on the effects of soil wetness on root growth are less definitive (Fig. 28).

Considering a limiting root growth of 0.1 cm hr^{-1} , the applied stresses that will cause excessive

Figure 24. Effect of applied stress on air permeability of Blount silty clay loam at four soil matric potentials, Ψ , (Fig. 24a) and relationship between air permeability of Blount silty clay loam and air porosity at four soil matric potentials (Fig. 24b).

Figure 25. Effect of applied stress on saturated hydraulic conductivity of Blount silty clay loam at four matric potentials, Ψ , (Fig. 25a) and relationship between saturated hydraulic conductivity of Blount silty clay loam and total porosity at four soil matric potentials (Fig. 25b).

Figure 26. Effect of applied stress on diffusion coefficient of Blount silty clay loam at four soil matric potentials, Ψ , (Fig. 26a) and the relationship between diffusion coefficient and air porosity of Blount silty clay loam at four soil matric potentials (Fig. 26b).

Figure 27. Effect of applied stress on resistance of Blount silty clay loam to the penetration of steel probe at four soil matric potentials, Ψ , (Fig. 27a) and the relationship between penetration resistance of Blount silty clay loam and bulk density at four soil matric potentials (Fig. 27b).

Figure 28. Relationship between corn seedling root growth and applied stress (Fig. 28a), bulk density (Fig. 28b), and penetration resistance (Fig. 28c) of Blount silty clay loam at four soil matric potentials, Ψ .

compaction are >85, >170, >120 and >395 kPa for soil matric potentials of -33, -100, -500 and -1500 kPa, respectively. The effect of applied stress on root growth is smaller in Blount soil than in coarse textured soil. Also, at any given applied stress, the effect of soil matric potential is much smaller in Blount than coarse textured soils. This is expected because the amount of water in Blount soil is much above the critical limit for growing roots whereas in coarse textured soil, the water contents are very low and any small change in soil wetness would result in much larger change in root growth.

Holtville silty clay: Bulk density (Fig. 29a) increases where as porosity (Fig. 29b), void ratio (Fig. 29c), and air-filled porosity (Fig. 29d) decreases with an increase in applied stress. At a given applied stress, the effects of soil matric potential at the time of compaction on soil mechanical properties are relatively small and can be grouped into two groups i.e. soils at matric potentials of -33 and -100 kPa and -500 and -1500 kPa had similar mechanical properties. In general, bulk density increases and other soil mechanical properties decrease with an increase in soil wetness.

Soil water retention characteristics changed both with applied stress and soil wetness at the time of soil compaction (Fig. 30). At any given soil matric potential, water retention is higher for soils subjected to higher applied stresses. With increase in soil wetness at the time compaction, the differences in soil water retention due to applied stress decreases.

Air permeabilities decreases with an increase in applied stress and decrease in soil wetness (Fig. 31a). However, the effects of soil wetness at applied stress greater than 197 kPa are erratic. Again the effect of soil wetness can be grouped into two groups, one belonging to soil matric potentials of -33 and -100 kPa and other belonging to soil matric potentials of -500 and -1500 kPa. Except at very low air porosities, the air permeability is uniquely related to air porosity irrespective of applied stress and soil wetness (Fig. 31b). Air permeabilities decrease four folds with a decrease in air-filled porosity from about 0.35 to 0.05 $\text{m}^3 \text{m}^{-3}$. Air permeabilities at applied stress of 395 kPa and soil matric potential of -33 and -100 kPa may be in error and additional measurements will be taken to further check these data points.

Figure 29. Effect of applied stress on bulk density, porosity, void ratio and air porosity of Holtville silty clay at four soil matric potentials.

Figure 30. Effect of applied stress (σ_a) and soil matric potential at the time of compaction (Ψ_c) on water retention characteristics of Holtville silty clay.

Figure 31. Effect of applied stress on air permeability of Holtville silty clay at four soil matric potentials, Ψ , (Fig. 31a) and relationship between air permeability of Holtville silty clay and air porosity at four soil matric potentials (Fig. 31b).

Saturated hydraulic conductivity decreases with an increase in applied stress or soil matric potential at the time of compaction (Fig 32a), but the effect of applied stress on saturated hydraulic conductivity is much greater. Saturated hydraulic conductivity is uniquely related to total porosity irrespective of applied stress or soil wetness at the time of soil compaction. With change in total porosity from about 0.62 to 0.42 $\text{m}^3 \text{m}^{-3}$, saturated hydraulic conductivity decreases by about five folds.

Resistance of Holtville silty clay soil to cone penetrometer increases with an increase in applied stress (Fig. 33a). Also, the differences in penetration resistance due to differences in soil matric potential at the time of compaction are smaller at lower applied stress and increase with an increase in applied stress. In general, at a given applied stress, the penetration resistance increases with a decrease in soil matric potential. Penetration resistance increases with an increase in bulk density but there was no single relationship for all applied stresses and soil matric potentials at the time of compaction (Fig 33b). Penetration resistance of Holtville silty clay at all combination of four applied stresses and four soil matric potentials is below 2 MPa, a limit below which root growth is considered to stop. The maximum penetration resistance for Holtville silty clay corresponds to about 1800 kPa at applied stresses of 395 kPa and soil matric potentials of -500 and -1500 kPa.

Root growth decreases with an increase in applied stress, bulk density, or penetration resistance (Fig. 34). At a given applied stress, the effect of soil wetness on root growth is relatively minor. Since rate of root growth for all combinations of applied stresses and soil matric potentials at the time of compaction is less than the assumed critical root growth rate of 0.1 cm hr^{-1} , this will suggest that all applied stresses > 49 kPa will cause excessive compaction at the four soil matric potentials used in this study.

Sharpsburg silty clay loam: Bulk density (Fig. 35a) increases whereas porosity (Fig. 35b), void ratio (Fig. 35c) and air-filled porosity (Fig. 35d) decreases with an increase in applied stress. At any given applied stress, the effect of soil matric potential at the time of soil compaction is also relatively important on changes in soil mechanical properties of this soil. Except at an applied stress of 395 kPa, the bulk density increases, whereas porosity, void ratio and air-filled porosity.

Figure 32. Effect of applied stress on saturated hydraulic conductivity of Holtville silty clay at four matric potentials, Ψ , (Fig. 32a) and relationship between saturated hydraulic conductivity of Holtville silty clay and total porosity at four soil matric potentials (Fig. 32b).

Figure 33. Effect of applied stress on resistance of Holtville silty clay to the penetration of steel probe at four soil matric potentials, Ψ , (Fig. 33a) and the relationship between penetration resistance of Holtville silty clay and bulk density at four soil matric potentials (Fig. 33b).

Figure 34. Relationship between corn seedling root growth and applied stress (Fig. 34a), bulk density (Fig. 34b), and penetration resistance (Fig. 34c) of Holtville silty clay at four soil matric potentials, Ψ .

Figure 35. Effect of applied stress on bulk density, porosity, void ratio and air porosity of Sharpsburg silty clay loam at four soil matric potentials.

decrease with an increase in soil matric potential at the time of soil compaction.

For applied stresses of 98, 197 and 395 kPa, the water retention characteristics curves are nearly similar (Fig. 36). At soil wetness corresponding to soil matric potential of -33 (Fig. 36a) and -100 kPa (Fig. 36b) at the time of soil compaction, the water retention curves corresponding to an applied stress of 49 kPa are slightly lower than those at other applied stresses. For a given applied stress, the effect of soil wetness at the time compaction on water retention characteristics is small.

Air permeability decreases with an increase in applied stress (Fig. 37a). Except for soil matric potential of -33 kPa, the effect of soil wetness on air permeability is generally small. Air permeability at soil matric potential of -33 kPa and applied stress of 49 kPa is high and does not fit the trend of air permeability changes with soil wetness for this soil. Considering all the data, air permeability decreases by about 12 folds from applied stress of 49 to 395 kPa (Fig. 37), which seems excessive. However, excluding the measurement at applied stress of 49 kPa and at soil matric potential of -33 kPa, air permeability changes by about 5 folds which is similar to the trends of other soils of similar texture. Further measurements will be made to validate the air permeability measurements at soil matric potential of -33 kPa. Except for air permeability at soil matric potential of -33 kPa and applied stress of 49 kPa, air permeability is nicely related to air porosity and increases with an increase in air porosity (Fig. 37b). Above air-filled porosity of $0.24 \text{ m}^3 \text{ m}^{-3}$, the air permeability is uniquely related to air porosity.

As expected, saturated hydraulic conductivity also decreases with an increase in applied stress (Fig. 38a). At applied stresses greater than 49 kPa, saturated hydraulic conductivity of Sharpsburg silty clay loam compacted at matric potential of -33 kPa is much lower than those compacted at other soil matric potentials. Saturated hydraulic conductivity increases with an increase in total porosity (Fig. 38b) but there is too much variation in saturated hydraulic conductivity at a given porosity to provide a unique relationship. As expected, diffusion coefficient also decreases with an increase in applied stress and an increase in soil wetness (Fig. 39a). Soil diffusion coefficient is nearly zero at soil matric potential of -33 and -100 kPa and applied stress of 98 kPa. Diffusion coefficient decreases with increase in air porosity and is uniquely related to air-filled porosity

Figure 36. Effect of applied stress (σ_a) and soil matric potential at the time of compaction (Ψ_c) on water retention characteristics of Sharpsburg silty clay loam.

Figure 37. Effect of applied stress on air permeability of Sharpsburg silty clay loam at four soil matric potentials, Ψ , (Fig. 37a) and relationship between air permeability of Sharpsburg silty clay loam and air porosity at four soil matric potentials (Fig. 37b).

Figure 38. Effect of applied stress on saturated hydraulic conductivity of Sharpsburg silty clay loam at four matric potentials, Ψ , (Fig. 38a) and relationship between saturated hydraulic conductivity of Sharpsburg silty clay loam and total porosity at four soil matric potentials (Fig. 38b).

Figure 39. Effect of applied stress on diffusion coefficient of Sharpsburg silty clay loam at four soil matric potentials, Ψ , (Fig. 39a) and the relationship between diffusion coefficient and air porosity of Sharpsburg silty clay loam at four soil matric potentials (Fig. 39b).

irrespective of soil wetness and applied stress (Fig. 39b). At about air porosity of 0.06 to 0.08 $\text{m}^3 \text{m}^{-3}$, soil diffusion coefficient is zero.

Resistance of Sharpsburg to cone penetrometer increases with an increase in applied stress (Fig. 40a) and bulk density (Fig. 40b) but the increase is much smaller at soil matric potentials of -33 and -100 kPa. Also, penetration resistance of Sharpsburg silty clay loam soil is not uniquely related to soil bulk density (Fig. 40b). Penetration resistance for all combination of applied stresses and soil wetness is less than 2 MPa, a critical limit where root growth is presumed to stop.

Root growth decreases with an increase in applied stress (Fig. 41a), bulk density (Fig. 41b), and penetration resistance (Fig. 41c). Except for soil wetness of -33 kPa, root growth decreases with a decrease in soil wetness. Also, except for an applied stress of 49 kPa, the root growth at soil matric potential of -33 kPa is less than the corresponding values at other soil matric potentials. The reasons for this is not clear. Root growth seems to be uniquely related to penetration resistance (Fig. 41c) except at lower penetration resistance. Assuming 0.1 cm hr^{-1} as a critical rate of root growth, the applied stresses considered excessive correspond to stresses greater than 100, 270, 197, 130 kPa at soil matric potential of -33, -100, -500, and -1500 kPa, respectively.

Webster clay loam: Bulk density increases (Fig. 42a), and porosity (Fig. 42b), void ratio (Fig. 42c), and air-filled porosity (Fig. 42d) decrease with an increase in applied stress. At any given applied stress, the effect of soil matric potential at the time compaction is minimal.

At a given soil wetness at the time of compaction, water retention increases with an increase in applied stress (Fig. 43). However, at any given applied stress, the effect of soil wetness at the time of compaction on water retention characteristics is minimal.

Air permeability decreases with an increase in applied stress (Fig. 44). Except at applied stress of 395 kPa, there is not much difference in air permeability of Webster clay loam as a result of the difference in soil wetness. The differences in air permeability due to the differences in soil wetness at an applied stress of 395 kPa are also small. Air permeability decreases with an increase in air-

Figure 40. Effect of applied stress on resistance of Sharpsburg silty clay loam to the penetration of steel probe at four soil matric potentials, Ψ , (Fig. 40a) and the relationship between penetration resistance of Sharpsburg silty clay loam and bulk density at four soil matric potentials (Fig. 40b).

Figure 41. Relationship between corn seedling root growth and applied stress (Fig. 41a), bulk density (Fig. 41b), and penetration resistance (Fig. 41c) of Sharpsburg silty clay loam at four soil matric potentials, Ψ .

Figure 42. Effect of applied stress on bulk density, porosity, void ratio and air porosity of Webster clay loam at four soil matric potentials.

Figure 43. Effect of applied stress (σ_a) and soil matric potential at the time of compaction (Ψ_c) on water retention characteristics of Webster clay loam.

Figure 44. Effect of applied stress on air permeability of Webster clay loam at four soil matric potentials, Ψ , (Fig. 44a) and relationship between air permeability of Webster clay loam and air porosity at four soil matric potentials (Fig. 44b).

filled porosity and is uniquely related to air porosity irrespective of the applied stress and the soil matric potential at the time of compaction (Fig. 44b). Saturated hydraulic conductivity also decreases with an increase in applied stress (Fig. 45a). Except at an applied stress of 395 kPa, the effect of soil wetness at the time of compaction on saturated hydraulic conductivity is relatively small. Saturated hydraulic conductivity also seems to be uniquely related to total porosity irrespective of applied stress and soil wetness at the time of compaction (Fig. 45b).

Resistance of Webster clay loam soil to steel probe penetration increases with an increase in applied stress (Fig. 46a). At any applied stress, the effect of soil matric potential at the time of compaction on penetration resistance is minimal. Penetration resistance is also uniquely related to bulk density (Fig. 46b). Penetration resistance of Webster clay loam soil at applied stress of 395 kPa and soil matric potential of -100, -500, and -1500 kPa are above the 2 MPa, a limit when root growth is considered to stop. Root growth of corn seedling decreases with an increase in applied stress (Fig. 47a), bulk density (Fig. 47b), and penetration resistance (Fig. 47c). Except for soil matric potential of -33 kPa, root growth decreases with a decrease in soil matric potential. Root growth is slightly higher at soil matric potential of -100 kPa than at -33 kPa. Considering 0.1 cm hr^{-1} as a critical rate of root growth, all stresses greater than 395, 500, 280, and 140 kPa will be considered excessive at soil matric potentials of -33, -100, -500, -1500 kPa, respectively. There is no unique relationship between root growth and bulk density or root growth and penetration resistance for Webster clay loam.

Generalized Relationships

The following discussion summarizes the generalized relationships of soil flow properties and root growth to easily measurable parameters based on the above data base. The premise of the discussion is that if relationships can be generalized based on this data base, then these relationships can be used to estimate soil flow properties and root growth for other soils from their easily soil measurable properties.

Air permeability: Previous studies (Bowen, 1966; Kirkham, 1946) in the literature have shown

Figure 45. Effect of applied stress on saturated hydraulic conductivity of Webster clay loam at four matric potentials, Ψ , (Fig. 45a) and relationship between saturated hydraulic conductivity of Webster clay loam and total porosity at four soil matric potentials (Fig. 45b).

Figure 46. Effect of applied stress on resistance of Webster clay loam to the penetration of steel probe at four soil matric potentials, Ψ , (Fig. 46a) and the relationship between penetration resistance of Webster clay loam and bulk density at four soil matric potentials (Fig. 46b).

Figure 47. Relationship between corn seedling root growth and applied stress (Fig. 47a), bulk density (Fig. 47b), and penetration resistance (Fig. 47c) of Webster clay loam at four soil matric potentials, Ψ .

that air permeability of soil is related to air-filled porosity. The data in this report also shows that the air permeability is related to air-filled porosity for both coarse (Fig. 48a) and fine textured (Fig. 48b) soils. At any given air-filled porosity, the air permeability for all three coarse textured soil is within one order of magnitude whereas for fine textured soils, the scatter in air permeability at high air-filled porosities is small (one fold) and increases with a decrease in air-filled porosity (five fold). Combined air permeability data of all seven soil (Fig. 49) show that within an order of magnitude variation, air permeability is related to air-filled porosity irrespective of soil type, applied stress and soil matric potential at the time of compaction. Exception to the generalized relationship is one data point corresponding to Sharpsburg silty clay loam at applied stress of 49 kPa and soil matric potential of -33 kPa. In general, air permeability of coarse textured soils is slightly lower than those of the fine textured at the same air-filled porosity.

Saturated hydraulic conductivity: Several studies (Green and Corey, 1971; Brakensiek, 1979) in the literature has shown that saturated hydraulic conductivity of soils is a power function of total porosity. Data base in this report also shows that with an order of magnitude, saturated hydraulic conductivity of coarse textured soils (Fig. 50a) increases with an increase in total porosity, however, there is much larger variation in saturated hydraulic conductivity for fine textured soils at any given total porosity (Fig. 50b). Combined data of saturated hydraulic conductivity for all soils shows no single relationship as a function of total porosity (Fig. 51). This is very similar to the observation of Voorhees et al. (1986) who stated that saturated hydraulic conductivity was not uniquely related to either pore volume or macropore space of two soils that have been subjected to heavy axle loads. The hydraulic conductivity vs. soil wetness and applied stress data in this report did not show any peak or valley, as pointed out by Akram and Kemper (1979) in their laboratory measured infiltration data. Although the reasons for this difference is not entirely clear except that the range of soil water content at the time of compaction in our study are different than those of Akram and Kemper (1979). Soil wetness at the time of compaction in the present study varied from a soil matric potential of -33 to -1500 kPa whereas the soil wetness at the time of compaction in Akram and Kemper's (1979) ranged from air dried to slightly above field capacity water content. In addition, the data in our study corresponds to saturated hydraulic conductivity whereas the data of Akram and Kemper (1979) refers to constant head infiltration

Figure 48. Relationship of air permeability to air porosity for coarse (Fig. 48a) and fine (Fig. 48b) textured soils.

Figure 49. Relationship of air permeability to air porosity for all seven soils used in the soil compaction study.

Figure 50. Relationship of saturated hydraulic conductivity to total porosity for coarse (Fig. 50a) and fine (Fig. 50b) textured soils.

Figure 51. Relationship and saturated hydraulic conductivity to total porosity for all seven soils used in the soil compaction study.

rates. If hydraulic head was same through for all measurements, then the infiltration rates in Akram and Kemper (1979) study will be directly proportional to saturated hydraulic conductivity.

Diffusion coefficient : Xu (1990) showed that combined data of diffusion coefficient for four soils is nicely related to air-filled porosity irrespective of the soil type, applied stress and the soil matric potential (Fig. 52). Xu (1990) also showed that diffusion coefficient data can be described by the following relationships suggested by Currie (1960) or Troeh et al. (1982).

$$\text{Currie (1960)} \quad D/D_0 = r \, f_a^u \quad [4]$$

$$\text{Troeh et al. (1982)} \quad D/D_0 = \{ (f_a - m)/(1 - m) \}^v \quad [5]$$

The values of r and u in Eq. [4] for the combined data corresponded to 2.12 and 2.44, respectively. Similarly, for Eq. [5], v was equal to 1.53 when m was assume to equal 0.05 (Xu, 1990). The assumption of $m=0.05$ implies that the diffusion coefficient was equal to zero at an air-filled porosity of $0.05 \, \text{m}^3 \, \text{m}^{-3}$. The relationship in Fig. 52 is very similar to that of Grable and Siemer (1968) and shows that at an air filled porosity of 10 percent, the diffusion coefficient is nearly zero. In this study, we have used a 10 percent air-filled porosity as one of the critical limits that defines excessive compaction.

Root growth: In general, root growth rates decrease with an increase in soil resistance for both textural groups. However, there is no unique relationship of root growth to penetration resistance either by textural group (Fig. 53) or for all seven soils data combined together (Fig. 54). In other words for a given penetration resistance, root growth varies by soil type and in some cases by applied stress and soil water content. This is contrary to the observations of Taylor et al. (1966), who showed that percentage of cotton tap roots that penetrated through 0.025 m thick cores were uniquely related to penetrometer resistance of four soils. It was this relationship of Taylor et al. (1966) that suggested that root penetration is nearly zero at penetrometer resistance of 2 MPa.

Figure 52. Relationship of diffusion coefficient to air porosity for four soils.

Figure 53. Relationship of root growth to penetration resistance for coarse (Fig. 53a) and fine (Fig. 53b) textured soils.

Figure 54. Relationship of root growth to penetration resistance for all seven soils used in the soil compaction study.

Subsequently, Gerard et al. (1982) showed that penetrometer resistance where root elongation stops varies with clay content. Gerard et al. (1982) database comprised of 9 horizons of two soils. The reasons for variation between different studies may be the parameters used for defining root growth in different studies. For example, in the current study, we are using rate of root growth over 72 hours whereas Taylor et al. (1966) used percentage of tap root that penetrated through 0.025 m thick soil and Gerard et al. (1982) used root length after 3 days. The other reason for the differences between the current study and the studies of Taylor et al. (1966) and Gerard et al. (1982) is the type of crop. In the present study, we used the corn (no tap root system) seedling whereas in other studies, the investigators used cotton (tap root system) seedlings.

Criterion Of Excessive Compaction

Two sets of criterion are used in this report for defining stresses that cause excessive compaction. First set of criterion considers those stresses as excessive which result in soil conditions that completely stop root growth, root respiration or aerobic microbial activities in soils. As discussed earlier, the above criterion when translated into measurable parameters defines excessive compaction as those when soil resistance to steel probe penetration is above 2 MPa (the root growth stops) and when the air-filled porosity reduce to below 10 percent level (the gas diffusion is zero and root respiration and aerobic microbial activities are impaired). In Tables 3 and 4 are summarized the excessive applied stresses for seven soils based on the penetration resistance of 2 MPa and the air-filled porosity of 10 percent, respectively.

Second set of criterion of excessive compaction assumes that an applied stress is excessive if that stress creates soil conditions that reduces the rate of root growth to less than 0.1 cm hr^{-1} or reduces the aerobic microbial activity to less than optimum. Although selection of 0.1 cm hr^{-1} root growth rate for defining excessive compaction is arbitrary, this assumption implies that laboratory measured root growth rates below 0.1 cm hr^{-1} are not sustainable in the field over a long periods of time. The criteria of less than optimum aerobic microbial activity is based on the

Table 3. Applied stress above which soil resistance to steel probe is greater than 2 MPa, σ_a (PR=2), for seven soils at four matric potentials.

Soil	Soil Matric Potential, kPa			
	-33	-100	-500	-1500
	----- σ_a (PR=2), kPa -----			
<u>Coarse-textured</u>				
Cecil	395 ⁺	395	395	395
Miles	395	395	395	395
Norfolk	395	395	395	395
<u>Fine-textured</u>				
Blount	395	395	395	395
Holtville	395	395	395	395
Sharpsburg	395	395	395	395
Webster	310	310	360	395

⁺ Value of 395 kPa indicates that applied stress when soil resistance to penetrometer exceeded 2 MPa was outside the range of applied stresses used in this study, i.e., greater than 395.

Table 4. Applied stress above which gas diffusion through soil is zero, σ_a ($D=0$), for seven soils at four matric potentials.

Soil	Soil Matric Potential, kPa			
	-33	-100	-500	-1500
	----- σ_a (D=0), kPa -----			
<u>Coarse-Textured</u>				
Cecil	395	395	395	395
Miles	395 ⁺	395	395	395
Norfolk	395	395	358	395
<u>Fine-textured</u>				
Blount	198	198	395	395
Holtville	98	130	285	280
Sharpsburg	98	98	240	NA
Webster	395	395	395	395

Bold values are estimated assuming the diffusion coefficient is zero at air-filled porosity of 10 percent.

⁺ Value of 395 kPa indicates that the applied stress when diffusion coefficient is zero occurs outside the range of highest applied stress used in this study.

concepts of Linn and Doran (1984). These authors suggested that aerobic activities were maximum at 60 percent water filled pore space (degree of saturation) and the anaerobic processes increased rapidly as the degree of saturation increased above 60 percent. Based on this criteria, we defined those stresses as excessive which resulted in the degree of saturation to greater than 60 percent. Stresses at 60 percent degree of saturation were obtained from the relationship of degree of saturation vs. applied stress for seven soils at four soil matric potentials (Figs. 55 and 56). In Tables 5 and 6 are summarized the excessive applied stresses for seven soils based on the root growth rate of 0.1 cm hr^{-1} and 60 percent degree of saturation, respectively.

Another criteria used for defining excessive compaction related to the shearing of soil aggregates. Larson and Gupta (1980) showed that during uniaxial compression, the pore water pressure decreased, reached a minimum and then increased with an increase in applied stress. Larson and Gupta (1980) hypothesized that stress corresponding to minimum pore water pressure corresponded to the conditions when soil aggregates sheared. These authors also showed that the degree of saturation at minimum pore water pressure was unique for each soil. Also, the degree of saturation corresponding to the minimum pore water pressure increased with an increase in soil clay content of the soil. The pore water pressure in Larson and Gupta (1982) study ranged from -5 to -80 kPa. Although the soil matric potential in the present study (-33 to -1500 kPa) is outside the range of pore water pressure of Larson and Gupta (1982), we assumed that Larson and Gupta's (1982) relationship of degree of saturation at minimum pore water pressure can be extrapolated to lower water contents. Thus, using the clay content of seven soils used in this study, we estimated the degree of saturation at the minimum pore water pressure from the relationships of Gupta et al. (1985) and converted these degrees of saturation into applied stresses above which soil aggregates will shear using Figs. 55 and 56. Table 7 lists the applied stresses above which the soil aggregates will shear for seven soil at four soil matric potentials. Of course, the assumption that degree of saturation at minimum pore water pressure is same over the soil matric potential of -33 to -1500 kPa needs further studying and evaluation.

Figure 55. Effect of applied stress on degree of saturation for Cecil (Fig. 55a), Miles (Fig. 55b), and Norfolk (Fig. 55c) loamy sands at four soil matric potentials, Ψ .

Figure 56. Effect of applied stress on degree of saturation for Blount silty clay loam (Fig. 56a), Holtville silty clay (Fig. 56b), Sharpburg silty clay loam (Fig. 56c), and Webster clay loam (Fig. 56d) at four soil matric potentials, Ψ .

Table 5. Applied stress above which root growth is less than 0.1 cm hr^{-1} σ_a (RG=0.1), for seven soils at four matric potentials.

Soil	Soil Matric Potential, kPa			
	-33	-100	-500	-1500
	σ_a (RG=0.1), kPa			
<u>Coarse-textured</u>				
Cecil	180	70	49	49
Miles	395 ⁺	130	49	49
Norfolk	180	105	49	49
<u>Fine-textured</u>				
Blount	85	170	120	395
Holtville	49 ⁺	49	49	49
Sharpsburg	100	270	197	130
Webster	395	500	280	140

⁺ Values of 49 and 395 kPa indicate that root growth of a 1 cm hr^{-1} was outside the range of applied stresses in this study, i.e., less than 49 kPa and greater than 395 kPa, respectively.

Table 6. Applied stress above which degree of saturation is greater than 60 percent σ_a (60), for seven soils at four matric potentials.

Soil	Soil Matric Potential, kPa			
	-33	-100	-500	-1500
	----- σ_a (60), kPa -----			
<u>Coarse-textured</u>				
Cecil	395 ⁺	395	395	395
Miles	395	395	395	395
Norfolk	395	395	395	395
<u>Fine-textured</u>				
Blount	49 ⁺	78	100	395
Holtville	49	52	115	130
Sharpsburg	49	51	100	305
Webster	280	395	395	395

⁺ Values of 49 and 395 kPa indicate that 60 percent degree of saturation occurred outside the limits of applied stresses considered in this study, i.e., less than 49 and greater than 395 kPa, respectively.

Table 7. Estimated degree of saturation at minimum pore water pressure, θ_m , and the corresponding critical stresses above which soil aggregates will shear σ_a (Sh) for seven soils at four soil matric potentials.

Soil	θ_m	Soil Matric Potential, kPa			
		-33	-100	-500	-1500
----- σ_a (Sh) -----					
<u>Coarse-textured</u>					
Cecil	0.42	395 ⁺	395	395	395
Miles	0.43	395	395	395	395
Norfolk	0.41	395	395	395	395
<u>Fine-textured</u>					
Blount	0.54	49 ⁺	54	76	395
Holtville	0.59	49	53	130	120
Sharpsburg	0.57	49	52	97	280
Webster	0.54	210	305	395	300

⁺ Values of 49 and 395 kPa indicates that critical stresses were outside the ranges of applied stresses used in this study, i.e., less than 49 kPa and greater than 395 kPa, respectively.

Probability Of Soil Wetness

As demonstrated above, applied stress and soil wetness are intricately linked together in defining excessive soil compaction. Although the effects of applied stress is much greater than those of soil wetness, one still needs to know the soil wetness in order to delineate applied stresses that are not conducive to excessive compaction. Of course, soil wetness at a given time and place depends upon the hydraulic properties of the soil and the climate of the area. To the authors knowledge, no long term daily soil wetness records are available especially for those soils that are known to be compaction prone. Most soil wetness information available in the literature is either weekly or biweekly values and that too are only for limited soil conditions. Because of this lack of data base, a soil water balance model (SWBM) was used to simulate the daily probability of soil wetness for three soils (Blount, Sharpsburg and Webster) in our data base.

The SWBM code was written by Nieber and Lopez-Bakovic (1989) and considers various hydrology processes like runoff, infiltration, plant transpiration, soil evaporation and percolation in calculating the soil wetness. The model is based on the code and the theory presented in SWRRBS (Williams et al., 1985) and CREAMS (Knisel, 1980). The model includes the climate generator of Nicks (1974). Soil inputs needed for the model are the soil hydraulic properties, curve number, amount of irrigation, Ritchie's soil evaporation parameter, starting and ending dates of simulation, soil depth, and initial soil water content. Runoff calculations are based on the curve number approach of Soil Conservation Service (USDA, 1972). In our simulation, we assumed a low curve number. This assumption implies that there was no runoff and all rain water infiltrated into the soil. Plant and climate inputs include leaf area index, total root depth, rainfall amount, maximum and minimum daily temperatures, daily solar radiation and albedo. Output of interest in our study was the daily water content of each soil layers.

For our simulation, we divided the soil profile into four soil layers (0 to 20, 20 to 40, 40 to 100, and 100 to 400 cm) and assumed that the hydraulic properties of all soil layers were similar. Climate inputs were internally generated by the climate generator (Nicks, 1974) corresponding to the location closest to where the soil sample were collected. We assumed an albedo of 0.1 for

early spring conditions. The simulations were run for 18 years (1960-77) starting on 1 April through 31 May of each year. At the start of each year's simulation, it was assumed that the soil water content corresponded to the field capacity water content (soil matric potential = -33 kPa). Hydraulic properties included the water retention curve and the saturated hydraulic conductivity. Simulations were run for applied stress of 49 and 395 kPa. It was assumed that the hydraulic properties of the whole profile corresponded to the laboratory measured hydraulic characteristics of soil sample that has been subjected to the applied stress of 49 or 395 kPa.

Figure 57 is an example of calculated cumulative soil wetness probability for Webster clay loam as a function of calendar day between 1 April and 31 May. Hydraulic properties in this simulation corresponded to an applied stress of 49 kPa. Soil matric potential corresponding to a cumulative probability of 50 percent (5 out of 10 years) will be an equivalent to an average soil wetness. In general, average matric potential in 0 to 20 cm of Webster clay loam between 1 April and 31 May (Fig. 57a) is in the range of -33 and -500 kPa. At higher cumulative probabilities soil matric potential is relatively higher than average soil matric potential whereas at lower cumulative probabilities, soil matric potential is relatively lower than the average soil matric potential. For 20-40 cm depth (Fig. 57b), the average (50% probability) matric potential of Webster clay loam between 1 April and 31 May is between -33 and -100 kPa. In Fig. 58 is plotted the cumulative probability as a function of soil matric potential for first two layers of Webster clay loam on three different days (15 April, 1 May, and 15 May). For any given depth, the cumulative probabilities for above three days vary slightly. On an average, the matric potential in 0-20 cm soil depth for the above three days is about -1020, -550, and -180 kPa at cumulative probability of 25, 50 and 75 percent, respectively. Similarly, the corresponding soil matric potentials for 20-40 cm depth are -70, -50, and -33 kPa at cumulative probability of 25, 50, and 75 percent, respectively. Similar to the concept of Gupta(1985), the cumulative probabilities of 75, 50, and 25 percent can be assumed to represent wet, average and dry year, respectively. Further discussions in this report only relate to the cumulative probabilities on 1 May.

Table 8 summarizes the soil matric potentials on May 1 of Webster clay loam at cumulative probabilities of 25, 50, and 75 percent for four different locations (Minneapolis, MN; Des

WEBSTER CLAY LOAM (0-20 cm)
Minneapolis, MN

WEBSTER CLAY LOAM (20-40 cm)
Minneapolis, MN

Figure 57. Cumulative probability of various soil matric potentials as a function of calendar day in 0-20 cm and 20-40 cm of Webster clay loam that has been subjected to an applied stress of 395 kPa. The weather input data for these graphs corresponded to Minneapolis, MN.

Figure 58. Cumulative probability as a function of soil matric potential on April 15 (Day=105), May 1 (Day=121) and May 15 (Day=135) in 0-20 and 20-40 cm depths of Webster clay loam soil that has been subjected to an applied stress of 49kPa.

Table 8. Soil matric potential of Webster clay loam at various cumulative probabilities at four locations on May 1.

Location	Soil Depth, cm					
	0-20			20-40		
	-Cumulative Probability, %-					
	25	50	75	25	50	75
	-Soil Matric Potential, kPa-					
Minneapolis, MN	-1400	-740	-140	-73	-55	-41
Des Moines, IA	-1400	-330	-66	-73	-53	-28
Dubuque, IA	-210	-80	-47	-64	-46	-27
Huron, SD	-1300	-620	-140	-74	-56	-42

Moines, IA; Dubuque, IA; Huron, SD). The cumulative probabilities figures like Figs. 57 and 58 for other three locations are given in the Appendix A. The four locations in Table 8 are the closest sites where climate generator variables were available. These four location were assumed to represent the outer boundaries of the area where Webster clay loam or soils similar to Webster are found. Table 8 shows that at any given cumulative probability, the soil matric potential of Webster clay loam at 20-40 cm depth is nearly same at all four locations, however, soil matric potential at 0-20 cm depth decreases from South to North (Des Moines, IA to Minneapolis, MN) and East to West (Dubuque, IA to Huron, SD). This is expected considering that the rainfall decrease from South to North and East to West in the U. S. upper Midwest. Table 8 shows that under loose soil conditions (surface applied stress = 49 kPa), the soil matric potential in the 0-20 cm of Webster clay loam or soils similar to it, will vary from -47 to -140, -80 to -740, and -210 to -1400 kPa in a wet (75%), average (50%) and dry (25%) year, respectively.

In Table 9 are summarized the effect of surface applied stress on soil matric potential on 1 May for Blount silty clay loam, Webster clay loam and Sharpsburg silty clay loam at three cumulative probabilities. Climate input corresponded to the locations closest to where these soil are found. The cumulative probability diagram for these sites is given in the Appendix A. As expected, the data shows that at any given probability, increasing the applied stress from 49 to 395 kPa increases the matric potential of a given soil. In other words, soil is wetter at higher applied stress. This is expected considering higher applied stress reduces soil hydraulic conductivity and slows drainage. The data in Table 9 also shows that effect of increasing the stress from 49 to 395 kPa on soil matric potential is much greater on Sharpsburg silty clay loam followed by Blount silty clay loam and Webster clay loam. This is due to a combination of both greater reduction in soil hydraulic properties of Sharpsburg and Blount soils at higher applied stress and also due to the differences in weather conditions between different locations.

Other than the increase in the absolute wetness of a soil, the increased compaction will also result in an increase in time the soil remains wet after rainfall. In other words, increase in applied loads will lead to reduction in time available for farm operations. Cumulative probability diagrams like Fig. 57 can be used to calculate the probability of soil wetness above a given matric potential for

Table 9. Soil matric potential of Blount silty clay loam, Webster clay loam, and Sharpsburg silty clay loam at various cumulative probabilities on May 1.

Location	Soil	Applied Stress kPa	Soil Depth, cm					Cumulative Probability, %		
			0-20		20-40			25	50	75
			25	50	75	50	75			
			Soil Matric Potential, kPa							
Columbus, OH	Blount	49	<-1500	-360	-53	-24	-18	-14		
Columbus, OH	Blount	395	-410	-140	-18	-7	-4	-2		
Minneapolis, MN	Webster	49	-1400	-740	-140	-73	-55	-41		
Minneapolis, MN	Webster	395	-440	-220	-105	-24	-18	-14		
Grand Island, NE	Sharpsburg	49	<-1500	-1500	-150	-13	-18	-24		
Grand Island, NE	Sharpsburg	395	-280	-130	-40	-12	-17	-23		

series of consecutive days on any given date. For example, Figs. 59 and 61 show the probability of soil matric potential of Webster clay loam being greater than -100 kPa for one to seven consecutive days after the soil has been subjected to an applied stress of 49 and 395 kPa, respectively. As expected, for a given applied stress, the probability of soil being above -100 kPa decreases with an increase in the number of consecutive days. For any consecutive day, the probability that the matric potential of Webster clay loam will be greater than -100 kPa, increases as the applied stress increases from 49 to 395 kPa. This analysis demonstrates that in defining excessive compaction one also need to consider the number of days the soil will remain wet without causing economic loss in term of delayed field operations. In other words, we need a criteria of excessive compaction based on the level of consecutive days the soil remains wet. This criteria of excessive compaction should encompass the soil matric potential above which soil is considered wet (i. e. the soil cannot be tilled / trafficked), and the level of consecutive days with its corresponding probability that will be acceptable in a given farming situation. Although a rigorous approach should involve an economic analysis in defining above limits, a crude rule could be that those applied stresses that increase the probabilities of soil matric potential being greater than -33 kPa to above 25 percent for three consecutive day can be defined as excessive applied stress. Stated in other way, this means that a low level probability of soil remaining wet due to applied stress is acceptable. This concept needs further evaluation and validation before being included in defining the susceptibility of soils to excessive compaction.

Figures 61 through 66 show the effect of applied stress on cumulative probability of matric potential being greater than -33 kPa for a series of consecutive days for Blount silty clay loam, Sharpsburg silty clay loam, Webster clay loam soils. Comparing figures corresponding to three consecutive days show that increasing the applied stress from 49 to 395 kPa results in the greatest increase in the probability of soil matric potential being above -33 kPa for Sharpsburg silty clay loam, followed by Blount silty clay loam and Webster clay loam. Probability of matric potential being greater than -33 kPa for Webster clay loam is below 25 percent and does not change much with an increase in applied stress from 49 to 395 kPa (Figs. 65c and 66c). For Blount silty clay (Figs. 61c and 62c) and for Sharpsburg silty clay loam (Fig. 63c and 64c), a majority of the increase in probability (>25 percent) due to increase in applied stress occurs before and after

SOIL WETNESS >100 kPa FOR 1 DAY

SOIL WETNESS >100 kPa FOR 2 CONSECUTIVE DAYS

SOIL WETNESS >100 kPa FOR 3 CONSECUTIVE DAYS

SOIL WETNESS >100 kPa FOR 4 CONSECUTIVE DAYS

SOIL WETNESS >100 kPa FOR 5 CONSECUTIVE DAYS

SOIL WETNESS >100 kPa FOR 6 CONSECUTIVE DAYS

SOIL WETNESS >100 kPa FOR 7 CONSECUTIVE DAYS

Figure 59. Cumulative probability that the matric potential is >100 kPa for 1, 2, 3, 4, 5, 6, and 7 consecutive days in 0-20 cm depth of Webster clay loam soil that has been subjected to an applied stress of 49 kPa.

SOIL WETNESS >-100 kPa FOR 3 CONSECUTIVE DAYS

SOIL WETNESS >-100 kPa FOR 2 CONSECUTIVE DAYS

SOIL WETNESS >-100 kPa FOR 1 DAY

SOIL WETNESS >-100 kPa FOR 6 CONSECUTIVE DAYS

SOIL WETNESS >-100 kPa FOR 5 CONSECUTIVE DAYS

SOIL WETNESS >-100 kPa FOR 4 CONSECUTIVE DAYS

SOIL WETNESS >-100 kPa FOR 7 CONSECUTIVE DAYS

Figure 60. Cumulative probability that the matric potential is >100 kPa for 1, 2, 3, 4, 5, 6, and 7 consecutive days in 0-20 cm depth of Webster clay loam soil that has been subjected to an applied stress of 395 kPa.

SOIL WETNESS >33kPa FOR 3 CONSECUTIVE DAYS

SOIL WETNESS >33kPa FOR 6 CONSECUTIVE DAYS

SOIL WETNESS >33kPa FOR 2 CONSECUTIVE DAYS

SOIL WETNESS >33 kPa FOR 5 CONSECUTIVE DAYS

SOIL WETNESS >33kPa FOR 1 DAY

SOIL WETNESS >33kPa FOR 4 CONSECUTIVE DAYS

SOIL WETNESS >33kPa FOR 7 CONSECUTIVE DAYS

Figure 61. Cumulative probability that the matric potential is >33 kPa for 1, 2, 3, 4, 5, 6, and 7 consecutive days in 0-20 cm depth of Blount silty clay loam soil that has been subjected to an applied stress of 49 kPa.

Figure 62. Cumulative probability that the matric potential is >33 kPa for 1, 2, 3, 4, 5, 6, and 7 consecutive days in 0-20 cm depth of Blount silty clay loam soil that has been subjected to an applied stress of 395 kPa.

Figure 63. Cumulative probability that the matric potential is >33 kPa for 1, 2, and 3 consecutive days in 0-20 cm depth of Sharpshurg silty clay loam soil that has been subjected to an applied stress of 49 kPa.

Figure 64. Cumulative probability that the matric potential is >33 kPa for 1, 2, 3, 4, 5, 6, and 7 consecutive days in 0-20 cm depth of Sharpsburg silty clay loam soil that has been subjected to an applied stress of 395 kPa.

Figure 65. Cumulative probability that the matric potential is >33 kPa for 1, 2, 3, 4, and 5 consecutive days in 0-20 cm depth of Webster clay loam soil that has been subjected to an applied stress of 49 kPa.

Figure 66. Cumulative probability that the matric potential is >33 kPa for 1, 2, 3, 4, and 5 consecutive days in 0-20 cm depth of Webster clay loam soil that has been subjected to an applied stress of 395 kPa.

calendar day 120, respectively. Since the planting dates are slightly earlier in Ohio compared to Nebraska (Gupta, 1985), this would suggest that the applied stress of 395 kPa will reduce the available time for field operations and thus applied stress of 395 kPa will be considered excessive for both Blount silty clay loam as well as Sharpsburg silty clay loam soils.

Probability Of Applied Stress

Like soil wetness, size of farm machinery and thus surface applied stress to soil also varies with soil type or location. A comprehensive data base on the use of farm machinery by soil type or location is currently not available. Wertz and Grisso (1988) presented a survey of 40 tractor owners on primary, second and third tractor use in Lancaster county in Nebraska. The survey included tractor drive, wheel pressures, conditions, types, sizes, and amount of ballast used. Table 10 summarizes the unballasted and ballasted rear and total weight of 40 tractor in the county. The overall rear weight of 40 tractors ranged from a minimum of 1431 kg for unballasted to a maximum of 7779 kg for ballasted condition. Most popular (62%) rear tire size on the primary tractor was 18.4-38. Ten percent used 20.8-38 or 18.4-42 and 18.4-34 was used by 5 percent. Bias-ply rear tire were used by 48 percent and radial-ply tires were used by 27 percent.

In Table 11 summarizes the estimated wheel traffic stresses on three Minnesota soils for two type of field operations (tillage and planting, harvesting). The minimum applied stress corresponds to 60 kPa from tillage and planting equipment on Fayette silt loam in east central Minnesota whereas the maximum applied stress (300 kPa) is from the harvesting equipment on Webster clay loam in south central and Barnes loam in west central Minnesota. Similar data bases on applied loads/stresses and their probabilities of use are needed for other locations in order to classify soils according to their susceptibility to excessive compaction.

Susceptibility Of Soils To Excessive Compaction

In the absence of any generalized tractor use data base, three tractor loads given in Table 12 are used to demonstrate a procedure of delineating soils according to their susceptibility to excessive

Table 10a. Estimated ballasted weights of tractors in Lancaster County in Nebraska (Wertz and Grisso, 1988).

Tractor Type ⁺	No. of Tractors	Rear Wheel Weight, kg			Total Weight, kg		
		Max	Avg.	Min	Max	Avg.	Min
Overall	40	7779	5493	1431	12823	7796	2193
2 W D	34	7779	5521	1431	9966	7385	2193
4 W D	5	6173	4859	3969	12833	10012	18620
F W A	1	--	7725	--	10705	--	--

+ 2 WD = 2 wheel drive, 4 WD = 4 wheel drive, FWA = front wheel assist.

Table 10b. Nebraska tractor test unballasted weights of tractor in Lancaster County in Nebraska (Wertz and Grisso, 1988).

Tractor Type ⁺	No. of Tractors	Rear Wheel Weight, kg			Total weight, kg		
		Max	Avg.	Min	Max	Avg.	Min
Overall	40	6437	4581	1431	12823	6683	2193
2 W D	34	6187	4515	1431	8364	6164	2193
4 W D	5	6173	4660	3599	12823	9812	7992
F W A	1	--	6437	--	--	8691	--

+ 2 WD = 2 wheel drive, 4 WD = 4 wheel drive, FWA = front wheel assist.

Table 11. Estimated wheel Traffic Loads under Minnesota Field Conditions.
Bard Project, December, 1988.

Soil Type & Location	Soil Matric Potential, kPa			Operation	Surface Applied Stress, kPa ⁺		
	-10	-100	-1000		max	min	ave
	--Water Content, kg/kg--						
Barnes loam 31% clay west central	0.33	0.22	0.15	tillage, planting	150	75	100
				harvesting	300	100	200
Webster clay loam, 38% clay south central	0.34	0.33	0.23	tillage, planting	150	75	100
				harvesting	300	100	150
Fayette silt loam, 22% clay east central	0.37	0.17	0.07	tillage, planting	120	60	75
				harvesting	200	100	140

⁺ All surface applied stress calculated assuming a spherical footprint

Barnes - singles @ 22" and 7,000 kg = 150 kPa
 duals @ 18" and 5,000 kg = 75 kPa
 duals @ 18" and 7,000 kg = 100 kPa
 12 row-duals @ 18" and 20,000 kg = 300 kPa
 4 rows-duals @ 18" and 7,000 kg = 100 kPa
 6 rows-singles @ 22" and 10,000 kg = 200 kPa

Webster - same as Barnes except for average harvest:
 6 rows-duals @ 18" and 10,000 kg = 150 kPa

Fayette - singles @ 22" and 6,000 kg = 120 kPa
 duals @ 18" and 4,000 kg = 60 kPa
 duals @ 18" and 5,000 kg = 75 kPa
 6 rows-singles @ 22" and 10,000 kg = 200 kPa
 4 rows-duals @ 18" and 7,000 kg = 100 kPa
 4 rows-singles @ 22" and 7,000 kg = 140 kPa

Table 12. Tractor load and wheel characteristics used in simulating principle stress in soil.

Total Load	Load on ⁺ Single Rear Wheel	Tire Width	Contact ⁺⁺ Avg.
kg	kg	m	m ²
3632	1090	0.315	0.101
6356	1907	0.394	0.154
9080	2724	0.528	0.161

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

⁺⁺ Contact area corresponds to area on a hard surface.

compaction. The procedure involves simulating stress distribution in the soil profile for a given surface applied load. Figure 67 through 69 show the iso-stress lines for various surface applied loads and soil-tire contact area given in Table 12. Iso-stress lines are generated from the modified Boussinesq (1885) equations (Frohlich, 1934) using the procedure of Gupta and Larson (1982). Predicted iso-stress lines are at concentration factor (v) of 3, 4, 5, and 6. Higher the value of v , more concentrated are the stresses towards the load axis. Soehne (1953) recommended values $v = 4$ for hard or dry soil, $v = 5$ for firm or average moisture condition, and $v = 6$ for soft and wet soil. Since that recommendation, several researchers (see review by Gupta and Allmaras, 1987) have investigated v values that give the best prediction of iso-stress or iso-bulk density lines using the modified Boussinesq's equations. At this time, there is no specific consensus for selecting v values by soil type. Based on a field experiment, Ram's (1984) showed that v increases with an increase in soil moisture content at a constant bulk density and decreases with an increase in bulk density of a soil at the same moisture. This conclusion broadly matches with the recommendations of Soehne (1953). However, Ram (1984) also showed that v varied from 3.28 to 5.84 for sandy and loamy soils in normal fields and this factor increased to 7.74 for a low-strength powered silt loam soil. Considering the above results in the literatures, we assumed that v values of 3, 4, 5, and 6 represent the soil matric potentials of -1500, -500, -100 and -33 kPa used in this study. This assumption need to be field tested on various soil types at various soil wetness and initial bulk density conditions.

Iso-stress lines at a given load for various v values (Figs. 67 through 69) were then compared with the stress values defining excessive compaction for Blount silty clay loam, Sharpsburg silty clay loam and Webster clay loam in Tables 3 through 7. The deepest depth of penetration of an iso-stress line corresponding to the stress defining excessive stress were then grouped into following categories.

Figure 67. Predicted iso-stress lines under a tractor wheel (contact area= 0.101 m²) with a surface applied load of 1090 kg at four different concentration factors.

Figure 68. Predicted iso-stress lines under a tractor wheel (contact area= 0.154 m²) with a surface applied load of 1907 kg at four different concentration factors.

Figure 69. Predicted iso-stress lines under a tractor wheel (contact area= 0.161 m²) with a surface applied load of 2724 kg at four different concentration factors.

DEPTH OF PENETRATION OF ISO-STRESS LINE (cm)	CATEGORY
20-30	I
30-40	II
40-50	III
50-60	IV
60-70	V
70-80	VI
80-90	VII

Details of the above procedure have been given by Gupta and Allmaras (1987). The lowest category was chosen to correspond to a depth of 0-30 cm for the penetration of most limiting condition. This criteria assumes that excessive compaction in 0-30 cm depth can be easily alleviated next year by regular tillage practice and are not of long term consequences. In Table 13 is given an example of the categories that apply to Blount soil using the various criterion of excessive compaction. Table 13 shows that diffusion of gases and penetration of roots is only limited in the top 30 cm (category I) of the Blount soil at an applied load of 2724 kg at the soil surface. Considering the limiting root growth rate of 0.1 cm hr^{-1} , Blount soil falls under the category # I, II, I, and III for soil matric potential of -33, -100, -500 and -1500 kPa, respectively. Similarly, considering the criteria of 60 percent degree of saturation for optimal microbial activity, the corresponding classification for Blount soil is I, II, IV, and V whereas with criteria of stress greater than critical stress, the categories are I, III, IV, and V for soil matric potential of -33, -100, -500 and -1500 kPa, respectively. Comparison of all these categories shows that excessive compaction will not be a problem in Blount soil at soil matric potential of -1500 kPa (category=I), and surface applied load of 2724 kg. However, at soil matric potential of -500, -100, and -33 kPa and same applied loads, the excessive compaction will exist in the approximately top 50 (category=III), 60 (category=IV), and 70 cm (category = V) profile, respectively. Also, the most limiting conditions in Blount soil will correspond to stress above the critical stress for shearing aggregates (category III) for soil matric potential of -500 kPa and stress greater than the critical

Table 13. Classification of Blount silty clay loam soil according to the greatest penetration of the limiting condition defining excessive compaction at the surface applied load of 2724 kg.

Limiting Condition	$\psi = -1500$ kPa) $\psi = 3$	$\psi = -500$ kPa) $\psi = 4$	$\psi = -100$ kPa) $\psi = 5$	$\psi = -33$ kPa) $\psi = 6$
----- category ⁺ -----				
Penetration Resistance= 2MPa	I	I	I	I
D/Do = 0	I	I	I	I
Root Growth ≤ 0.1 cm hr ⁻¹	I	II	I	III
$\theta_s > 0.60$	I	II	IV	V
Stress > Shear Stress	I	III	IV	V

⁺ Category corresponding to the greatest penetration of the limiting condition.
Category I corresponds to 0-30 cm and each next category corresponds to an additional 10 cm depth.

stress (category IV) and degree of saturation greater than 60 percent (category IV) at soil matric potentials of -100, and -33 kPa.

In Table 14 are summarized the most limiting conditions for a surface applied load of 2724 kg on Blount silty clay loam, Sharpsburg silty clay loam and Webster clay loam soils. At the surface applied load of 2724 kg, Sharpsburg soil behaves similar to that of Blount but excessive soil compaction conditions are absent in Webster clay loam. The limiting conditions in Sharpsburg are also stress greater than the critical value for shearing aggregates and degree of saturation greater than 60 percent. In Tables 15 and 16 are summarized the categories corresponding to the maximum penetration of limiting conditions for above three soils at surface applied loads of 2724, 1907 and 1090 kg and soil matric potential of -33, -100, -500, -1500 kPa. As expected, with a decrease in surface applied load the classification of Blount and Sharpsburg soils shift to the lower category. For Webster clay loam, the classification category is I for all three surface applied loads at all four soil matric potentials.

In Tables 13 through 16 are included only five criterion for defining excessive compaction. These criterion are based on the greatest penetration of most limiting soil and plant condition in the profile. These criterion does not include the criteria based on the effects of applied stress on soil hydraulic properties and processes. As stated earlier, the effects of compaction on hydraulic processes include the increased time when the soil remains wet and increased surface runoff. In calculating the probabilities of soil being above a given soil matric potential, we assumed all three soils were level and all the rainfall will eventually find its way into the soil. However, this will not be the case for all soil types. The water balance model can be used for both estimating the probabilities of soil being above a given level of soil matric potential for a series of consecutive days and also for defining the probability of runoff from a soil for a given slope. To define the excessive surface applied stress in terms of soil hydraulic characteristics, we need to define the acceptable number of consecutive days for which soil can remains wet, an acceptable level of runoff and acceptable probabilities associated with each of these factors. Once the surface applied load are defined that donot cause excessive runoff or longer wetness, these loads can then be incorporated as separate criterion in defining the susceptibility of soils to excessive compaction.

Table 14. Classification of Blount silty clay loam, Sharpsburg clay loam and Webster clay loam according to the most limiting condition defining excessive compaction at the surface applied load of 2724 kg.

Soil Type	$v = 3$ ($\psi = -1500$ kPa)	$v = 4$ ($\psi = -500$ kPa)	$v = 5$ ($\psi = -100$ kPa)	$v = 6$ ($\psi = -33$ kPa)
	- - - - - category and limiting condition ⁺ - - - - -			
Blount	I	III (Sh)	IV (Sh,60)	V (Sh,60)
Sharpsburg	I	II (Sh,60)	IV (Sh,60)	V (Sh,60)
Webster	I	I	I	I

⁺ Category corresponding to the greatest penetration of all the limiting conditions. Letters and numbers in the parentheses define the most limiting condition associated with the given category. Sh = stress > shear stress, 60 = degree of saturation $\geq 60\%$, D = Diffusion = 0.

Table 15. Classification of Blount silty clay loam, Sharpsburg silty clay loam and Webster clay loam according to the most limiting conditions defining excessive compaction at three levels of surface applied loads and concentration factor, ν , of 3 ($\psi = -15$ kPa) and 4 ($\psi = -500$ kPa).

Soil Type	$\nu = 3$ ($\psi = -1500$ kPa)			$\nu = 4$ ($\psi = -500$ kPa)		
	2724	1907	1090	2724	1907	1090
	- - - - -Surface Applied Loads, Kg- - - - -					
	- - - - -Category and limiting condition ⁺ - - - - -					
Blount	I	I	I	III(Sh)	II(Sh)	I
Sharpsburg	I	I	I	II(Sh,60)	I	I
Webster	I	I	I	I	I	I

⁺ Category corresponding to the greatest penetration of all the limiting conditions. Letters and numbers in the parentheses define the most limiting condition associated with the given category. Sh = stress $\geq$ Shear stress, 60 = degree of saturation $\geq$ 60%.

Table 16. Classification of Blount silty clay loam, Sharpsburg silty clay loam and Webster clay loam according to the most limiting condition defining excessive compaction at three levels of surface applied loads and concentration factor, v , of 5 ($\psi = -100$ kPa) and 6 ($\psi = -33$ kPa).

Soil Type	$v = 5$ ($\psi = -100$ kPa)			$v = 6$ ($\psi = -33$ kPa)		
	2724	1907	1090	2724	1907	1090
	- - - - - category and limiting condition ⁺ - - - - -					
Blount	IV (Sh,60)	III (Sh)	II (Sh)	V (Sh,60)	IV (Sh)	III (Sh,60)
Sharpsburg	IV (Sh,60)	III (Sh,60)	II (Sh,60)	V (Sh,60)	IV (60)	III (Sh,60)
Webster	I	I	I	I	I	I

⁺ Category corresponding to the greatest penetration of all the limiting conditions. Letters and numbers in the parentheses define the most limiting condition associated with the given category. Sh = stress > Shear stress, 60 = degree of saturation > 60%.

FIELD STUDY

Objective

The objective of the field study was to relate root growth rates as affected by applied mechanical stress under laboratory conditions to rates observed under field conditions.

Material And Methods

Replicated field studies were initiated in the fall of 1986 on a Webster clay loam located in the southern Minnesota. This soil was also used in the detailed laboratory study. The plot site was compacted by the wheel traffic from a vehicle with axle load of 21 Mg applying a surface pressure on the soil of about 230 kPa. This applied pressure was within the range used in the laboratory study on re-molded soil cores. This treatment was imposed to produce compaction in the sub soil (deeper than 30 cm). A control treatment received no heavy wheel traffic. Both treatments were then tilled to a depth of 20 cm to ameliorate compaction in the surface layer of soil. The following spring, bulk density and penetrometer resistance were slightly higher in the 20-40 cm depth on the treatments that received the high axle load the previous fall.

Corn was planted on all plots in May, 1987. Within a few days after planting, mini-rhizotron tubes were installed. These tubes are transparent plastic tubes inserted into the soil for later observation of root growth by means of a small video camera. The tubes were installed under the plants and inclined at an angle of about 27 degrees from the vertical. By observing and recording the intersection of roots by the clear plastic tubes over a period of time, quantitative estimations of root length can be made. One of the limitations of this methodology is the requirement that there be excellent contact between the soil and the plastic tube, plus that the soil in direct contact with the tube not be physically different than the bulk soil some distance away from the tube. For Webster clay loam, with occasional small stones, this was not possible with the equipment available for installation. Thus, there were some serious limitations to the collection and interpretation of data. Preliminary experiments showed that considerable effort would be needed to modify and perfect a satisfactory method that would work for this soil. Such an effort was beyond the scope and resources of this study. Thus, the observation of root growth under field conditions was abandoned after the initial year.

In spite of the inability to get quantitative root length measurements, it was possible to get an estimate of root depth (Fig.70). Problem with the equipment prevented timely measurements until the end of the growing seasons. At that time, the data shows that rooting depth was about 20 cm deeper in the non-compacted soil than in the compacted soil. However, there was no difference in corn grain yield. Neither could these limited root growth data be related to bulk density or penetrometer resistance.

Figure 70. Rooting depth of maize as affected by subsoil compaction.

SUMMARY

Compaction of soil is a problem of worldwide concern because of (1) larger tractors, tillage, and harvesting equipment; (2) increases in intensive cropping practices; and (3) new lands being brought into cultivation particularly in the tropics. Excessive compaction lowers the rate of movement of water and air through soil, decreases plant root proliferation, reduces the plant population and consequently decreases crop yields.

Limited information is available about variables and levels that could be used to define excessive soil compaction. Most often bulk density has been used as an indicator of excessive compaction. In reality, primary indicator of excessive compaction is not the bulk density but those soil physical properties which directly control flow mechanism or soil mechanical behavior. Currently, limited information exist on the effects of compaction on soil properties related to flow mechanisms and mechanical behavior. The objectives of this study were to (1) investigate the effects of applied stress and soil wetness on soil physical properties and root growth parameters that characterize excessive compaction and then (2) present a method of characterizing and classifying soils as to their susceptibility to excessive compaction.

The report discusses the results of laboratory studies on the changes in soil physical and root growth properties at four applied stresses and four soil wetness conditions at the time of compaction. The soils in the United States study included Blount silty clay loam from Ohio, Cecil loamy sand from Alabama, Holtville silty clay from California, Miles loamy sand from Texas, Norfolk loamy fine sand from South Carolina, Sharpsburg silty clay loam from Nebraska, and Webster clay loam from Minnesota. These soils are known for susceptibility to compaction. Laboratory measurements included air permeability, saturated hydraulic conductivity, water retention characteristics, gas diffusion coefficient, penetration resistance, and corn seedling root growth. Air permeability of all seven soils decreased with an increase in air-filled porosity. Combined data of all seven soils showed that within an order of magnitude the air permeability was uniquely related to air-filled porosity irrespective of soil types, applied stress and soil matric potential at the time of compaction. Similarly, saturated hydraulic conductivity of all seven soils increased with an increase in total porosity but there was no unique relationship covering all seven

soil types. Diffusion coefficient of four soils was uniquely related to air-filled porosity irrespective of soil type, applied stress and soil matric potential. Between air-filled porosity of 5 and 10 percent, diffusion coefficient of all four soils was zero. Root growth rates of corn seedling decreased with an increase in penetration resistance but there was no unique relationship when data was grouped by texture.

Based on the data in this study and the literature, two sets of criterion were defined to delineate stresses that cause excessive compaction. The first set of criterion assumed that stresses are excessive if they increase the penetration resistance of soil to >2 MPa (root growth stops), or if the diffusion of oxygen is nearly absent (air-filled porosity $<10\%$). The second set of criteria assumed a stress as excessive, if it results in laboratory measured corn seedling root growth of less than 0.1 cm hr^{-1} or if the aerobic microbial activities are less than optimal (degree of saturation less than 60%). Selection of 0.1 cm hr^{-1} as a limiting root growth rate is based on the assumption that these low values of laboratory measured root growth rates can not be sustainable for long times in the field. Based on earlier studies of the authors on pore water pressure changes during compaction, an additional criteria on the degradation of soil aggregates due to excessive compaction was also included in the classification scheme.

The data from the present study showed that above criterion of excessive compaction were generally applicable to fine-textured soil. The major consequences of excessive compaction in coarse-textured soils were an increase in soil resistance to root growth and a lack of sufficient available water for plant growth.

The procedure for classifying soils according to their susceptibility to excessive compaction is based on the concept of predicting the deepest penetration of soil and plant limiting condition for a given soil type, applied stress and soil wetness condition. The procedure uses the criterion of excessive compaction and the data base developed in this study in conjunction with the output of iso-stress lines from our earlier soil compaction model. The application of the procedure was demonstrated by comparing the susceptibility of Webster clay loam, Blount silty clay loam, and Sharpsburg silty clay loam. For a given applied stress and soil wetness condition, Sharpsburg

silty clay loam was more susceptible to excessive compaction followed by Blount silty clay loam and Webster clay loam. The application also showed how this procedure can be used to define maximum applied stress that is not conducive to excessive compaction for a given soil type and soil wetness condition.

Since wetness and applied stress for a given soil type will vary due to variation in weather conditions and variation in field equipment, respectively, the classification procedure in this report describes the degree of excessive soil compaction on a probability basis. A procedure based on a water balance model is suggested to predict the variation in soil wetness from long-term weather records. Using the soil hydraulic properties at various applied stresses, the procedure also defines the probabilities of a soil remaining wet (above a given soil matric potential) for a given number of consecutive days. Although, in this report increase in number of days a soil remains wet due to applied stress is not included as a criteria in classifying soils, it is strongly recommended that this criteria be included in future classification schemes for defining excessive compaction. All simulations in the current report assumed a level soil with all rain water infiltrating into the soil and hence no runoff. It is recommended that the future classification system also include the topographic features of a soil during the simulation of soil wetness probabilities and develop a criteria of excessive compaction based on the increases in surface runoff as a result of applied stress.

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Final Report on BARD project No.

entitled:

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The Israeli Report was prepared by

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Objectives of the Research

Soil compaction has become a problem of worldwide concern, since a) new lands are brought into cultivation and on others agricultural practices are intensified; b) traditional tillage practices are converted into highly mechanized tillage, plant control and harvesting practices resulting in c) increasing loads and power systems such as heavier tractors to till and spray, larger and heavier crop harvesters and tracked conveyors. All result in increased soil compaction conducive to impaired air, water and soil strength conditions for plants, namely, lower plant roots proliferation in the soil reduced water and air transport through soil. All these factors ultimately lead to reduced, highly variable crop stands lower yields and further soil degradation.

The original objectives of this project were:

Major Objective: To define relationships of soil physical and mechanical properties and processes to soil compaction including the threshold values that would characterize excessive compaction."

The general objective was subdivided into the following "specified objectives":

- a. To develop relationships of soil resistance to penetration, bulk density, water content, root development and proliferation;
- b. To develop relationships of hydraulic conductivity and air permeability so influenced by soil density and packing or compacting mechanisms;
- c. To compare and validate the laboratory measured soil physical properties with measured limits of excessive compaction in the field.

These objectives were drawn in view of the a) existing models to predict the distribution of applied mechanical stresses and their effects on soil compaction (Soene 1953, 1958; Gupta et al. 1985); and b) the acknowledged gap between this capability and the knowledge of soil compaction levels detrimental to plant root development, soil water and air regimes, biotic activity and soil structure maintainance.

The tests program had to be partially curtailed in view of fiscal cuts by the BARD's Board members. The extent of field work for validating the laboratory findings had to be narrowed down to some field observations of

compaction, infiltration rates and hydraulic conductivity. Other soils then contemplated (clays) have been added into the program (e.g., sandy loams or other soils highly susceptible to compaction).

BODY OF THE REPORT

Introduction

This report consists of the following sections, arranged in accordance with the objectives listed above:

- a. Chemical and physical properties of the nine Israeli soils used for the experiments;
- b. Induced changes by soil compaction in the soils: bulk density, total porosity, air-filled porosity, void ratio, hydraulic conductivity, air permeability, and resistance to cone penetration, as affected by initial water contents and applied compressive loads. This data will be presented for each soil in a sequential order as given in (a);
- c. Field validation of: compaction-induced soil compression (bulk density, measured vs. predicted); hydraulic conductivity, measured as final infiltration rate and estimates of seepage from compacted water reservoir, using field-measured soil bulk densities, use of laboratory-measured hydraulic and capillary conductivities, and field-validated final infiltration rates;
- d. Comparison between standard cone penetrometer used in field and laboratory (sec. b) and fine needles (section d);
- e. Root elongation rates in a soil packed to different bulk densities as affected by transpiration, soil bulk densities, water contents and resistance to penetration of fine gauge penetrometer needles;
- f. Estimates of cotton root system degrees of proliferation under different soil density, strength and water contents prevailing in the field;
- g. General discussion of the results presented and suggestions for future research.

a. Soil characterization procedure

Nine different soils were chosen for this project. These soils cover soils ranging from pure sands on which vegetables and bulks are grown under highly mechanized drip irrigation systems to clay soils. Out of the selected nine soils, six are highly susceptible to compaction.

Approximately 50 kgs of soils for each soils were sampled from nine sites typical to the genetic designation of the selected soils (Table 1). The soils are given by their common name (e.g., Nahal Oz) or sign given by the soil survey staff of the Soil and Water Institute, Drs. M. Koyumdjisky and J. Dan (e.g., BG-27, G-37).

The samples were brought to the laboratory (at the Technion or A.R.O.-Yolcani Center) and dried to air-dryness, then crushed, sieved to 2mm size and mixed thoroughly.

Table 1: Soil designations and their physical chemical and mechanical characteristics

Soil <3	Soil characteristics		Water retention										C.E.C. <1		ESP ⁽¹⁾	Organic matter (%)	S.S.A ⁽¹⁾ [m ² /g]	CaCO ₃	Atterberg ⁽¹⁾ limits		Proctor ⁽²⁾ Mg.m ³ / (g.w./w)	Remarks ⁽⁴⁾
	Texture -- (W/W%)	clay	Silt	Sand	dry	-1.5	-0.5	-0.1	-0.03	-0.01	[mmole.kg ²]	<1	<1	PL					LL			
Taxonomical designations																						
1	Typic Quartzipsamment	0.3	1.2	98.5	0.2	0.9	1.4	1.8	3.1	6.8	-	-	-	15.8	0.37	15.0	--	--	--	--	Sharon 2, clay fraction consists of mostly Montm. 75% & Kaolin. 25%	
2	Typic Xerochrept	3.9	3.3	92.8	0.6	1.5	1.8	2.6	3.8	7.0	38.0	-	-	2.0	0.23	86.0	0.2	19.8	29.9	1.838 /16.2	Natanya 8, Clay fractions similar to Sharon 2.	
3	Typic Rhodoxeralf	22.6	6.2	71.2	3.2	8.6	10.5	13.1	17.5	25.9	136	-	-	2.1	0.47	136	0.2	16.3	45.2	1.138 /15.2	Natanya 6, Clay made of approx. 80% Montm. & 20% Kaolinite.	
4	Typic Rhodoxeralf	35.2	14.5	50.3	5.5	14.5	17.5	20.5	25.5	36.2	234	-	-	1.4	0.9	135	--	19.1	35.2	1.762 /23.2	Golan 37 or G-37, Clay fraction made of some smectites, but mostly of Halloysite amorphous Quartz and ~9% FeO ₃ .	
5	Typic Rhodoxeralf	55.4	34.9	9.7	4.8	13.3	16.2	20.1	27.8	36.8	231	-	-	4.3	2.6	108	11.3	21.7	34.3	1.791 /15.1	Kfar Aza or Nahal Oz, Clay fraction made ~45% Montm., 5% Illite, and 40% Kaolinite	
6	Calcic Haploxeralf	18.1	28.3	51.7	2.1	8.1	11.0	14.2	18.3	26.1	151	-	-	3.2	1.7	269	15.1	25.7	51.0	1.562 /22.0	Vertic Soil or Nachsholim. Almost purely Montmorillonite.	
7	Aquic Chromoxerert	54.1	37.0	8.9	8.4	16.1	20.6	25.8	30.2	38.4	412	-	-	3.1	5.2	74	64.7	34.9	48.3	1.391 /31.0	Bet Gubrin 27 or BG 27 (at Hitzpe Mashua)	
8	Eutric Haploxerol	22.7	62.4	14.9	4.1	14.5	22.0	26.9	33.1	38.3	18.2	-	-	17.9	--	92	22.5	19.2	25.1	1.785 /22.1	Fatzael or K-28, Clay made of mostly Montm.	
9	Typic Haplagrid.	29.3	46.0	23.2	3.2	12.7	16.8	20.6	27.6	37.8	262	-	-	-	-	-	-	-	-	-	-	

1. Soil characteristics were taken from Smith et al. 1985.

2. Proctor is given as maximal soil bulk density [Mg.m⁻³] at water content on (w/w %) basis.

3. Soil Taxonomy is based on USDA soil classification. Local names/signs are given under remarks.

4. Characterization of clay mineralogy was given by Drs. H. Koyumdjisky and M. Gal, of the Div. of Soil Genesis and Pedology and Div. of Physical Chemistry of Soils, Soil and Water Institute, A.R.O. - Volcani Center, Bet Dagan, Israel.

Subsamples were then subjected to the following laboratory procedures in order to determine their texture, chemical composition and physical properties or characteristics. (The data were compiled and given in Table 1, means out of two to three replicates.)

- Particle size distribution (texture) was determined by the hydrometer method (Day 1956). Soil water retention values were determined following methods, suggested by the Soil Survey staff (1975).

Cation exchange capacity and Exchangeable Sodium percentage (C.E.C. and E.S.P., respectively, were determined following procedures suggested by U.S. Soil Survey staff (1975).

Organic matter content was determined from Organic carbon content (Jackson 1958) multiplied by a factor 1.724. Calcium carbonate contents were determined using the Hydrochloric acid volumetric procedure (Schlichting and Blume 1966, see Soil Survey Staff 1975). The CO_2 volumes measured were calculated to yield a mass of CaCO_3 .

Specific surface area was determined by the Ethylen Glycol method (Mostland and Kemper 1965).

Soil consistency (Atterberg limits) and Proctor density were determined according to Lower (1965).

(-- Table 1 --)

Sampling locations - Notes:

Sand Soil, No.1, (Typic Quartzipsamment) was taken from an uncultivated plot next to a cultivated plot.

Soils No. 2, 3 and 4 come from a soil sequence (a catena) and exhibit varying degrees of pedogenic development (increased weathering and alluviation of clay) within the same sequence (Typic Rhodoxeralf) developed on sand dunes and calcified sand stones, found along the Mediterranean sea coast in Israel.

Soil no.5 (Typic Rhodoxeralf) is a clay soil which developed from Volcanic parent material (pumic, volcanic dust and basaltic deposits), and is located in the Golan Heights.

Soil No.6 (Calcic Haploxeralf) is typical to the Negev soils. It is an aeolic, fluvatile, loessial

soil which covers large areas in the southern coastal plain and the Negev desert.

Soil No. 7 is typical to the inner valleys of Israel and alluvial troughs along the mediterranean coastal plain in Israel. This soil is a very active vertisol (Aqui Chromoxerert) which swells and shrinks to large extents forming wide cracks in the summer and is practically saturated for several weeks every rainy winter.

Soil No.8 (Eutric Haploxeralf) is typical to the cultivated hillsides and plateaus and developed on marshy, soft chalk deposits.

Soil No. 9 (Typic Haplargid) is an alluvial soil formed in the rain "shade" caused by the Judean and Samarian hills, (rainfall varies between 450 to 300 mm annually).

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B. Changes in soil physical and mechanical properties induced by soil compaction

The soil compaction process affects agricultural production, soil and water losses, consequently, it poses many problems to soil and water conservationists, farmers, agricultural engineers, soil scientists, etc. The effects that soil compaction has on agricultural production have received wide attention, and hence soil compaction has been researched as to its causes, modes of measuring it and the assessment of its effects on agricultural practices (Barnes, Taylor 1971), and means to alleviate its effects (Taylor and Arkin 1982). Recently, Soans (1985), in his review on soil compaction and its modelling, summarized his opinion that soil compaction appears to be a simple process, yet, is very difficult to describe and predict, due to the highly complex and broad range of soil characteristic variability as well as the complexity of defining the natural and applied stresses affecting soils.

In a previous BARD Report (US-337-80), a large database on soil compression characteristics was established, and soil compression characteristics were related to rather easily measured soil properties (e.g., texture, clay content). A finite differences model was developed (Gupta and Larson 1982) that links compressive stress distributions in the soil to simple laboratory measurements (e.g., virgin soil compressive curve) yielding bulk density changes in the soil, and finally soil bulk density distributions predicted by the model were compared to those measured under field and soil bins conditions, to validate the model developed. The model provides means to predict iso-density or porosity profiles in the soil after wheel traffic. The laboratory tests led to suggest a procedure to delineate the range of permissible loads or applied stresses at given water contents which may not be conducive to excessive compaction. The problems of what is it that determines excessive compaction or what are the exact permissible loads not conducive to excessive compactions were left unattended. The missing bits of information at that stage were the changes in the transport characteristics of water, gases and the rooting characteristic changes due to soil compaction and their relations to the soil physical properties (texture, surface area and consistency). The existing information is scarce, incomplete and at times self-negating. Akram and Kemper (1979) have shown that for similar soil densities attained under varying soil water contents different final infiltration rates were measured. Davidovski and Koolen (1985) have shown that for similar soil density attained under differing combinations of spherical and deviatoric stresses, namely varying compressive and shear loads, hydraulic conductivities, and air permeabilities, decreased as shear stress was increased. Effects of soil structure on compression and water or air transport characteristics were not studied.

Soil sampling and testing procedure (flow chart)

Soil sampled in the field, air-dried,
crushed and sieved through 2 mm sieves.

Soil samples were wetted and mixed
simultaneously to reach the predetermined
water content, corresponding to the matrix
on the right.

Soil samples were taken and analyzed for soil
characteristics: texture, chemical constituents
water retention, and mechanical properties
(see Table 1).

Sub samples 6 replicates per ψ x σ_n
combinations were subject to the proper
 σ_n for 1 min, at this in 3 1/2" diam ± 3 "
high cell's rings.

Predesignated normal compressive loads
 σ_n and water contents matrix potentials
 ψ

Bulk density D volumetric water content θ_v
air filled velocity θ_a , porosity η and
void ratio - calculated

ψ [MPa]	0.01	0.03	0.10	0.50	1.5
σ_n [kPa]					
50	+	+	+	+	+
100	+	+	+	+	+
200	+	+	+	+	+
400	+	+	+	+	+

3 samples - closed in Large Tempe Cells,
and air permeability was determined.
then CO_2 was passed to flush air and
prepare the samples for K_{sat} .

Air permeability calculated

3 samples were subjected to measurements of
resistance to penetration to a cone 30° apex
angle.

Samples discarded.

Samples were saturated from below and
measurements of saturated hydraulic
conductivity was made using falling head
procedure.

K_{sat} - hydraulic conductivity was calculated

(Provisional)

One sample was subjected to two steps,
outflow test to -0.1 and -0.5 MPa

Two samples were subjected to retention pressure
plate tests - to obtain retention of water at
-0.01; 0.03; -0.05 -0.01 and -1.5 MPa

(Provisional)

K_{unsat} - capillary diffusivity was calculated

Samples were discarded

Results

The results obtained will be presented for each soil separately according to the sequential order given in Table 1. The points represent the averages of three replicates each.

1. Typic Quartzipsamment - Sandy Soil

As pointed above, this sand was chosen since it is part of a soil sequence on which vegetable and bulb crops are grown under intensive drip irrigation and heavy traffic practices. As it consists almost entirely of sand grains compression of most samples did not affect their bulk densities or total porosity (Figs. 1-1,2,3,4). This is due to the high friction between the sand grains and cell walls friction which in turn reduced the effective compressive stress on the samples.

Air permeability k_a was found to be very high as expected due to the rather large voids to be found between coarse sand grains. There is a definite reduction in k_a with load (reduced porosity)-Fig.1-5, and water content. When same data are plotted against air-filled porosity there is a unified line showing a marked reduction in k_a with reduction in air-filled porosity (Fig.1-6).

Hydraulic conductivity K_{sat} shows the same trends as air permeability k_a except that when plotted vs. void ratio (Fig.1-8) or porosity no single line can be drawn. The apparatus for K_{sat} determination could not allow fast flows and thus the initial head had to be lowered to few cm. Therefore a large error was introduced and it is believed that the absolute values could be higher by an order of magnitude.

Sand resistances to cone penetration are not realistic since the sand did not reach high densities and holds almost no cohesion. Resistances to cone penetration were determined only when cone top surface became flush with the samples surface. Thus only the resistance to the cone forming a cavity was registered. As such the values reflect only the non-existing cohesion, sandwater minisci pull and sand-steal friction effects (Bradford 1980).

In Figure 1-11 diffusivities to water vs. volumetric water content are given for five out of twenty combinations of water content*loads.

Soil No.2 - Sharon 2 - (Typic Xerochrept)

This soil consists as Soil No.1 mostly of sand fractions and only 4% clay. Therefore, high sand-metal friction precluded attainment of high soil densities or low porosities and void ratios that are found in the field ($P=1.62$ to 1.70 Mg.m^{-3}). The highest density attained was similar to that of the sandy soil (No.1) around $1.5 [\text{Mg.m}^{-3}]$. In Figs. 11-1 to 11-4 the measured bulk densities, void ratios, total and air-filled porosities are given.

Fig. 1-1. Total porosities n [$\text{m}^3 \cdot \text{m}^{-3}$] as functions of loads ζ_n [kPa] and initial water potentials ψ [kPa]

Fig. 1-2. Airfilled porosities θ_a [$\text{m}^3 \cdot \text{m}^{-3}$] as functions of loads $\bar{\sigma}_n$ [kPa] and initial water potentials ψ [kPa]

Fig. 1-3. Void ratios e as functions of loads σ'_n [kPa] and initial water potentials ψ [kPa]

Fig. 1-4. Soil bulk densities [$\text{Mg}\cdot\text{m}^{-3}$] as functions of loads ζ_n [kPa] and initial water potentials ψ [kPa]

Fig. 1-5. Air permeabilities k_a [cm²] as functions of loads c'_n [kPa] and initial water potentials ψ [kPa]

Fig. 1-6. Air permeabilities k_a [cm²] as functions of airfilled porosities θ_a [m³·m⁻³].

Fig. 1-7. Hydraulic conductivities K_{sat} [$m \cdot day^{-1}$] as functions of loads c'_n [kPa] and initial water potentials ψ [kPa]

Fig. 1-8. Hydraulic conductivities K_{sat} [$m \cdot day^{-1}$] as functions of void ratio e and initial water potentials ψ [kPa]

Fig. 1-9. Resistances to penetration [kPa] as functions of loads ζ_n [kPa] and initial water potentials ψ [kPa]

Fig. 1-10. Resistances to penetration [kPa] as functions of soil bulk density $\rho[Mg \cdot m^{-3}]$ and initial water potentials $\psi[kPa]$

Fig. 1-11. Diffusivities to water [$\text{cm}^2 \cdot \text{day}^{-1}$] as functions of loads σ_n [kPa], initial water potentials ψ [kPa] and volumetric water contents θ [$\text{m}^3 \cdot \text{m}^{-3}$].

Air permeabilities decreased under higher loads and water content as expected (Fig. II-5). Measured air permeabilities when plotted against air-filled porosities did not merge to a common line but rather remained in four lines with the same general trend of diminishing air permeability with decreasing air-filled porosity (Fig. II-6).

Hydraulic conductivities diminished as compressive loads and initial water contents increased (Fig. II-7 and 8). When hydraulic conductivities are drawn as functions of void ratio they cluster, yet form four distinct lines for each load-water content combination as found for the sand (soil No. 1), with a general trend of decreasing hydraulic conductivity with diminishing void ratio.

Resistances to cone penetration increase with loads or bulk density and diminish with initial water content. The observed relationships result from increased soil cohesion and metal-soil friction with bulk density and which in turn diminish as water content increases and serves as lubricant in soil-metal interface friction (Figs. II-9 and 10).

Soil No. 3 - Natanua 8 - (Typic Rhodoxeralf)

This soil is one of the four soils of a catena (Soils #1, 2, 3 and 4), and areawise it is the prevailing one. Due to its 22% clay it is designated as Sandy Clay Loam.

In Figs. III - 1 to 4, volume changes caused by applied load in the soils, bulk density, void ratio, total and air-filled porosities, are given. Same patterns observed for soils 1 and 2 are discerned in these figures, with two exceptions: 1. for the high initial water content highest load did not cause the highest bulk density since saturation was attained and soil consolidation was not complete although water started to ooze out, and b) under these conditions air permeability could not be determined samples with the highest initial water content, as given in Figs. III - 5 and 6.

There is a definite trend: as total and air-filled porosities diminish air permeabilities decrease, and when plotted versus air-filled porosity θ_a there is a definite one line for all water content, loads combinations. This clustering into a common line or almost so suggests the air conducting voids in all samples to be arranged the same way for the same void ratio, irrespective of the initial water content, load combinations.

total porosity, n
(cu. cm/cu. cm)

soil 2

Fig. II-1. Total porosities $n[m^3.m^{-3}]$ as functions of loads $\sigma_n[kPa]$ and initial water potentials $\psi[kPa]$

Fig. II-2. Void ratios e as functions of loads ζ_h [kPa] and initial water potentials ψ [kPa]

soil 2

Fig. 11-3. Soil bulk densities $[Mg.m^{-3}]$ as functions of loads $\zeta_n [kPa]$ and initial water potentials $\psi [kPa]$

air filled porosity
(cu. cm/cu. cm)

soil 2

Fig. 11-4. Airfilled porosities θ_a [$\text{m}^3 \cdot \text{m}^{-3}$] as functions of loads ζ_h [kPa] and initial water potentials ψ [kPa]

air permeability (sq. cm.)

soil 2

Fig. II-5. Air permeabilities k_a [cm²] as functions of loads ζ_h [kPa] and initial water potentials ψ [kPa]

Fig. 11-6. Air permeabilities k_a [cm^2] as functions of initial water potentials ψ [kPa] and airfilled porosities θ_a [$\text{m}^3 \cdot \text{m}^{-3}$]

Fig. II-7. Hydraulic conductivities K_{sat} [m.day⁻¹] as functions of loads σ_n [kPa] and initial water potentials ψ [kPa]

Fig. II-8. Hydraulic conductivities K_{sat} ($m \cdot day^{-1}$) as functions of void ratio e .

Fig. 11-9. Soil resistances to penetration [kPa] as functions of loads ζ_h [kPa] and initial water potentials ψ [kPa]

Fig. II-10. Soil resistances to penetration [kPa] as functions of soil bulk density $\rho[Mg \cdot m^{-3}]$ and initial water potentials $\psi[kPa]$

Fig.III-1. Total porosities $n[m^3.m^{-3}]$ as functions of loads $\zeta_h[kPa]$ and initial water potentials $\psi[kPa]$

Fig. III-2. Void ratios e as functions of loads C_n (kPa) and initial water potentials ψ (kPa)

soil 3

Fig.III-3. Bulk densities $[Mg.m^{-3}]$ as functions of loads $\zeta_h[kPa]$ and initial water potentials $\psi[kPa]$

air filled porosity
(cu. cm/cu. cm)

soil 3

Fig.III-4. Airfilled porosities e_a [$\text{m}^3.\text{m}^{-3}$] as functions of loads C_n [kPa] and initial water potentials ψ [kPa]

air permeability (sq. cm.)

soil 3

Fig.III-5. Air permeabilities k_a [cm²] as functions of loads ζ_n [kPa] and initial water potentials ψ [kPa]

Fig. III-6. Air permeabilities k_a [cm^2] as functions of initial water potentials ψ [kPa] and air-filled porosities θ_a [$\text{m}^3 \cdot \text{m}^{-3}$]

Hydraulic conductivities K_{sat} vs. loads and void ratios for different initial water contents are given in Figs. III - 7 and 8. Hydraulic conductivities depend on the loads applied and the initial water content. For a given load the K_{sat} diminishes with an increase in initial water content and so it is in a similar pattern for a given water content vs. increasing loads. One should note that for the two highest initial water contents the void ratios and total porosities were practically the same for the two highest loads (Figs. III 1-2) the corresponding K_{sat} are much lower for the highest initial water contents (2.5 and 1.75 orders of magnitude for 200 and 400 [kPs] (Fig.III-7). Plotting K_{sat} vs. void ratios the line for the highest initial water content departs by one to almost three orders of magnitude from the almost common line observed for the other water content and loads combinations. This suggests a different arrangement of voids free to water passage for the last four highest water content x load combinations to be different than those of the other combinations. We stress also the fact that there may be air blocks between water carrying voids which reduce the K_{sat} in the initial high water content samples.

Resistance to cone penetration increased with loads or bulk density (given initial water content) and diminished with water content. As observed in soil #2, there is a very marked reduction in the soil resistances to cone penetration at high soil densities and water content. These effects are more distinct than in Soils 1 and 2 due to the higher water and clay contents, which lead to lower soil-metal friction.

In Fig. III-11 diffusivities to water are given for five out of twenty water content-load combinations.

hydraulic conductivity
(m/day)

soil 3

Fig.III-7. Hydraulic conductivities K_{sat} [$m \cdot day^{-1}$] as functions of loads $\bar{\sigma}_h$ [kPa] and initial water potentials ψ [kPa]

Fig.III-8. Hydraulic conductivities K_{sat} ($m \cdot day^{-1}$) as functions of void ratio e .

soil 3

Fig. III-9. Soil resistances to penetration [kPa] as functions of loads ζ_h [kPa] and initial water potentials ψ [kPa]

Fig.III-10. Resistances to penetration [kPa] as functions of soil bulk density $\rho[Mg \cdot m^{-3}]$ and initial water potentials $\psi[kPa]$

Fig.III-11. Diffusivities to water [$cm^2 \cdot day^{-1}$] as functions of volumetric water contents $\theta [m^3 \cdot m^{-3}]$, loads $\zeta_n [kPa]$ and initial water potentials $\Psi [kPa]$.

Soil No. 4 - Natanya 6 - (Typic Rhodoxeralf)

Natanya 6 is the most developed, mature or aged soil in the "sandy" catena (soils #1, 2, 3, and 4), as such its clay content is the highest (35%) partially due to local weathering and partially by clay transferred during the rainy season from the higher points (soil #3) in the undulating land relief.

Volume changes caused by applied loads under the different initial water contents (wc) show in a more pronounced form the same patterns described for Natanya 8 (Soil #3). Namely, given high initial wc, highest densities and lowest total air-filled porosities and void ratios were attained only for the two median initial wc. This is due to the fact that for highest initial wc the lower loads brought the soil almost to saturation (Figs. IV-1-4).

As for Soil #3, air permeability could not be determined for most samples of the highest wc for any load applied and for the highest load for the second highest wc (Fig. I:V-5).

A definite trend of diminishing air permeability k_a , as void ratio and total airfilled porosities decrease, is observed and when plotted as a function of airfilled porosity one line typical to the soil emerges for all wc-load combinations. This means that all air conducting voids, irrespective of the load applied and initial wc, are connected in the same form, and the same permeability is attained.

Hydraulic conductivities K_{sat} as functions of applied loads, or void ratio for the different initial wc and loads are given in Figs. IV - 7 and 8. Hydraulic conductivity dependence on loads applied and initial wc (Fig. IV-7), show that for a given load K_{sat} diminishes with an increase in initial wc, same pattern is found for a given wc and applied loads.

The lowest K_{sat} is observed for intermediate wc and high loads. This is due to the fact that highest wc was least deformed under any load and thus its void system was only slightly destroyed. Thus the K_{sat} is relatively high (Fig. IV - 7,8).

When K_{sat} is plotted vs. void ratio all K_{sat} data obtained for the different wc - loads combinations form a common line which supports the idea that the void system has been deforming and changing in the same pattern for all load-wc combinations.

Resistances to cone penetrations increased with loads or bulk density for given initial wc and diminished with water content for given load (Fig. IV- 9 and 10). The reduction in the soil's resistance to cone penetration with wc is very marked at high bulk densities or loads and point to the reduction in metal-soil friction due to higher clay content and wc than in the other soils of the same catena.

Fig. IV-1. Total porosities $n[m^3.m^{-3}]$ as functions of loads $\sigma_n[kPa]$ and initial water potentials $\psi[kPa]$

Fig. IV-2. Void ratios e as functions of loads σ_n [kPa] and initial water potentials ψ [kPa]

soil 4

Fig. IV-3. Soil bulk densities $[Mg.m^{-3}]$ as functions of loads $\zeta_n [kPa]$ and initial water potentials $\psi [kPa]$

air filled porosity
(cu. cm/cu. cm)

soil 4

Fig.IV-4. Airfilled porosities Θ_a [$\text{m}^3 \cdot \text{m}^{-3}$] as functions of loads ζ_h [kPa] and initial water potentials ψ [kPa]

air permeability (sq. cm.)

soil 4

Fig. IV-5. Air permeabilities k_a [cm²] as functions of loads ζ_n [kPa] and initial water potentials ψ [kPa]

Fig. IV-6. Air permeabilities k_a [cm²] as functions of initial water potentials ψ [kPa] and air-filled porosities θ_a [m³·m⁻³]

hydraulic conductivity
(m/day)

soil 4

Fig. IV-7. Hydraulic conductivities K_{sat} [$m \cdot day^{-1}$] as functions of loads σ'_n [kPa] and initial water potentials ψ [kPa]

Fig.IV-8. Hydraulic conductivities K_{sat} ($m \cdot day^{-1}$) as functions of void ratio e .

Fig. IV-9. Soil resistances to penetration [kPa] as functions of soil bulk density ρ [$Mg \cdot m^{-3}$] and initial water potentials ψ [kPa]

soil 4

Fig.IV-10. Resistances to penetration [kPa] as functions of loads ζ_h [kPa] and initial water potentials ψ [kPa]

In Fig. IV-11 diffusivities to water as functions of volumetric water contents θ are given for three combinations of w_c and loads. For given initial water content and different loads ($w_c = 20\%$ w/w and $\sigma_n = 50, 400$ kPa) water diffusivities at given volumetric water contents vary and are lower for higher loads by 1/3 to 1.5 orders of magnitude than those for small loads.

Soil No. 5 - Golan 37 - Typic Rhodoxeralf

This clay soil differs from the other soils of the same type - (Typic Rhodoxeralf) e.g., Natanya 8 and 6. The parent material on which it was developed and matured was volcanic dust, pumic and some basaltic outcrop as compared to sand stones or sand dunes for the later types.

Volume changes induced by the applied loads under different initial w_c show similar patterns as described for Natanya 6 and 8, namely, total airfilled porosities and void ratio diminish and bulk density increase with increased w_c and loads except for the highest initial w_c . Samples reached apparent saturation at highest initial w_c under smallest load and those with the second highest w_c under high loads. Since compressive loads were applied for rather short durations final consolidation was not attained (Fig. V, 1-4). These effects are apparent in Figs. V - 5 and 6 where air permeability k_a becomes indeterminable (smaller than $1 \cdot 10^{-13}$ cm²) for the two last sets of samples of the high initial w_c and all loads. The measured air permeabilities follow the same pattern of diminishing k_a values with increased w_c and loads (Fig. V-5) and when plotted vs. airfilled porosity θ_a they align around a common line as found for Natanya 6.

Measured hydraulic conductivities K_{sat} decrease as initial w_c and loads increase except for the highest initial w_c where volume changes were smaller than those of the second highest initial w_c , (Fig. V-7). When K_{sat} values are plotted vs. void ratio they cluster with a rather nice fit around a common line (Fig. V-8).

Soil resistances to penetration increase with loads and bulk densities, and with low and intermediate initial w_c ; but with high initial w_c there is a large, rather abrupt decline in the soil resistance to cone penetration. This abrupt change can be attributed to the clay mineralogy consisting mostly of halloysite; hence the fast change in cohesion with increasing water contents.

Fig.IV-11. Diffusivities to water [$\text{cm}^2 \cdot \text{day}^{-1}$] as functions of volumetric water contents $\theta [\text{m}^3 \cdot \text{m}^{-3}]$, loads $\sigma_n [\text{kPa}]$ and initial water potentials $\psi [\text{kPa}]$

Fig.V-1. Total porosities $n[m^3.m^{-3}]$ as functions of loads $\sigma_h[kPa]$ and initial water potentials $\psi[kPa]$

Fig.V-2. Void ratios e as functions of loads σ_v [kPa] and initial water potentials ψ [kPa]

soil 5

Fig.V-3. Soil bulk densities $[Mg.m^{-3}]$ as functions of loads $\zeta_h[kPa]$ and initial water potentials $\psi[kPa]$

air filled porosity
(cu. cm/cu. cm)

soil 5

Fig.V-4. Airfilled porosities Θ_a [$\text{m}^3.\text{m}^{-3}$] as functions of loads ζ_h [kPa] and initial water potentials ψ [kPa]

air permeability (sq. cm.)

soil 5

Fig.V-5. Air permeabilities k_a [cm²] as functions of loads ζ_h [kPa] and initial water potentials ψ [kPa]

Fig.V-6. Air permeabilities k_a [cm²] as functions of initial water potentials ψ [kPa] and airfilled porosities θ_a [m³·m⁻³]

Fig.V-7. Hydraulic conductivities K_{sat} [$m \cdot day^{-1}$] as functions of loads ζ_h [kPa] and initial water potentials ψ [kPa]

Fig.V-8. Hydraulic conductivities K_{sat} [m.day⁻¹] as functions of void ratio e .

Fig.V-9. Soil resistances to penetration [kPa] as functions of soil bulk density ρ [$Mg \cdot m^{-3}$] and initial water potentials ψ [kPa]

soil 5

Fig.V-10. Resistances to penetration [kPa] as functions of loads σ_v [kPa] and initial water potentials ψ [kPa]

Soil No. 6 - Kfar Aza - (Calcic Haploxeralf)

Soil No. 6 is generally accepted as a loessial soil - a silty clay loam. The soil samples were taken from a site where the profile is uniform and deep (almost 3.7 m deep). The soil sampled is typical to a large region. The soil exhibits high susceptibility to surface crusting and compaction.

Volume changes under loads show the same pattern as found in the previous soils. Namely, total airfilled porosity and void ratio decrease and bulk density increase with increased loads at all initial water content except for the changes at the two highest initial water content were smaller or equal to those observed for the intermediate initial water content. This is attributed to the fact that these samples reached the state of apparent saturation and were not left long enough under load to reach the state of complete consolidation (Fig. VI, 1-4). Air permeabilities were measured only on some wc and load combinations where airfilled porosity was greater than $0.1 \text{ [m}^3 \cdot \text{m}^{-3}]$.

The few data of K_a when plotted vs. θ_a (airfilled porosity) clustered (with a relative wide spread) around a single line (Figs. VI - 5 and 6).

Hydraulic conductivities followed same patterns as for soils # 5, 4, and 3 (Figs. VI, 7 and 8). Namely, K_{sat} diminished with loads and higher wc and in some cases (Fig. VI-7), the K_{sat} values were smaller than $1 \cdot 10^{-7} \text{ m/day}$. A plot of K_{sat} values vs. void ratios yields a line common for all wc and load combinations, similar to that found and described before (soils #5 and 4).

Resistance to cone penetration shows the same patterns as those for Soils No. 5 and 4 and not No. 1 or 2 (Figs. VI, 9 and 10).

Soil No. 7 - Nachsholim - (Aquic Chromoxerert)

This vertic soil consists of an approx. 55% clay (mostly montmorillonite) and 37% silt. As such, it exhibits extreme volume changes with water content variations. Only four initial water contents were used since the highest (40% w/w) produced a slurry that could not be packed or handled because of its high fluidity.

Fig.VI-1. Total porosities $n(m^3.m^{-3})$ as functions of loads $\zeta_p[kPa]$ and initial water potentials $\psi[kPa]$

Fig.VI-2. Void ratios e as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

soil 6

Fig.VI-3. Soil bulk densities $[Mg.m^{-3}]$ as functions of loads $\zeta_h[kPa]$ and initial water potentials $\psi[kPa]$

Fig.VI-4. Airfilled porosities θ_a [$\text{m}^3\cdot\text{m}^{-3}$] as functions of loads C_h [kPa] and initial water potentials ψ [kPa]

Fig.VI-5. Air permeabilities k_a [cm²] as functions of loads ζ_n [kPa] and initial water potentials ψ [kPa]

Fig.VI-6. Air permeabilities $k_a[\text{cm}^2]$ as functions of initial water potentials $\psi[\text{kPa}]$ and airfilled porosities $\theta_a[\text{m}^3 \cdot \text{m}^{-3}]$

Fig.VI-7. Hydraulic conductivities K_{sat} [$m \cdot day^{-1}$] as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

Fig.VI-8. Hydraulic conductivities K_{sat} (m.day⁻¹) as functions of void ratio e .

Fig.VI-9. Soil resistances to penetration [kPa] as functions of soil bulk density $\rho[Mg \cdot m^{-3}]$ and initial water potentials $\psi[kPa]$

Fig. VI-10. Resistances to penetration [kPa] as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

As for other soils, total airfilled porosities and void ratios decreased while bulk density increased with increasing water contents and/or loads (Figs. VII, 1-4). Marked reductions in air permeabilities k_a were observed with increased wc and loads or reduction in airfilled porosity, as expected (Fig. VII, 5-6).

Hydraulic conductivities diminished with loads and initial water contents (Fig. VII-7), and when K_{sat} are plotted vs. void ratio the values cluster around a common line with rather small data scattered around the line.

Soil resistances to cone penetration decrease with water content and increase with loads or soil bulk density (Figs. VII, 9 and 10).

Soil No. 8, BG-27 or Mitzpe Maresha, (Eutric Haploxeralf)

This soil is unique because of its origin and constituents. The parent material is either soft chalk of senonian depositions or marls.

Almost two third of this soil material is calcium carbonate, mostly in the silt-size fraction, and its organic matter content is 5%, a rare, rather high value as seen from other soil data in Table 1.

Total airfilled porosities and void ratios decrease and bulk densities increase with increased water content and loads (Fig. VIII, 1-4). Apparent saturation was reached under low load for the highest wc, intermittent loads for second highest wc and highest load for third highest wc (Fig. VIII-4)

resulting in attaining fewer data sets of air permeabilities (Fig. VIII-5). Average values of air permeability plotted against airfilled porosity yield a tight fit to a common line, showing reduced k_a values with increased water content and loads and decreasing airfilled porosities (Figs. VIII, 5 and 6).

Hydraulic conductivities K_{sat} decreased as initial water contents and loads increased (Fig. VIII-7) and fall along a single line, though with rather a wide-scatter, when plotted versus void ratios (Fig. VIII-8).

Resistances to cone penetration increased with loads or bulk density but diminished with increased initial water contents (Figs. VIII, 9 and 10).

Fig.VII-1. Total porosities $n[m^3.m^{-3}]$ as functions of loads $\tau_n[kPa]$ and initial water potentials $\psi[kPa]$

Fig.VII-2. Void ratios e as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

soil 7

Fig.VII-3. Soil bulk densities [Mg.m⁻³] as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

Fig.VII-4. Airfilled porosities θ_a [$\text{m}^3.\text{m}^{-3}$] as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

Fig.VII-5. Air permeabilities k_a [cm²] as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

Fig.VII-6. Air permeabilities $k_a[\text{cm}^2]$ as functions of initial water potentials $\psi[\text{kPa}]$ and airfilled porosities $\theta_a[\text{m}^3 \cdot \text{m}^{-3}]$

hydraulic conductivity
(m/day)

soil 7

Fig.VII-7. Hydraulic conductivities K_{sat} [$m \cdot day^{-1}$] as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

Fig.VII-8. Hydraulic conductivities K_{sat} (m.day⁻¹) as functions of void ratio e .

Fig.VII-9. Soil resistances to penetration [kPa] as functions of soil bulk density $\rho[Mg \cdot m^{-3}]$ and initial water potentials $\psi[kPa]$

soil 7

Fig.VII-10. Resistances to penetration [kPa] as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

Fig.VIII-1. Total porosities $n[m^3.m^{-3}]$ as functions of loads $\tau_n[kPa]$ and initial water potentials $\psi[kPa]$

Fig.VIII-2. Void ratios e as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

soil 8

Fig.VIII-3. Soil bulk densities [Mg.m⁻³] as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

air filled porosity
(cu. cm/cu. cm)

soil 8

Fig.VIII-4. Airfilled porosities Θ_a [$\text{m}^3.\text{m}^{-3}$] as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

air permeability (sq. cm.)

soil 8

Fig.VIII-5. Air permeabilities k_a [cm²] as functions of loads τ_n [kPa] and initial water potentials ψ [kPa]

Fig.VIII-6. Air permeabilities $k_a[\text{cm}^2]$ as functions of initial water potentials $\psi[\text{kPa}]$ and airfilled porosities $\theta_a[\text{m}^3 \cdot \text{m}^{-3}]$

soil 8

Fig.VIII-7. Hydraulic conductivities K_{sat} [$m \cdot day^{-1}$] as functions of loads $\bar{c}_h$ [kPa] and initial water potentials ψ [kPa]

Fig.VIII-8. Hydraulic conductivities K_{sat} ($m \cdot day^{-1}$) as functions of void ratio e

Fig.VIII-9. Soil resistances to penetration [kPa] as functions of soil bulk density $\rho[Mg \cdot m^{-3}]$ and initial water potentials $\psi[kPa]$

soil 8

Fig.VIII-10. Resistances to penetration [kPa] as functions of loads C_n [kPa] and initial water potentials ψ [kPa]

Soil No. 9., Fatzeal or K-28. (Typic Haplargid)

Texturally, this soil consists of almost 50% silt and as such is a silty, clay loam. Volume changes at different initial water contents under differing compressive load show a diminishing total airfilled porosities and void ratios and increase in bulk densities with initial wc and loads except for samples at the highest water contents which reached apparent saturation under small loads (Fig. IX, 1 to 4) and thus air permeabilities k_a values became immeasurable (Fig. X-5). Air permeability data when plotted vs. airfilled porosity yields a single line (Fig. IX-6).

Hydraulic conductivities K_{sat} diminished with increasing loads and initial water contents (Fig. IX-7), yet, unlike previous soils the K_{sat} observed at the highest water content was even lower than those obtained at lower wc and lower void ratios (see Fig. IX - 8). All other wc and load combinations yielded when plotted vs. void ratio a common line.

Resistance to penetration increased with bulk density and loads and the first two initial water contents and diminished as initial water content increased further on (Figs. IX, 9 and 10).

Fig. IX-1. Total porosities n [$\text{m}^3 \cdot \text{m}^{-3}$] as functions of loads ζ_n [kPa] and initial water potentials ψ [kPa]

Fig. IX-2. Airfilled porosities θ_a [$\text{m}^3.\text{m}^{-3}$] as functions of loads ζ_h [kPa] and initial water potentials ψ [kPa]

soil 9

Fig. IX-3. Void ratios e as functions of loads $\bar{\sigma}_n$ [kPa] and initial water potentials ψ [kPa]

soil 9

Fig. IX-4. Soil bulk densities [$\text{Mg}\cdot\text{m}^{-3}$] as functions of loads ζ_n [kPa] and initial water potentials ψ [kPa]

Fig. IX-5. Air permeabilities k_a [cm²] as functions of loads c_n [kPa] and initial water potentials ψ [kPa]

Fig. 1X-6. Air permeabilities $k_a[\text{cm}^2]$ as functions of airfilled porosities $\theta_a[\text{m}^3 \cdot \text{m}^{-3}]$ and initial water potentials $\psi[\text{kPa}]$.

Fig. IX-7. Hydraulic conductivities K_{sat} [$m \cdot day^{-1}$] as functions of loads ζ_n [kPa] and initial water potentials ψ [kPa]

Fig. IX-8. Hydraulic conductivities K_{sat} [$m \cdot day^{-1}$] as functions of void ratio e and initial water potentials ψ [kPa]

Fig. IX-9. Soil resistances to penetration [kPa] as functions of soil bulk density ρ [$Mg \cdot m^{-3}$] and initial water potentials ψ [kPa]

soil 9

Fig. IX-10. Soil resistances to penetration [kPa] as functions of loads ζ_n [kPa] and initial water potentials ψ [kPa]

Discussion

Common trends were found in the soils tested, namely,

- 1) Total and airfilled porosities and void ratios decreased, bulk density increased as initial water contents and loads increased, except for samples that reached apparent saturation and were not allowed to complete their consolidation while being subjected under the prescribed loads. In soils, which consist mostly of sand grains, the loads applied at the appropriate water content could not cause to high sample densities as those observed in fields. The reasons for that may be attributed to the very high sand-metal friction in the cells and lack of lubrication effects at the low water contents in these soils.
2. Air permeabilities K_a and hydraulic conductivities K_{sat} which are completely void system-dependent decreased with increased volume changes under increasing initial water contents and loads except for those samples where volume changes were small since samples reached searched apparent saturation.
3. Soil resistance to cone penetration increased with bulk density and loads and decreased with initial water contents in most soils except for those soils with high sand or silt contents where resistance to cone penetration increased loads and initial low to low-intermediate water content and decreased with further increase of initial water contents.
4. Effects of soil structure, or aggregate strength on compression, volume changes and the derived air permeabilities k_a and hydraulic conductivities K_{sat} could not be discerned, since soil samples were homogenized by crushing the soil samples and using the material that passed a 2mm opening sieve.
5. Changes in soil water retention within the range of -0.01 MPa to 0.1 MPa were measured but the data, although each set (replicate) followed the expected pattern, showed very large variability around the mean value. The high degree of variability and inconsistency may be attributed to several reasons. The first and most important one is the problem of attaining complete Saturation and plant soil content of the compressed samples prior to subjecting them to air pressure in a tempe-pressure cell or on a pressure plate apparatus. The second one is that for loamy clay and clay soils, swelling on the pressure plates caused great differences in retention measurements, or complete sample destruction during transfer to the pressure plate. Due to this inconsistency the data are not given here.

Samples flushed with CO_2 , which were allowed to conduct water and were then subjected to the diffusivity to water by outflow measurment procedure, have yielded somewhat better results which generally followed Hill and Sumner's (1967) data. Namely, increased density reduced water content at high matric water potential, for most of the loams, silty loams. With clay soils the variations were greatest in the few tests performed, therefore no general pattern can be discerned.

6. Comparison between general trends in air permeabilities vs. airfilled porosity (k_a vs. θ_a) show a similar trend for all soils except the two most sandy ones (soils No. 1 and 2), but the lines differ from one another. These differences which are within one order of magnitude for k_a vs. θ_a are due to their clay contents and ratios of silt and clay to sand (Fig. X, 1), determining the different pore size distributions.

7. Similar patterns as those found for k_a vs. θ_a , are found for the hydraulic conductivity K_{sat} vs. void ratio e (Fig. x - 2). The differences between the

soils (excluding # 1 and 2) vary but fall within a range of one order of magnitude for $e=1.400$ to two ($1.1 < e < 1.2$) and three for $e < 1.00$.

One should note that when the data sets (K_{sat} vs. e) of soils belonging to a given soil catena, where a change in clay percentage exists (Soils #2, 3 and 4) are compared. There is a large difference between soil #2 (39.2 clay) and #3 and 4 (22.6 and 35.2 % clay, respectively) which are very similar in their $K_{sat}(e)$ values. This observation suggests that for predicting $K_{sat}(e)$ function, based on texture clay percentage should be used either by a powerd function, exponential or logarithmic relationships.

Comparison between soils having the same clay content (22 to 23% clay) but which differ in their silt content 6.2% and 62.4% silt as for soils No.3 and 8, respectively, one can see a marked difference in K_{sat} up to one order of magnitude lower, the higher the silt content is.

Another comparison can be made between two clay soils, their texture being practically the same but their clay mineralogy is different (Table 1 and Soils No.5 and 7). The vertic soil (#7) made mostly of smectites shows lower hydraulic conductivities (K_{sat}) for given void ratios e than those observed for the Kaolinitic - Halloisitic clay soil (#5). The differences are less than one order of magnitude for $0.85 < e < 1.3$ and reach almost two orders of manitude difference (the smectitic soil #7 yield lower K_{sat}) for the range $0.9 < e < 1.2$.

When $K_{sat}(e)$ patterns of silly loam soil (#8) is compared to silty sandy loam (#6) are compared it is interesting to note that the $K_{sat}(e)$ line for a better graded soil having silt and fine sand (6) falls below that of a soil (#8) having mostly silt by approximately one order of magnitude.

Fig. X-1. Air permeabilities k_a [cm²] as functions of airfilled porosities θ_a [m³.m⁻³] for the nine soils studied.

Fig. X-2. Hydraulic conductivities K_{sat} [$\text{m} \cdot \text{day}^{-1}$] as functions of void ratio e for the nine soils studied.

Since all these K_{sat} data, obtained for several soils differing in their texture and clay types, are related to void ratio it is possible also to relate them directly to total free porosity to water conductance θ_{sat} namely the volumetric water content at saturation which also signifies the water conducting cross-section fraction of the soil sample. The differing values point out the differences in pore size distribution, between the various soils, degrees of pore continuity and pores tortuosity prevailing in the different soil studies.

In other words, pore size distribution and geometry have important effects on:

- 1) Soil water retention; and
- 2) Soil hydraulic conductivity

In each soil tested the general mean line k_{sat} vs. e is drawn between the different k_{sat} vs. e lines of the various soil samples under loads at different initial water contents or initial water suctions show great scatter around it. This means that the pore size distribution, continuity and tortuous interconnections depend on the initial water content, loading path and probably on structure. These pore network characteristics cannot be modelled at this stage and thus in order to model K_{sat} vs. e for all the soils tested one has to use different methods which a) neglect these characteristic parameter and are based either on direct correlations between water retention and texture, organic matter and bulk density (e.g., Ohu et al. 1987, Wosten & Van Genuchten 1988), or b) on packing to estimate the water characteristics or retention (e.g., Arya and Paris 1981, Gupta and Larson 1981, Saxton et al. 1986) or c) utilize parameters or measured data to predict the retention and the water conductivity or air permeability (e.g., Marshal 1958, Millington and Quirk 1961, Green and Corey 1971, Muallem 1976, Van Genuchten 1980). All these models require a correction factor based on some measured soil water data as reference or calculation base, but all neglect the changes in pore shape, continuity and connectiveness between pores.

In view of all points raised above, one is led to conclude that in order to model and evaluate the effects of loads and initial water contents have on the resultant k_a or k_{sat} , one has to measure some soil-water data sets and then develop the procedure, similar to that described by Libardi et al. (1982), to generalize the discrete data sets measured. Yet when relative values are to be referred to evaluate the effects loads and initial water content have on the soil transport properties the generalized relations for air permeability $k_a b(\theta_a)$ or saturated conductivity $k_{sat}(e)$ are sufficient.

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Field validation of compaction induced soil water transport properties.

Introduction

Laboratory measured hydraulic conductivities of soil samples affected by varying initial water contents and compressive loads were described in the previous chapter. The questions are whether these data sets represent field conditions, provided void ratios are the same? . Will compaction efforts similar to those applied in the laboratory exercised under field conditions yield similar situations as those found in small cells in the laboratory? .And finally, if good or agreeable correspondence is found between laboratory findings and field measured soil properties and conditions, what practical purposes or field applications can laboratory obtained data sets serve?.

In this part of the work, field validation of laboratory data and their possible practical applicability will be pointed out and reported in the following order:

1. Field measured soil bulk density distributions, caused by wheel traffic as compared to computer predictions;
2. Measured final infiltration rates on wheel ruts as compared to calculated values based on laboratory data of saturated and capillary conductivities for the same soil conditions;
3. Estimates for seepage from water reservoirs using the laboratory measured K_{sat} values and compared to field measured K_{sat} ;
4. Estimated soil water diffusivity and conductivity to water or permeability to air spatial distributions as related to field measured parameters characterizing compacted soil (e.g., bulk density, void ratio, air filled porosity, and ambient soil water distribution throughout the season or between impaction or rain cycles;
5. Graphic presentation of the "parametric space" available for plant roots to grow, respire under currently accepted various constraints (air permeability, air diffusion, O.D.R. soil resistance to root or cone penetration; and
6. Root elongation rates measured in the laboratory under differing water contents bulk density conditions, and transpirational demand.

1. Field soil compaction induced by wheel traffic

Traffic across arable land became the prevailing practice of any cropping system. Most traffic passes, performed on tilled and/or wet soils cause soil compaction or densification, the degree of which depends on the soil type, existing water contents and loads applied (Hadas et al., 1986, 1988; Gupta and Larson, 1982; Gupta and Allmaras, 1986; and Gupta et al., 1985).

Soil compaction is the result of soil compression (the process describing decreasing soil volume (soil denitrification) under an externally applied force.

Soils in trafficked fields are driven across when unsaturated or even air dried, and thus the relationships between external load and the change in soil volume should be determined on unsaturated samples. Under these conditions the interfacial forces exerted by water minisci on the soil matrix may add to partially augment the applied external force, depending on the degree of saturation.

The stress force per affected area acting on the unsaturated soil σ' or effective stress is given by:

$$(1) \quad \sigma' = \sigma - X(S) [-\psi(S)] = \sigma - X'(\theta) \cdot [-\psi'(\theta)]$$

where σ is the externally applied stress, $\psi(S)$ is the matric potential in stress units and $X(S)$ is stress transfer efficiency coefficient. Both $\psi(S)$ $\psi'(\theta)$ and $X(S)$ $X'(\theta)$ are volumetric or water content (θ) or as stated here, saturation degree (S) dependent. Due to the great experimental difficulty in determining $X(S)$ or $X'(\theta)$, it became quite common to ignore the matric potential term and relate the volume changes directly to the externally applied stress and incorporate the matric potential component into the slope or proportionality coefficient C of the following relationship (after Larson et al., 1980), where P , P_k are bulk:

$$(2) \quad P = P_k + c \log (\sigma/\sigma_k)$$

densities at any applied load σ and a known load applied σ_k respectively whereas $C = dP/d \log \sigma$.

Koolen and Knipers (1983) suggested that bulk density varied mainly according to the normal stress applied and only to a small degree to side load stresses. Therefore, Larson et al. (1980) used the unidirectional compression tests to develop equation (2) and modified it to include the effects of degree of saturation S_k in equation (3) where

$$(3) \quad P = [P_k + \Delta_t(S_1 - S_k) + C \log (\sigma_a / \sigma_k)]$$

P_k is the bulk density at a reference degree of water saturation S_k and a reference stress σ_k , S_1 is the desired degree of water saturation and Δ_t is the slope of P_k vs degree of water saturation when the relationships between stress and soil bulk density is combined with any model predicting the stresses at a given point in the soil space, then one can predict the bulk density distributions after stressing the soil by an external force or load..

Gupta and Larson (1982) developed a model based on the theory of Boussinesq for calculating stresses in an elastic medium, as modified by Frolich (1934) and Sohne (1953, 1958) for predicting the isostress and isodensity lines in a soil profile under a tractor wheel. According to this theory the resultant stress σ_R at a point $R(x,y,z)$ under a point stress P is given by

$$(4) \quad \sigma_R = \nu P / 2\pi R^2 \cdot \cos \nu^{-2} \beta$$

where β is the angle of R with normal and ν is "the number of enhancement orders of stress distribution" or concentration factor. The σ_z normal stress and the other stresses σ_h and τ acting on this point can be derived from (eq. 4) to yield:

(4a) vertical normal stress

$$\sigma_z = \nu P / 2\pi R^2 \cos \nu \beta = \nu P / 2\pi z^2 \cos \nu+2 \beta;$$

(4b) horizontal radial stress

$$\sigma_h = \nu P / 2\pi R^2 \cos \nu^{-2} \beta \cdot \sin^2 \beta = \nu P / 2\pi z^2 \cos \beta \sin^2 \beta;$$

and

(4c) vertical-horizontal shear stress

$$\tau = \nu P / 2\pi R^2 \cos \nu^{-1} \beta \cdot \sin \beta = \nu P / 2\pi z^2 \cdot \cos \nu+1 \beta \cdot \sin \beta;$$

these stresses derived from a point of stress at the soil surface are calculated for any point in the soil volume underneath (Jumikis, 1964) and can be used for calculating the stresses at a given point $R(x,y,z)$ under a wheel by dividing the contact area to small "area contact cells" and computing the integrated stress on the desired point, exerted on that point by all the stresses applied to the contact cells (Sohne, 1953, 1958). The concentration factor ν values suggested by sohme (1953) where 3, 4, 5 and 6 dry compact, hard, firm and soft soils respectively.

Experimental

The finite differences model of Gupta and Larson (1982) was used to predict the bulk densities under the same wheeled tractor on two soils (soil No. 6 and 7). The "C" values used were taken from the uniaxial compression tests

performed and various ν values were used. The computed results supported and consolidated the already reported observation (Gupta and Allmaras, 1986), that changes in ν did not alter significantly or to a large extent the differences between measured and predicted bulk densities in both soils (Gupta et al., 1985). Void ratios and air filled porosities determined for the measured and predicted bulk densities were used to read the corresponding air permeability and hydraulic conductivity values.

Results and discussion

A comparison between simulation-predicted and measured soil bulk densities, under tractor wheel for soil No. 6 (Kfar Aza) is given in Figure 1-1 and for soil No. 7 in Figure 1-2. There are definite differences (within 10 to 15%) between the predicted bulk distribution and the measured ones. Similar differences were reported by Gupta et al. (1985), which have suggested using the model's predicted bulk density distributions to delineate zones of excessive compaction with respect to air diffusion to roots resistant to penetration among other indices. Using these computer and measured data to delineate low air filled porosity in the soil will lead to great errors as one can see from Figures 1-3 and 1-4 (soils No. 6 and 7 respectively) or from estimating the desired transport coefficients such as air permeabilities (in Figures 1-5 and 1-6). If hydraulic conductivities are to be used to estimate final infiltration rates these discrepancies between the measured and predicted isobulk densities (Figs. 1 and 2) or isovoid ratios (Figures 1-7 and 1-8) show also great discrepancies and different distributions of K_{sat} in Figures 1-9 and 1-10 for observed soils No. 6 and 7 respectively. The reason for the large discrepancies between the transport coefficients inferred from measured and those from predicted data is that although volumetric differences between the measured and computed are rather small (10 to 15%) the transport coefficient following nonlinear relationships with volume changes vary to a far greater extent. Furthermore, these differences, suggest a man-made great spatial variability on a small almost microscale in soil characteristic that usually are neglected when measured in the fields but are reflected in the crop response.

Conclusions

One is led to conclude that the present degree of variability between predicted and actually measured bulk density distribution, small as it may seem to some, can not yield satisfactory results when used as a basis for deliniating zones deficient in aeration or of very low K_{sat} or in their ability to absorb water. Yet, for planning and managing tillage operations under adverse soil-climate conditions the soil compaction predictions used and the derived soil properties are of great importance.

Fig. 1-1 Inferred measured and predicted soil bulk density ρ [Mg.m⁻³] distributions for soil No. 6 (VI).

Fig. 1-2 Inferred measured and predicted soil bulk density. ρ [Mg.m⁻³] distributions for soil No. 7 (VII)

Fig. 1-3,4 Inferred measured and predicted airfilled porosity θ_a [$\text{m}^3 \cdot \text{m}^{-3}$] distributions for soil No. 7 (VII), No. 6.

Fig. 1-5 Measured and predicted air permeability k_a . Inferred $[cm^2]$ distributions for soil No. 6 (VI)

Fig. 1-6 Inferred measured and predicted air permeability k_a $[cm^2]$ distributions for soil No. 7 (VII)

fig. 1-7

fig. 1-8

Fig. 1-7 Inferred measured and predicted void ratio e distributions for soil No. 6 (VI)

Fig. 1-8 Inferred measured and predicted void ratio e distributions for soil No. 7 (VII)

Fig. 1-9 Inferred measured and predicted void ratio e distributions for soil No. 6 (VI)

Fig. 1-10 Inferred measured and predicted void ratio e distributions for soil No. 7 (VII)

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2. Comparison between field measured and calculated final infiltration rates based on laboratory data of hydraulic and capillary conductivities and retention curves for Kfar Aza soil

Common problems resulting from traffic caused soil compaction are reduced infiltration capacity, increased runoff, decreased soil water distribution uniformity across the field.

It is very difficult to quantitatively assess these crop yield effective factors experimentally. The use of computer modelling is a simple way to quantify water uptake and distribution in a field, provides good data bases of soil compactness and resulting values of which transport and retention in soils are available. Yet, modelling is not an end in itself unless verified occasionally by experimental data. This chapter deals with field verifications of:

- (1) Hydraulic conductivities measured in the field and compared those measured in the laboratory;
- (2) Field measured final infiltration rates compared to model estimates based on laboratory measured hydraulic, capillary conductivities and retention curves; and
- (3) Estimates of water seepage from earthen water reservoirs, the bottom of which has been compacted by tractor's wheels following engineering specifications based on proctor compaction tests and a simple water transport model (Zaslavsky, 1964; Tagaki, 1960).

The use of the hydraulic properties and resultant estimates were chosen to validate the laboratory data bases because of their high sensitivity to soil size distribution, and soil structure.

Experimental methods

One of soils (#7 Kfar Aza) was chosen for the above mentioned validation tests. Air dry samples sieved through 2 mm sieves were packed into temper cells at three initial bulk densities 1.45 ± 0.02 ; 1.63 ± 0.04 and 1.75 ± 0.03 [$\text{Mg} \cdot \text{m}^{-3}$] vacuumed and then saturated with water. Air pressure was applied stepwise in ever increasing pressure increments allowing pressure equilibrium to be attained prior to a new step of changing air pressure. Rates and total outflow of water during each and at the end of each air pressure measurement were monitored and used to calculate the points on the retention curves and compute the capillary conductivities (Ryttema, 1959).

On field plots wetted to 17-18% (w/w) (best according to proctor test) by sprinklers to a depth of 60 to 70 cm, compaction lanes were produced by trafficking two Case 2290 tractors once and three times on the same tracks producing lanes 2 to 2.4 m wide. Soil water and bulk density distributions were determined to a depth of 50 cm. These data were used to compute the cumulative probabilities of water content distribution and soil density distributions which were then used to compute the expected infiltration rate and seepage rates. The computations were based on a simplified model by Zaslavsky (1964) and Takagi (1960). A flow chart is given below (Fig. 2-1).

Figure 2-1. Flow chart for calculation of seepage flow from compacted earth reservoirs.

Results and discussion

Hydraulic conductivity of Kfar Aza soil as a function of soil bulk density for different initial water contents given in percents of the water content optimal for maximal soil compaction by the proctor test is given in Fig. 2- 2. It is obvious that variations of K_{sat} by two orders of magnitude for the high soil bulk densities, attained at different initial water contents result from the degree of relative reorientation of microaggregates to their complete failure and pastic deformation. For low water contents the former probably dominates the reformed pure system whereas at higher water contents the latter process predominates. The maximal decrease in K_{sat} is attained around the water content optimal for the proctor test (0.98 of proctor water content). The cumulative probabilities of water contents smaller than a given value for three layers prior to compaction in Fig. 2-3 are given for the Kfar Aza field.

Cumulative probabilities of measured bulk density smaller than a given value for three layers after one and three compactive passes are given in Figs. 2-4 and 2-5, respectively.

Retention curves $\psi(\theta)$ and capillary conductivities $K(\theta)$ for three different bulk densities are given in Figs. 2-6 and 2-7, respectively.

Final infiltration rates were calculated using the procedure given in Fig. 1-11, for different soil bulk densities of the top layer and the corresponding densities of the following layers (as found in the field), by assuming a constant head of 1 cm of water, and are given in the following Table 2-1, and compared with field-measured data. It is clear that the calculated final infiltration rates fall within range with data of final infiltration rates measured in the field and averaged for the two years measurements.

Fig. 2-2 Hydraulic conductivities K_{sat} [$\text{m} \cdot \text{day}^{-1}$] as functions of soil bulk density ρ [$\text{Mg} \cdot \text{m}^{-3}$] distributions for soil No. 6 (VI).

Fig. 2-3 Cumulative distribution of water content smaller than at three different depth layers prior to compaction (Soil No. 6).

Fig. 2-4 Cumulative distribution of soil bulk density [Mg.m⁻³] smaller than after one passage of a tractor (front wheel pressure 392 kPa and rear wheel pressure 196 kPa), at a speed of 3.2 k.p.h. (soil No.6)

Fig. 2-5 Cumulative distribution of soil bulk density [Mg.m⁻³] smaller than after three passages of a tractor (front wheel pressure 392 kPa and rear wheel pressure 196 kPa), at a speed of 3.2 k.p.h. (soil No.6)

Fig. 2-7 Soil capillary conductivities $K(\theta)$ [$\text{m}^3 \cdot \text{m}^{-3}$] as functions of volumetric water content θ [$\text{m}^3 \cdot \text{m}^{-3}$], at three soil bulk densities. Soil No. 6.

Fig. 2-6 Soil water matric potentials [kPa] as functions of volumetric water content θ [$\text{m}^3 \cdot \text{m}^{-3}$], at the soil bulk densities. Soil No. 6.

Table 2-1: Calculated and field measured final infiltration rates

Bulk density (1) at the surface Mg.m ⁻³	calculated (2)	Final infiltration rates [mm.hr ⁻¹]		
		field measured (3)		
		wheat track	plant rows	bed center
1.30	-	-	-	-
1.40	28.3	-	65.0±35.5	77.6±49.0
1.51	9.8	-	-	-
1.55	-	9.6±14.4	-	-
1.65	6.6	-	-	-
1.76	1.3	-	-	-
1.84	0.4	-	-	-

(1) Data sequence picked up from depth distributions found in the field.

(2) Following flow chart procedure (Fig. 1-11) and use of data in Figs. 1-12 to 1-17.

(3) Infiltration values trail (mean ± s. deviation for data collected for two years) carried out for BARD Report NO. 1-812-84 (1989) by E. Ravitz et al. Bulk densities are within ±0.05 of the bulk density values on the left column.

Table 2-2: Saturated soils hydraulic conductivity values measured on Kfar Aza soil site during winter 1982 and values measured in the laboratory. (Values of 3 replic. in lab. and 18 for field.)

Bulk density (1) range [Mg.m ⁻³]	K _{sat} in [m.day] measured in					
	Laboratory			field		
	Ave.	Min.	Max.	Ave.	Min.	Max.
1.39±0.05	3.2*10 ⁰	9.8*10 ⁻¹	6.2*10 ⁰	3.53*10 ⁻¹	1.27*10 ⁻¹	6.94*10 ⁻¹
1.58±0.03	5.9*10 ⁻²	4.3*10 ⁻⁴	1.7*10 ⁻¹	7.68*10 ⁻²	5.52*10 ⁻³	1.97*10 ⁻¹

Hydraulic conductivities values measured during winter 1982 on Kfar Aza soil site under field conditions as compared with laboratory measured values (measurements of this project) are given in Table 2-2. The data shows that the laboratory and field measured average values fall within the same range but a greater variability is observed in data measured under laboratory conditions.

In view of the data shown so far, one is led to conclude that the laboratory - measured value of hydraulic, capillary conductivities and retention characteristics, for the soil tested (#6, Kfar Aza) are compatible to predict field phenomena as shown by validation. Probably for some data of the other soils tested, will be compatible as well, but not all of them. Calculations using K_{sat} for Nachsholim soil as vertic soil (Soil # 7), yielded infiltration rates lower by one order of magnitude than those

measured in the field (Table 2-3). This observation stresses the importance of soil structure in the field, especially in soils known to have such structure naturally (e.g., Soils # 4,5,7, and 9), as pointed out by Klute (1982) who questioned the indiscrete use of disturbed and sieved soil samples to determine and represent soil water properties for modelling field or tillage-affected soils. For soils which do not clearly exhibit natural structure laboratory measured hydraulic properties on disturbed soil samples probably produce representative dataset to yield good approximations of field conditions.

The rather good agreement between laboratory database estimates of field K_{sat} and final infiltration rates, suggest a further use of these dataset obtained in this project to estimate with all reservation mentioned above the seepage from earthen reservoirs, septic installations, field infiltrability provided the spatial distributions of soil bulk density values, are known.

For example, seepage from reservoirs were calculated using the bulk density distributions given in Figs. 2-4 and 2-5, the soil water properties measured and given in Figs. 2-2, 2-1 and 2-7, and the preceding given in 2-1. (Figs. 2-8 and 2-9, for Figs 2-4 and 2-5, respectively).

The results show that a rather slight difference in surface soil density, e.g., distribution 0-5 in Fig.2-6 vs. the same layer in Fig. 2-7 and the sequential layers bulk density values may lead to a difference in seepage rates, of about an order of magnitude (e.g., 25 to 26 mm.day, in Fig. 2- 8, vs. approx. 3.0 mm.day⁻¹ in Fig. 2- 9).

Fig. 2-8 Seepage rates [m.day⁻¹] for different area fractions and corresponding matric potentials [m. of water] for soil No. 6 compacted by one passage.

Fig. 2-9 Seepage rates [m.day⁻¹] for different area fractions and corresponding matric potentials [m of water] for soil No. 6 compacted by three passages.

Table 2-3: Calculated and field measured final infiltration rates for Nachsholim Soil (#7)

Bulk density (1) Mg.m ⁻³	Final infiltration rates [mm.hr ⁻¹]	
	<u>calculated</u> (2)	<u>field measured</u> (3)
1.20±0.03	5.0	5.1±3.2
1.31±0.03	2.1	6.3±6.2
1.38±0.02	0.8	6.2±4.3
1.45±0.05	0.1	2.1±1.3

Conclusions

The following conclusions may be drawn from the results discussed:

1. For soils which have exhibited natural soil structure, disturbed, sieved soil samples used to measure soil water properties may lead to great discrepancies between field-measured data and estimated ones based on laboratory measurements.
2. Soil water properties measured in laboratory on disturbed, sieved samples on naturally non-structured soils can produce reasonable predictions of field-measured hydraulic properties.
3. The compatible soil data yielding good agreement between field and laboratory based data can be used for various predictive purposes such as hydraulic phenomena.
4. A specially more refined procedure should be used to yield better laboratory techniques to treat naturally well structured soils, in order to determine their soil water properties.

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3. Comparison between soil resistance to penetration by standard cone penetrometer & fine still penetrometer needles

Introduction

Numerous studies have related soil strength, soil tilth and compaction root elongation rate or capability to penetrate the soil with soil resistance to penetration of cone tipped penetrometers (Simmons and Cassel 1989, Gerard et al. 1982, Taylor and Ratliff 1969, to list a few).

It is interesting to note that although penetrometers have been widely used to indirectly relate soil strength factors with root development and rate of elongation, few detailed comparisons were carried out between soil resistance to penetrometer penetration and resistance encountered by roots, most works were based on the penetrometer dimensions (e.g., 1 inch cone diameter vs. 2 or 4 mm in diameter), or configuration effects (Fritag 1968), effects that soil water content and bulk density have on resistance to penetration (e.g., Ayers and Bowen 1987, Perumpral 1987).

Cone penetrometer readings have been used to evaluate soil strength and deduce from these readings the rate of root elongation (Taylor et al. 1966, Taylor and Ratliff 1969, Bowen 1976, Gerard et al. 1982, Whitely et al. 1981, among others) in the field. The penetrometers used varied in length, diameter and cone shape were used for laboratory tests and differed from those of the standard cone penetrometer used for field work. This part in the work comes to compare values of soil resistances to penetration of cone tipped penetrometers under field and laboratory conditions.

Experimental Procedure

Two soils, one from Kfar Aza (soil #6) and a clay soil from Lachish (54% clay, 28% silt and 27% sand), similar to soil #7, were used. Soil samples were wetted to different initial water content by spraying water while mixing the soil. The samples were left to equilibrate for two weeks. Subsamples were then taken and pressed into 51 mm-diameter and 76 mm- height rings and brought to different initial predetermined bulk densities given in Table 3-1. Fine-needle penetrometers of 2 mm diameter made of stainless steel and having a cone tip apex angle of 60° were driven into the samples at penetration rate of 0.5 cm.min⁻¹ to depth of 1 and cm which represent depths 5 to 10 times greater than the needness diameter (Barley et al. 1965). Resistance to penetration was measured by a proving ring of 1×10^{-2} of an inch radial deformation per 98 kPa force and read by a dial of sensitivity of 1×10^{-4} inch. The soil metal friction resistance at 2 cm and 1 cm depth were read when the needles were pulled out of the soil samples.

Field soil resistances to penetrometer were measured by a standard cone penetrometer with proving rings and 1.0 inch diameter cone tip of 60° apex angle. The tests were made in Kfar Aza soil in commercial fields and on Lachish soil in cotton fields located near Kiriat Gat. The soil water contents and bulk densities on the field were sampled next to the penetration sites by a nondisturbing cone sampler 50 mm in diameter and 50 mm high, and determined in the laboratory. The field data of soil resistance to penetration at given water contents and bulk densities were correlated to values of soil resistance to penetration of the corresponding to values of water content and soil density.

Results and Discussion

Soil resistances to penetration (averages of four replicates) measured in the laboratory for the two soils are given in Figs. 3-1 and 3-2. As expected, an increase in soil resistance to penetration is observed as soil bulk density and penetration depth increase and/or water content decreases. The increase in soil resistance to penetration with increased depth of penetration is due to an increase in metal-soil friction. The differences between the soil resistance values for given soil water potential and bulk density between the two soils is due to their different textures and thus the different cohesive and friction properties affecting soil resistance to penetration.

Since roots do not penetrate as penetrometer, their main problem is to produce the tip cavity in order to penetrate new soil volumes. An estimate of the force required to produce a cavity for root tips was calculated by subtracting the soil-metal friction measured for each of the penetration depths from the corresponding measured soil resistance to penetration. These estimates (average of four replicates) of forces required to produce a conical cavity in the soil at different soil bulk densities and water contents for two soils are given in Figs. 3-3 and 3-4.

As expected, an increase in force to produce a conical cavity in the soil is required as the soil density increases and the water content decreases. These values are averages of the estimated values calculated for the two depths. The standard deviation is not shown but is about 24% and 31% for the depth of 1 cm and 39% and 54% for the 2 cm depth, for the two soils, respectively.

Fig. 3-1 Soil resistances to penetration of a 2 mm diameter probes [MPa] as functions of volumetric water contents θ [$\text{m}^3 \cdot \text{m}^{-3}$], bulk densities [$\text{Mg} \cdot \text{m}^{-3}$] and two depths of penetration. Soil No. 6.

Fig. 3-2 Soil resistances to penetration of a 2 mm diameter probes [MPa] as functions of volumetric water contents θ [$\text{m}^3 \cdot \text{m}^{-3}$], bulk densities [$\text{Mg} \cdot \text{m}^{-3}$] and two depths of penetration. Lachish Soil.

Fig. 3-3 Estimated soil resistances to a spherical cavity production [MPa] as functions of volumetric water contents θ [$\text{m}^3 \cdot \text{m}^{-3}$], and soil bulk density [$\text{Mg} \cdot \text{m}^{-3}$]. Soil No. 6.

Fig. 3-4 Soil resistances to penetration of a 2 mm diameter probes [MPa] as functions of volumetric water contents θ [$\text{m}^3 \cdot \text{m}^{-3}$], bulk densities [$\text{Mg} \cdot \text{m}^{-3}$] and two depths of penetration. Lachish Soil.

The differences between the two soils in forces needed to form a cavity reflect the different mechanical behaviour of the two soils and probably the variation in force and stress distributions imparted by the needle tips on the particles of the two soils. Another point should be stressed here in sandy soils most particles (sand grains) will be within particle-to-diameter ratios of 1:5 to 1:4 for needles of 2 mm diameter whereas for clay soils these ratios will be within a 1:50 to 1:1000 or more. The scale effect raised here is not known and casts a doubt about the validity of comparison between the data measured and presented here and data published in the literature. Farrell and Greacen (1966) have shown that for a fine textured soil needles of 2 to 5 mm diameter used to penetrate the soil yielded practically the same resistance to penetration values. But since they did not perform a similar test on a coarse textured soil, this question of probable effects grain size diameter ratio may have on soil resistances to penetration is still open.

Rather good agreement was found between field measured resistances to penetration and those measured in the laboratory for Kfar Aza soil (Fig. 3-5) and for the Lachish soil (Fig. 3-6). There is no proof that such good agreements will be attained under different comparison conditions such as needles of smaller or larger diameter, or different standard cone penetrometer.

Conclusions

In view of the data presented the following conclusions can be drawn:

1. Soil resistance to penetration can be used to represent qualitatively soil conditions for root development. The real factor involved or the one to be correlated to root penetration into the soil - the force to form a cavity in the soil - can be assessed by subtracting the penetrometer friction from the total readout, but one has to recall that it can serve only as an estimate and not as an absolute value to be correlated with root performance.

- (2) Good agreement can be achieved between laboratory measured resistances to penetration and corresponding values measured under field conditions.

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Fig. 3-5 Field measured soil resistance to penetration [MPa] as a function of laboratory measured soil resistance to penetration [MPa] for corresponding soil bulk density and water contents. Soil No. 6.

Fig. 3-6 Field measured soil resistance to penetration [MPa] as a function of laboratory measured soil resistance to penetration [MPa] for corresponding soil bulk density and water contents. Lachish Soil.

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Table 3-1: Soil volumetric contents [$\text{m}^3.\text{m}^{-3}$] and bulk densities [$\text{Mg}.\text{m}^{-3}$] for Kfar Aza and Lachish soils

Soil bulk density [$\text{Mg}.\text{m}^{-3}$]	Volumetric water contents [$\text{m}^3.\text{m}^{-3}$]				
	<u>Kfar Aza Soil</u>				
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
1.2	.96	.120	.156	.192	.216
1.3	.104	.130	.169	.208	.234
1.4	.112	.140	.182	.224	.252
1.5*	.120	.150	.195	.240	.270
1.6	.128	.160	.208	.256	.288
<hr/>					
Water matric potential (1) [kPa]	-1500	-500	-100	-50	-33

Soil bulk density [$\text{Mg}.\text{m}^{-3}$]	Volumetric water contents [$\text{m}^3.\text{m}^{-3}$]				
	<u>Lachish soil</u>				
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
1.2	.168	.204	.240	.276	.312
1.3	.182	.221	.260	.299	.338
1.4	.196	.239	.280	.332	.358
1.5*	.210	.255	.300	.345	.380
1.6	.224	.272	.320	.368	.406
<hr/>					
Water matric potential (1) [kPa]	-500	-100	-80	-50	-33

(1) Values are for bulk density of $1.5 [\text{Mg}.\text{m}^{-3}]$

4. Elongation rates of cotton tap roots grown in soil under different conditions of bulk densities, water contents and transpirational losses.

Mechanical impedance or soil compaction has widespread influence on soil transport properties, soil strength and soil resistance to root development and elongation. Values of soil resistance to penetration at which root elongation ceases or what is termed as soil critical strength have been reported in the past (Barley and Greacen 1967, Taylor and Burnett 1964, Taylor et al. 1966, Taylor and Ratliff 1969a, Eavis 1971, 1972, Eavis et al. 1979, among others). But under actual conditions, especially so under arid or semi-arid conditions, water storage limiting root elongation rate is of great importance and the reports listed above and others point out specifically that root elongation rate diminishes with increased soil resistance to penetration. This phenomenon is further aggravated by lack of oxygen due to impaired aeration (Glinski and Stepniewski 1985; Hamblin 1985).

The purpose of the work reported here was to measure the rate of elongation of cotton tap roots grown in a soil of differing strengths, water contents and under different transpirational demands.

Experimental procedures

The Kfar Aza soil was chosen for these experiments since no definite soil structure could be detected in soil sieved through 2 mm sieves. Soil samples were wetted by spraying and mixing in trays to soil water contents of 9%, 12, 16 and 18% on air-dry weight basis, then put into plastic bags and left to equilibrate for a week. Subsamples were then taken and packed into columns made of lucite rings 51 mm in diameter and 280 mm total length. The columns were either uniformly packed or packed in layers differing in bulk density or water content, according to the following combinations: 1) uniform density of 1.25 or 1.45 [Mg.m^{-3}]; 2) Top 50 mm at 1.25 [Mg.m^{-3}], 10 mm at 1.45 [Mg.m^{-3}], and 220 mm at 1.60 [Mg.m^{-3}]; 3) Top 50 mm at 1.25 [Mg.m^{-3}], 70 mm at 1.45 [Mg.m^{-3}] and 160 mm at 1.60 [Mg.m^{-3}]. These combinations were attained with samples at various soil moisture contents listed above which are in equivalence to matric potentials of -1000, -500, -50 and -30 kPa for soil density of 1.45 [Mg.m^{-3}] and -800, -320, -33 and -20 kPa for 1.25 [Mg.m^{-3}].

Into these columns at depth of 30 mm from the top cotton seeds (variety Accala 1517) were sown and the columns were covered by plastic to avoid evaporation from the columns. After seedling emergence the plastic cover was replaced by cotton wool and then covered with thin plastic film to avoid evaporation while allowing the seedlings to develop. Every day after the second day ten columns were taken, washed carefully and the root lengths were determined and checked if grown straight down. All deformed, discoloured seedlings were discarded. Due to these strict demands several sets of columns were repeated, so as to yield ten replicates for each treatment at each measurement date, the average values of which are given as results.

The tests were carried out in a constant humidity 60% constant temperature room at $22 \pm 1^\circ\text{C}$, and day light intensity produced by mixed fluorescent lamp and regular electric bulbs. Transpiration rate was brought down practically to zero by keeping these tubes under plastic chamber and at approximately 100% humidity.

Separate sets of columns at 12% and 16% water contents on air-dry weight basis were subjected to evaporation rates of 4 to 5 mm a day and 15-17 mm a day attained in the room temperature humidity controlled by fans.

Results and discussion

Root elongation rates under no-transpiration conditions are given in Table 4-1. In general, an increase in root elongation rates with an increase in water content and the consequential decreased soil resistance to penetration is observed. For a given water content an increase in soil bulk density and the resultant increased soil resistance to penetration caused root elongation rates to diminish. In particular, for bulk density of $1.25 \text{ [Mg.m}^{-3}\text{]}$ and water content of 9% (w/w) the radicles that appear ceased to elongate after the

first or the second day. For the same water content but at a density of $1.45 \text{ [Mg.m}^{-3}\text{]}$, resulting in almost a twofold increase in soil resistance; root elongation ceased after the fifth or sixth day and the total averaged root lengths were 1.6 to 1.7 cm and 3.4 to 4.0 cm, respectively. These observations suggest that impaired seed, radicle-soil contact in the less dense columns led to reduced water uptake by the radicle and thus the radicles ceased to develop whereas at a higher density improved seed, radicle-soil contact led to a better water uptake rate but not at an adequate rate to ensure steady development.

Data given in Table 4-1 are elongation rates observed for the tap roots but for columns with mixed layers show that the tap roots developed a bulbous tip whenever they hit the "hardest" layer and branching of rootlets began. The root washing technique used in this experiment caused some damage to the rootlet system due to partial disruption and loss of some in the soil-water slurry. Therefore as a rule of thumb, the observed root systems suggest an increase in rootlet branching as the tap root elongation rate decreases, provided enough water is taken up.

The effect of transpiration on root elongation rates is given in Figure 4-1 and a comparison to Ratliff and Taylor data (1969a) is included in this figure. As one can observe, the larger the transpiration rate the smaller the elongation rate, under a given soil resistance to penetration. Another point to note is that the data reported by Ratliff and Taylor (1969a) are lower than those found in this project. The soil used here is a silty loam soil whereas their soils were fine loamy sands.

Table 4-1: Dependence of tap root elongation rates on soil water contents, soil bulk density, soil water matrix potential, soil resistance to penetration and time, under no transpiration.

Soil bulk density [Mg.m ⁻³]	Gravimetric water content [% w/w]	Soil resistance to penetration [kPa]
1.25(1)	9	1200
	12	930
	16	260
	18	250
1.45(1)	9	2300
	12	1600
	16	1050
	18	850
Mixed layered (2)	9	3550 ⁽⁴⁾
	12	3300
	16	1400
	18	780
Mixed layered (3)	9	3550 ⁽⁴⁾
	12	3300
	16	1400
	18	780

1) Uniformly packed columns.

2) Top 60mm made of 50mm at 1.25[mg.m⁻³], 10mm at 1.45[mg.m⁻³] & 220mm at 1.60[mg.m⁻³].

3) Top 120" " " 50mm " 1.25 " " , 70mm " " " " & 160" " " " " "

4) Soil resistances to penetration are for bottom layer only.

CONT. Table 4-1

Time intervals after germination [days]					Ψ [bar]
0-2	2-4	4-6	6-10	10-12	
0.8	0.6	-	-	-	-8.0
1.5	1.2	1.3	1.0	1.2	-3.2
1.8	1.8	2.0	1.7	1.7	-0.3
2.2	1.8	2.0	1.9	1.7	-0.2
0.8	0.6	0.4	-	-	-10.5
0.8	0.7	0.4	0.6	0.4	-5.0
1.4	1.2	0.9	1.1	0.9	-0.5
1.7	1.4	1.1	1.2	1.3	-0.3
0.6	0.6	-	-	-	-15.0
1.4	1.6	.3	.2	0.3	-7.0
1.8	1.0	.7	.6	0.8	-0.6
2.1	1.0	0.6	0.7	0.8	-0.35
0.8	0.6	-	-	-	
1.5	1.7	0.5	0.3	0.3	
1.8	1.2	0.6	0.8	0.8	
2.2	1.7	1.1	1.0	1.1

Fig. 4-1 Cotton tape root elongation rates [mm·day⁻¹] as functions of soil resistance to penetration [MPa] and transpiration.

One possible explanation as the low capillary conductivity in their soils and the high contact impedance (Hadas and Russo 1974) at the seeds and root surfaces due to the coarse textured soils they used. Therefore, the roots could not take up water at the proper rate to support higher elongation rates. A qualitative simple model presented below will serve to understand better the effects various factors (e.g., transpiration rate, water uptake rate, developmental stage of the plant, soil mechanical and physical properties), may have on root elongation rates and root system proliferation.

Plant roots exert pressures on the soil. The balance of forces at equilibrium - no elongation is given by equation [4-1] where Ψ_{hyd} is the total net cell hydrostatic pressure, T - the wall or turgor pressure

$$[4-1] \quad \Psi_{hyd} - T - \sigma = 0$$

exerted by the tissue cell walls on their content counteracting and σ is the soil resistance to penetration. The term Ψ_{hyd} is equal to the: $\Psi_{p,e} - \Psi_{p,s} + \Psi_{os,e} - \Psi_{os,s} - \Psi_{mat}$, where p , os , signify pressure and osmotic components, respectively. Whereas σ_{hyd} depends on the cell contents and net water uptake by the elongating root tissue, σ depends on the cell wall elasticity and structure. Both are functions of plant system interactions with soil water availability and evaporative demands whereas σ depends only on soil parameters. For given σ a high transpiration demand will cause a large drawout of water and T and Ψ_{hyd} will diminish therefore for a balance to zero σ must also diminish or in other words roots will be able to develop only in a less resistive soil (low T values). Root elongation can thus occur when the following inequality $\Psi_{hyd} > \sigma$ exists. The greater the difference between Ψ_{hyd} and T , the higher the elongation rate will be.

Elongation rates measured under no-transpiration conditions (Fig. 4-1) and Figures 1,2,3,4,5,6, and 7 of Taylor and Ratliff (1969a) show non-linearity between elongation rates of cotton, pea and peanut roots and soil resistance to penetration for all water contents except for the lowest soil resistances to penetration where almost a linear dependence can be detected. Similar non-linear relationships were reported by Gerard et al. (1982).

Several factors may lead to these non-linear relationships at a non-uniform seedlings batch (Misra et al. 19885, Taylor et al. 1966, Taylor and Ratliff 1969b); b) differential physiological age (Misra et al. 1985); and c) changing water regime in the seedlings, namely, reduced elongation causes reduced root length and reduction in water uptake by the root while seedling is developing its aerial canopy and the developing tissues draw the water from the root systems thus reducing the Ψ_{hyd} . Another factor affecting the decreasing elongation rates is the diminishing solutes which are partially respired by the seedling, leading to reduced ψ hydraulic.

Taylor and Ratliff (1969b) have reported varying root pressures, e.g., 600 to 2600 kPa for Garden Pea, 600 to 1600 kPa for cotton, 500 to 2000 kPa for peanuts; Eavis (1969) reported similar values, 700 to 1600 kPa for garden pea, 400 to 1300 kPa for Cotton. Aggraval and Prihar (19975) reported values of 1090 ± 187 kPa for corn and 450 ± 120 kPa for chickpea radicles. These values suggest that different seedlings from the same batch exert different root tip pressures. The same phenomena was pointed out by Misra et al. (1985) for given seedlings at different ages. The older the seedlings the lower the pressures they exerted onto the soil. Therefore, it is obvious that a single unique correlation between root elongation rates and soil strength is not a real possibility, but rather a probabilistic approach is the more realistic one. Such an approach should lead to probability density functions relating elongation rates and soil strength or soil resistance to penetration for a root population.

For Taylor and Ratliff (1969b) data the following root tips pressures probability densities distributions were fitted and given in Table 4-2. The data published by Misra et al. (1985); Taylor and Ratliff (1969); Hewitt and Dexter (1984), show that maximal root growth pressures, root buckling stresses in aggregated beds and soil penetration strengths are anormally distributed and have a positive skew. In this report the bounded exponential distribution is used (Table 4-2) for Taylor and Ratliff (1969a) data with correlation factors of above 0.950 for fitted parameters. There is no particular preference to either distribution due to the lack of data available.

Taylor et al. (1966) have published percentages of cotton top roots that penetrated soil at different penetration strengths. By fitting hyperbolic functions to root penetration as function of soil penetration strength ($y = ax^{-1} + b$) the following threshold resistance values to cotton roots penetration (under their experimental conditions) were found and are given in Table 4-3. The

higher the percentage of clay and silt is, the higher resistive soil can be penetrated by roots. In other words, at a given soil resistance to penetration more roots will penetrate provided the soil is of a finer texture. The change in soil texture means significant changes in the soil mechanical properties (e.g., shear strength, compressibility) which were not included among the soil parameters measured in this project. The soil mechanical properties can be used to predict requires root pressures for penetrating the soi by using a soil mechanical model developed by Farrell et al (1966) and Greacen et al. (1968).

Table 4-2: Root tip pressure distributions and fitted parameters

Plant	Type of probability density function	Parameters									Bounded exponential***	Ref	
		normal*		Beta**									
		mean	variance										
		μ [MPa]	σ^2 [MPa] ²	a	b	c	d	e					
										β	γ	m	
Peanuts Peas	Normal	1.18	11.2	-	-	-	-	-	-	-			
	Bounded												
Cotton	exponential	-	-	-	-	-	-	-	-	4.097	4.00	2.028	1
	Bounded												
	exponential	-	-	-	-	-	-	-	-	6.274	6.00	1.544	1
Combined best of above	Beta distribution * 10 ⁻³	-	-	1.685	2.25	3.5	1.690	3.185		-	-	-	2

* $f(x) = 1/(\sigma\sqrt{2\pi}) \exp \{-(x-\mu)/(2\sigma^2)\}$

** $f(x) = a(x+b)^d (c-x)^e$

*** $f(x) = m/(\beta-\gamma) [(x-\gamma)/(\beta-\gamma)]^{m-1} * \exp \{-(x-\gamma)/(\beta-\gamma)^m\}$

(1) This report

(2) Hewitt and Dexter, 1984

Table 4-3: Cotton top root penetration percentages for four soils having different textures.
(Calculated after Taylor et al. 1966)

Soil	Texture			Soil resistances to penetration allowing			
	---% w/w ---			% root penetration of [kPa]			R ² *
	Sand	Silt	Clay	100%	50%	25%	
Miles	83	8	9	175.9	567.2	976.1	0.807
Naron	79	11	10	319.4	588.9	1018.7	0.782
Quintan	73	20	7	505.2	841.7	126.7	0.946
Columbia	44	37	19	531.8	897.7	1367.7	0.873

*R - Coefficient of regression equations used for estimating threshold soil resistances.

In the discussion above, inexplicitly, aeration problems were not considered as a limiting factor affecting root elongation rates, Tackett and Pearson (1964) have shown that increased CO₂ concentrations cause reductions in elongation rates of roots. Oxygen concentrations in the soil and oxygen diffusion rate to roots were also found to affect root elongation and development as reported by Eavis (1971) and Greenwood and Goodman (1971). One can indirectly relate aeration problems to root metabolic activity and thus to water uptake cell division and growth.

Conclusion

1. Root elongation rates decrease as soil resistance to penetration increases
2. Root elongation rates under given soil resistance to penetration decrease as the transpirational demand increases.
3. Mean elongation rates of roots serve only as a crude index for root development, while root proliferation into a soil depends directly on the root tip pressure distribution within the root system, and the soil texture or soil mechanical properties (e.g., shear strength and compressibility).

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5. Estimating the degrees of cotton root system proliferation under different soil density, soil strength (resistance to cone penetrometer) and changing soil water content conditions prevailing in the field.

In the previous sections root development and elongation rates were studied and discussed. Plants require water to be taken up by their root systems, to grow, develop and ultimately bear yields. In this section field data of soil water content resistances to penetration distributions will be analysed to yield an estimate of total required root length; elongation rate will be used to deduce the number of new root heads which are capable of elongation.

Theoretical considerations

Water uptake by roots is affected by length of young active roots capable to absorb water, water potential in the roots, soil water potential and capillary conductivity, soil strength or resistance to root penetration, photosynthesites for respiration, osmotic reputation and growth and oxygen to perform energy transfer and utilization.

The discussion to be conducted in this section will concentrate on water uptake, root system proliferation under field conditions where as nutrients, solutes, aeration temperature regimes are assumed to be adequate and not limiting.

Assuming root proliferation to be a function of cell elongation immediately next to the root tip allows us to suppose that a unit volume of newly formed root stamps in a spatial position while the root tip moves away from it. That root subvolume becomes active in taking up water at the same time it occupies that spatial point in the soil space. It is also

assumed that transpirational demand is met and no water stress exists in the roots. Water flow rate q from the soil into the root is governed by equation [5-1]:

$$[5-1] \quad \Delta\psi_{s,r} = q \frac{\{\ln [4 \hat{D}(\theta) t/a^2 - \gamma]\}}{4 \pi \hat{k}(\theta)}$$

where $\Delta\psi_{s,r}$ is the water potential difference between the soil and the root flow rate q ; $\hat{D}^*(\theta)$, $\hat{k}^*(\theta)$ The mean weighted time, water content averaged water diffusivity and capillary conductivity, respectively, a - root radius, and γ Euler's constant (Gardner 1960). It is obvious from the equation that as dwelling time of the root segment lengthens the flow rate should diminish for a given water potential difference. No knowing the time to reach equilibrium flow rate one has to

revert to a different approach bearing in mind that the root maintaining a given water potential difference $\Delta\psi_{s,r}$ at a constant rate which depending on a distance b following an approximate steady

state solution d (eq. 5-2), where b is the out radius of soil around the root which depends on the root density and should be taken as the one half distance between adjacent roots (Gardner 1960).

$$[5-2] \quad \Delta\psi_{s,r} = q \frac{[\ln b^2/a^2]}{4\pi k(\theta)}$$

The changing water content in the field and the water uptake rates can be safely taken as step-wise sequence of steady state situations, where $K(\theta)$ and $\Delta\psi$ do not change drastically.

Using root masses and length excavated and washed out of soil samples will yield data which will lead to a reasonable b value for a given root. Yet, not knowing the $\Delta\psi_{s,r}$ or an accurate $k(\theta)$ and/or $D(\theta)$ value may lead to erroneous q values.

Another way to estimate root lengths and number of active roots per unit soil volume is to estimate, using the law of conservation of matter, the amount of water drawn per unit time, per unit soil by the roots, estimating the mean weighted water uptake by a root segment for the time period for which the water balance is performed for a soil segment and dividing the total water uptake from that soil segment by the water uptake by the root segment and getting the no of segments of total root length.

Such a water balance can be performed by a finite difference approach or relaxation network.

Namely, the total water balance for a soil layer between depth of Z_1 and Z_2 is given in general terms by equation

$$[5-3] \quad \int_{t_1}^{t_2} \int_{z_1}^{z_2} \frac{\partial \theta_z}{\partial t} dz dt = \int_{t_1}^{t_2} \hat{v}_{z_1} dt + \int_{t_1}^{t_2} \hat{v}_{z_2} dt + \int_{t_1}^{t_2} \hat{R}(z) dt$$

where $\partial \theta_z / \partial t$ is the change in volumetric water content, $\hat{v}_{z_1}$, $\hat{v}_{z_2}$ the average rate of water flow through the depth boundaries.

Z_1 and Z_2 for the time interval $[t, t_2]$ and $R(z)$ is the average water volume taken up from the soil segment bounded between z_1 and z_2 by the roots.

The average flow rates are calculated from the average $K(\theta)$ values for the interval $[t_1; t_2]$ and the matrix water potential $h(\theta)$ determined either by tensiometers or inferred to from volumetric water contents and overburden corrections, using equation [5-4]:

$$[5-4] \quad \int_{t_1}^{t_2} \hat{v}_{z_1} dt = \left\{ \left[\left(\frac{\partial h}{\partial z} \right)_{z_1} + 1 \right] \hat{K}_{z_1}(\theta) \right\} T$$

Experimental Procedure

Field data collected during a tillage experiment on a clay soil were used for the analysis.

Cotton was planted in March on plots non-tilled and plots tilled to a depth of 35cm in the previous month of September; the total rainfall intercepted between tillage and planting was 623 mm. Soil water content, distributions were determined on a weekly basis to a depth of 140 cm in increments of 0 to 10, 10 to 20, 20 to 30, 30 to 45, 45 to 60, 60 to 90 and 90 to 120, 120 to 150 cm. Bulk density distributions were determined on a monthly basis (every fifth sampling sequence).

The analysis performed and presented here was on data sets of the 74th day and 81st day after emergence and the root density determination by sampling and washing the soil of the 77th day.

Hydraulic, capillary conductivity - water content, and retention curves were obtained from direct determination performed on undisturbed cores excavated on the 32nd day.

Results and Discussion

In Figure (5-1) water uptake rates per unit soil volume - root activity- are given as function of soil water matric potential. Root activity diminishes as soil water matric potential decreases. Since root activity is termed as water volume taken up per unit soil volume, per unit time it means that root activity is a compound term for new root length developed and exploring new soil volumes for water. The lower the activity is, the less the roots elongate and grow.

In Figure [5-2] root activities for the 77th day are presented for the non-tilled and the deeply plowed plots. Using the stand count and the total area the amounts of water taken up by the root systems were calculated to be 358 and 467 cm³ water per plant per day for non-tilled and deep-plowed plots, respectively. Using the hydraulic conductivities and diffusivities to water measured for these layers, the average water uptake per 1m active root was calculated using Eq.[5-1] and assuming a period of 3 days as "life expectancy" for "root activity" in taking up water. Total root length added per day was calculated to be 840 m and 1260 m/m² per day for non-tilled and deep-plowed plots, respectively.

Taking the average elongation rates of roots in the various layers from the penetrometer data and water contents measured in the field and dividing the total added length per day yields the total number of roots per plant or unit area (stand = 10⁵ plants/ha).

Fig. 5-1 Cotton root activity [$\text{cm}^3 \text{ H}_2\text{O} \cdot \text{cm}^{-3} \text{ soil} \cdot \text{day}^{-1}$] as a function of soil water matric potential [MPa]. Lachish field.

Fig. 5-2 Calculated cotton [$\text{cm}^3 \text{ H}_2\text{O} \cdot \text{cm}^{-3} \text{ soil} \cdot \text{day}^{-1}$] distributions with depth under no-till and deeply plowed plots on the 77th day. Lachish field.

These calculated values lead to the following estimates:

- 1) 0.7 to $1.5 \cdot 10^4$ and to $1.85 \cdot 10^4$ active roots in the non-tilled and plowed plots per active plant;
- 2) 0.8 to 1.3 and 0.7 to 1.8 new roots per 1 cm^3 for non-tilled and plowed plots, per day.

These calculations can serve to validate (or serve as a database for) interactive plant-soil-atmosphere models as those described by Feddes (1982).

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6. Concluding Remarks

In this project the major objective was:

To define relationships of soil physical and mechanical properties to soil compaction including the threshold values that would characterize excessive soil compaction.

Specific objectives were:

- a) To develop relationships of hydraulic conductivity and air permeability and soil density as influenced by the mechanisms of packing;
- b) To define relationships of soil resistance to penetration, bulk density, water contents and root development; and
- c) To test and validate the laboratory measured limits of excessive compaction in the field.

As pointed out by one of the reviewers of this project prior to its initiation,

1. The hypothesis that from a single soil-loading characteristics the resultant soil physical properties can be predicted is too optimistic. The results show general trends for both K_{sat} and K_a with diminishing void ratios e or air-filled porosities. θ_a resulting from different soil loading stresses. The fact that there is no unified line of K_{sat} - e for all the soils and also within a set of data for the same soil should be attributed to:

- a) Different textures (differences between soils);
- b) Different micro structural collapse (within the same)
- c) Loading path and relative degrees of micro structure collapse and reorientation. One cannot escape the realization that in spite of these

discrepancies under some instances field plot behaviour can be predicted within reasonable errors (e.g., seepage calculations, final infiltration rates). Yet when it comes to predict bulk densities from loads superimposed on the soil the predicted densities are lower than those predicted and thus the predicted hydraulic or pneumatic properties should be expected to show great discrepancies since attainment of a given volume mass distribution (bulk density) can be achieved by several combinations of water content and loads but the resultant void arrangement will be different or in other words the data brought up point that one may expect non-unique compression-void arrangement and continuity relationships.

1. There may be more than one critical value of a given soil property which will characterize "excessive soil compaction" on one hand (see Figures 6-1 to 6-6, which are based on data of this report), or that,

Fig. 6-1 Estimated distributions of final infiltration rates $\square$ less than 1, $\square$ 1 to 4; $\square$ 4 to 8, $\square$ 8 to 26 and $\square$ 26 or higher [mm.hr⁻¹] under one tractor passage on soil no. 6 ($P_w = 19\%$ on w/w basis).

Fig. 6-2 Estimated distributions of O.D. Rates $\square$ less than 32.0; $\square$ 32 to 68 and $\square$ higher than 68 [Mg.O₂. m⁻².s] under one tractor passage on soil no.6 ($P_w = 19\%$ on w/w basis).

Fig. 6-3 Estimated distribution of biotic activity zones ($P_w = 20\%$) under one tractor passage on soil no. 6 ($P_w = 19\%$ on w/w basis). ▨ anaerobic conditions, ▤ less than optimal conditions, □ optimal and ▩ more than optimal aerobic conditions. Delineation according to Zinn and Doron 1984.

Fig. 6-4 Estimated cotton tape root elongation rate distributions under one tractor passage at ($P_w = 20\%$). ▨ No elongation - ODR smaller than $32 [\mu\text{g.O}_2\text{m}^{-2}\text{s}^{-1}]$ □ 0 to 25; 0 to 18 and 0 to 10 [mm.day⁻¹] for 0; 5; and 15 [mm.day⁻¹] transpiration rates; ▩ greater than 25, 18 and 10 [mm.day⁻¹] for 0, 5 and 15 [mm.day⁻¹] transpiration rate [for soil no. 6 at 20% water content w/w basis]. Estimates are based on soil resistances to penetration and soil bulk densities.

Fig. 6-5 Estimated cotton tape root elongation rate distributions under one tractor passage at ($P_w = 19\%$ w/w). $\square$ No elongation at all $\square$ 0 to 16; 0 to 13 and 0 to 4 [mm.day^{-1}] for 0.5 and 15 [mm.day^{-1}] transpiration rates; $\square$ 16 to 21, 13 to 19 and 4 to 12 [mm.day^{-1}] for 0, 5 and 15 [mm.day^{-1}] and $\square$ greater than 21, 19, 12 [mm.day^{-1}] for 0, 5 and 15 [mm.day^{-1}] transpiration rate. Soil no. 6 at P_w 15% w/w basis). Estimates are based on soil resistances to penetration and soil bulk densities.

Fig. 6-6 Estimated cotton tape root elongation rate distributions under one tractor passage at ($P_w = 19\%$ w/w basis). $\square$ No elongation at all $\square$ 0 to 10; 0 to 15 and 0 [mm.day^{-1}] for 0, 5 and 15 [mm.day^{-1}] transpiration rates; $\square$ 10 to 18, 2 to 16 and 0 to 8 [mm.day^{-1}] for 0, 5 and 15 [mm.day^{-1}] transpiration rates, and $\square$ greater than 18, 16, and 8 [mm.day^{-1}] for 0, 5 and 15 [mm.day^{-1}] transpiration rate. Soil no. 6 at P_w 12% w/w basis). Estimates are based on soil resistances to penetration and soil bulk densities.

2. The resulting soil properties aimed at as parameters for future modelling and predictions of soil conditions adverse or conducive to plant development, are not single valued ones.

These two observations extensively dealt in the previous sections suggest that:

1. The cause-effect relationships shown, in this report, to exist between load, soil initial conditions and resultant soil physical properties are pore arrangement and continuity dependence.
2. Different soil structural initial conditions may yield different pore or void network for a given volume mass resulting in different physical properties and as a consequence.
3. Different plant rooting responses are to be expected.
4. Furthermore, in grosso modo, root development in the laboratory could support a rough root proliferation model as shown in section 5, but different soil structures will lead to different root elongation rates or mode of branching that will further complicate the rather "simple" relations between transpiration, water content and soil resistance to penetration and root elongation rates given in section 4.
5. There is a definite need for refined laboratory techniques (section 2) so that physical properties of structured soils can be determined in the laboratory applied to field situation and yield field conditions.

Summing up it seems that the major objective was attained and the specific objectices are partially achieved. Yet there is no doubt that specific, measured, single valued, limits to delineate excessive compaction for field predictions, may be also climatic and soil structure-dependentf, rather than as postulated in the working hypothesis which was the basis of our major objective. Therefore,

- a) The effect of soil structure on soil deformation and consequently on the derived soil physical properties governing soil air and moisture regimes should be further investigated; and
- b) There is a need for refined laboratory and field techniques to be developed in order to yield accurate and reliable physical and mechanical properties characteristic for structured soils.

LIST OF PUBLICATION

- Gupta, S. C., P. P. Sharma and S. A. DeFranchi. 1989. Compaction effects on soil structure. *Adv. Agron.* 42:311-338.
- Gupta, S. C., A. Hadas, and R. L. Schafer. 1989. Modeling soil mechanical behavior during compaction, p 137-152. *In* W. E. Larson (eds.) *Mechanics and related processes in structured agricultural soils*, NATO ASI Series E-vol, Kluwer Academic Publisher, Dordrecht.
- Larson, W. E., G. R. Blake, Allmaras, R. R., W. B. Voorhees, S. C. Gupta (eds.) 1989. *Mechanics and related processes in structured agricultural soils*. NATO ASI Series E-Vol. 172. Kluwer Academic Publishers, Dordrecht.
- Voorhees, W. B. 1989. Root activity related to shallow and deep compaction, p 173-186. *In* W. E. Larson (eds.) *Mechanics and related processes in structured agricultural soils*, NATO ASI Series E-vol, Kluwer Academic Publisher, Dordrecht.
- Xu, Xia. 1990. A model for predicting the gas diffusion coefficient in soils. M. S. Thesis. University of Minnesota, St. Paul, MN, p126. (RESEARCH ON THE SAME SOILS BUT NOT FUNDED BY BARD)

FUTURE RESEARCH NEEDS

- A. Testing and applying the present quantification scheme of excessive compaction under field conditions on a regional scale covering several soil type, weather conditions and load variations.
- B. Development of a criteria of soil matric potential above which soil may be considered wet to conduct any field operations.
- C. Development of a criteria of excessive compaction based on the probability and the number of consecutive days a soil remains wet.
- D. Development of criteria of excessive compaction based on increases in surface runoff due to a decrease in soil hydraulic conductivity on application of stress.
- E. Validation and testing of Soil Water Balance model used in this report to predict soil wetness from long term weather records.
- F. Development of a data base on applied stress (field equipment) by soil type and field operations.
- G. Development of data bases on soil wetness by soil type.
- H. Studies on the criteria of aggregates degradation due to applied stress.
- I. Developing limits of excessive compaction based on field measurements.
- J. Guides to select Frolich's concentration factor (v values) for given initial soil bulk density, soil wetness and soil type.

DESCRIPTION OF COOPERATION

This BARD grant was the second cooperative effort between the Israel and American teams. As a result of previous BARD project, Dr. Amos Hadas spent a sabbatical in Minnesota during 1985-86. It was during his sabbatical that this research proposal was conceptualized, written and submitted to BARD for funding. Before Dr. Hadas returned to Israel, the research details were cooperatively planned. Subsequently, information on methods and results was shared through written correspondence, bit-net messages, and personal exchanges at professional meetings. A thorough review of the project was undertaken when Dr. Hadas was in Minnesota during Fall 1988 to attend the NATO Advance Research Workshop "Mechanics and related processes in structured agricultural soils" organized by the American team. Modification in procedures and tentative conclusions were also discussed and decisions made. The American team took the lead in developing a procedure and the needed laboratory data bases for classifying soils on their susceptibility to excessive compaction. The Israel team developed the similar laboratory data base for Israeli soils and tested the adequacy of the laboratory measurements against field observations.

Parts of the final report were prepared by the two teams and reviewed at a meeting in Israel between Dr. Gupta and Drs. Hadas and Wolf. Interpretation of the data and criterion of defining excessive compaction were discussed and finalized. Complete drafts of the final report were subsequently exchanged through mail and final report was compiled in St. Paul.

Of prime value in this project was the sharing of the expertise and experiences among the Israel and American investigators. The shared expertise and the opportunity to work on the project was particularly helpful to Graduate Students. Our cooperation has led to advances in procedures for quantifying and classifying soil as to their susceptibility to soil compaction as well as increased visibility for both our teams among our National and International peers.

BENEFITS TO AGRICULTURE

Compaction of the soil by increasing intensive cropping practices and large farm tillage and harvesting equipment is a world-wide problem. Compaction of soil decreases the rate at which water can enter and move through the soil allowing less water storage 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.

This reports provides a procedure for quantifying soil as to their susceptibility to excessive compaction. To the authors knowledge, this is the first study of its kind that provides a framework to integrate the climatic, soil and applied load variability in quantifying soils susceptibility to excessive compaction. If the susceptibility to compaction is known, cropping, tillage and harvesting practices can be prescribed to growers which will prevent undue compaction. An example of this application is demonstrated in defining loads that are not conducive to excessive compaction for a given soil type and soil wetness. The pay-off from the research in this report is world-wide.