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Characterizing Soil Deformation by Direct Measurement Within the Profile

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ABSTRACT

A unique feature of the University of Kentucky soil bin enables deformation to be characterized by studying a cross-sectional soil profile grid pattern. Modular sections of the bin are laterally removed to expose the cross-section after passes of a pneumatic tire.

The measured displacements of the grid points were converted to values of volumetric strain and then compared to soil density as measured by a dual probe gamma-ray density gauge following tests at various soil conditions. Final soil bulk density determinations using the two methods were not statistically different.

INTRODUCTION

Excessive compaction of agricultural soils, which ultimately results in reduced crop yields, has become a major problem world-wide. Raghavan et al. (1976) reported that damages from this cause were estimated to exceed one billion dollars per year in the United States, with proportional losses associated with agricultural soils throughout the world.

Technological advances in the design of tractors and implements have resulted in larger, heavier machinery. Carpenter and Fausey (1983) reported that the average tractor weight in the United States has increased by more than 50% in the last 15 years, from 44.5 kN to more than 67.0 kN with large four-wheel drive units weighing in excess of 220.0 kN. While the advent of dual wheels and four-wheel drive has enhanced the tractive performance of modern tractors, their use in less-than-optimal field conditions can result in serious soil damage. Rigid planting and harvesting schedules, especially in modern systems of double cropping, heighten this problem.

The objective of this research was to characterize the soil response to wheel traffic by measuring actual displacements within the cross-section of the soil profile. These measurements were then compared to changes in soil bulk density as determined by a gamma density gauge.

To accomplish this goal a soil bin was designed and constructed at the University of Kentucky Agricultural Engineering Department with special features to study traffic compaction (Wood and Wells, 1983; Wood, 1984). The special features include nine modular bin sections that can be removed to study the soil profile, adjustable wheel positioning to study the effects of adjacent traffic and a dual probe gamma-ray density gauge to measure the soil response.

There are two basic types of soil bins: the movable bin and the stationary bin. The movable bin is driven past a stationary test tool, while the stationary bin has a movable tool carriage that runs along the top of the bin. The different types of soil bin facilities around the world have been described by Durant et al. (1979) and Wismer (1984).

LITERATURE REVIEW

While a moderate degree of compaction may be desirable to achieve the good soil-seed contact required for germination or to slow internal drainage, excessive compaction is detrimental. Compaction caused by off-road machinery is primarily a decrease in macroporosity within the soil matrix. Such a response leads to reduced yields by decreasing infiltration and impeding root growth and seedling emergence, as well as increasing erosion and reducing soil productivity. Raney et al. (1971) have shown that compaction influences nearly all phenomena associated with plant growth, affecting such properties as strength, as well as, the transmission and storage of heat, gas and water.

Wheel traffic is the primary cause of agricultural soil compaction (Cohron, 1971; Soane et al., 1980) and three factors contribute to its effect:

1. The first wheel pass can result in up to 90% of the total compaction from multiple passes, depending on the initial strength of the soil (Raghavan et al., 1979; Harris, 1971; Taylor et al., 1982).
2. Traffic can compact the soil below the depth of conventional tillage (Raghavan et al., 1976), making mechanical alleviation of the problem economically and practically unrealistic in many cases. In assessing the state-of-the-art in soil compaction, Taylor and Gill (1984) identified the total axle load as the basic cause of deep soil compaction.
3. The associated effect of tractive thrust can increase compaction 20 to 50% over the normal operating range by imposing shear stresses on the soil due to relative motion between the tire and soil (Raghavan et al., 1977, 1978; Raghavan and McKyes, 1977).

To characterize soil deformation, it is necessary to make measurements within the soil profile without significantly altering the soil response. Danfors (1974) established a grid pattern within the profile by the placement of soil deflection probes in the soil. This

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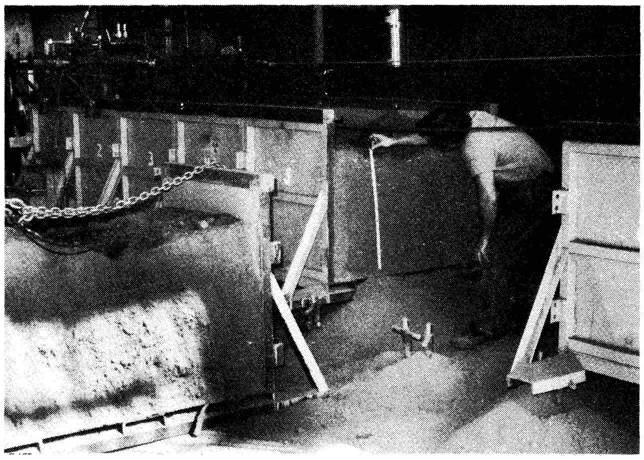

Fig. 1—The University of Kentucky soil bin and associated apparatus.

method was limited by the inability to measure deformation directly beneath the path of the tire. Gill and Vanden Berg (1968) discussed several methods of measuring initial and final positions within the soil mass including colored beads, brass rods, sticks, gypsum, coal dust and radioactive shot.

PROCEDURE

To determine the soil response to wheel loading, as measured by the displacement of grid points buried within the profile, powered wheel tests were conducted on each of four soil profiles prepared in the University of Kentucky soil bin (Fig. 1). Two levels of moisture content and two levels of dynamic load were investigated.

Soil Profile Preparation

Maury silt loam topsoil was placed in the bin so that preliminary wheel runs could be made to test the system in October, 1983. The bin was loosely filled to a depth of 76 cm. The soil was levelled and compacted with a roller in primary layers of 15 cm as described in detail by Wood (1984). Preliminary testing was completed in February, 1984. The soil was then removed so that the first soil condition could be prepared.

Grid Placement

For soil condition 1, five parallel lines of marble dust, 60 cm in length, spaced 15 cm apart, were placed along the length of the bin, between modules five and six at the interface of each soil layer, i.e. at depth increments of 15 cm. The marble dust was poured into 0.6 cm slots in a 76 cm square plywood board to form the lines (Fig. 2). The board was centered between the two modules such that the middle line would be directly under the centerline of the wheel path. This resulted in a rectangular grid within a cross-section of the soil profile with a spacing of 15 cm x 15 cm. The grid pattern was made finer near the surface to increase sensitivity for soil conditions 2, 3 and 4. Figure 3 shows the resulting pattern in the soil profile cross-section.

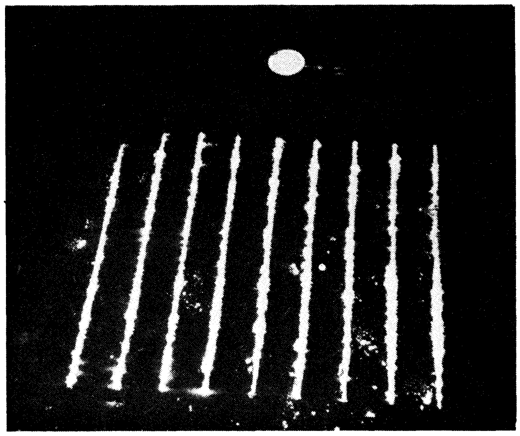

Fig. 2—Lines of marble dust and soil stress transducer placed within the profile.

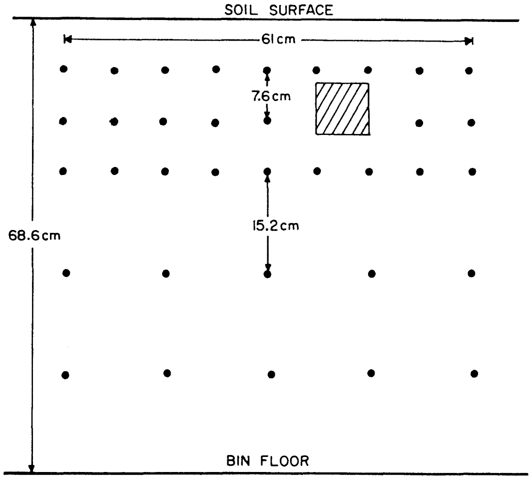

Fig. 3—Diagram of grid pattern geometry.

Soil Condition 1: As a result of four months of interior storage, the soil was in an extremely dry condition. A measured amount of water was uniformly applied to 5 cm primary layers with a hand sprayer to establish an initial moisture content of 14%, the soil was then compacted in five secondary layers of 15 cm as described by Wood (1984).

Soil Condition 2: The establishment of the second profile did not require a change in moisture content. The profile was established in primary layers of 15 cm up to the 45 cm level. To increase the sensitivity of the grid pattern in the upper 30 cm, the soil was levelled in 7.6 cm layers and the number of parallel lines of marble dust was increased from five lines spaced 15 cm apart to nine lines spaced 7.6 cm apart. The roller was used at 15 cm intervals to compact the profile.

Soil Condition 3: For this treatment, a measured amount of water was uniformly applied to each primary layer to increase the moisture content to 20% dry basis. The rest of the procedure was the same as for the first soil condition, except for the placement of the marble dust, which was the same as condition 2.

Soil Condition 4: No change in moisture content was required for this treatment. The procedure followed that of soil condition 3.

Initial Density Determination

An initial density scan was made with a Troxler* dual probe gamma-ray density gauge (Model 2376) and scaler-ratemeter combination (Model 2651) to characterize the initial state of the profile. The access

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*Trade names are provided for informational purposes and do not imply endorsement by the Kentucky Agricultural Experiment Station.

TABLE 1.
INITIAL SOIL CONDITION AND WHEEL PERFORMANCE CHARACTERISTICS FOR EACH SOIL CONDITION.

	Soil condition		Wheel performance		
Test no.	Moisture content, %	Initial density, g/cc	Dynamic load, kN	Net traction, kN	Travel reduction, %
1	14.0	1.18	—	—	—
2	13.0	1.09	11.56	0.84	6.5
3	20.9	1.14	6.54	0.72	12.6
4	18.9	1.10	6.43	0.52	8.9

holes for the probes were drilled on 30.5 cm centers using a vertical auger. Samples were taken to gravimetrically verify the existence of a uniform moisture content. Initial density readings were taken in two locations in the area on either side of the grid pattern. At each location, readings were taken 15.2 cm and 30.5 cm from the centerline of the tire track. Initial readings were not taken below the tire track so as to minimize soil disturbance. The access holes in the tire track were drilled after the wheel pass. Density readings were taken in 7.6 cm increments in depth at each location.

Powered Wheel Tests

A single powered wheel test using a 7.60 x 15 ribbed implement tire was run on each soil condition. Preliminary tests were run in the first half of the bin to determine the desired level of wheel speed and travel reduction. Actual forward velocity, angular wheel velocity, dynamic load and net traction were continuously monitored during each run as described by Wood (1984).

The first powered wheel test was hampered by mechanical and hydraulic problems. This resulted in the wheel losing traction before the test run was completed. Although this nullified the test, inspection of the grid profile indicated that a higher sensitivity to soil response was needed. A higher sensitivity was incorporated into the three remaining profiles. The wheel performance data is shown in Table 1 along with the soil condition before each test.

Post-Test Determinations

After the test was completed, the rolling radius of the tire was determined in the soil bin by measuring the distance travelled by the center of the loaded wheel during one revolution at zero torque. This distance was assumed to equal the circumference of the loaded tire, from which the rolling radius could be calculated.

Post-test soil densities were determined with the density gauge using access holes at the center of the tire track in addition to the previously-described holes located 15.2 and 30.4 cm from the center. Such readings were taken at 7.6 cm depth increments.

The bin was then separated and a vertical face was established on each of the modules containing the grid pattern by etching the disturbed area of separation. The resulting positions of the grid points were measured (Fig. 4) and compared to the assumed initial rectangular pattern.

RESULTS

Soil Profile Preparation

The average variation in soil moisture with depth for all conditions was 1.5% dry basis indicating that the experimental method for developing uniform moisture conditions was successful.

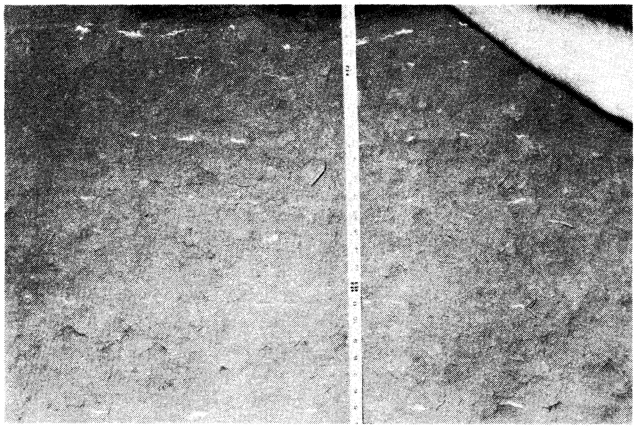

Fig. 4—Deformed grid pattern within a soil profile.

Since no initial density readings were taken beneath the tire track, the four initial readings (replicated measurements at 15.2 cm and 30.4 cm from the center of the tire track) at each depth were averaged to obtain the initial density profile beneath the tire track. The average standard deviation of these four measurements was 0.05 g/cc.

Although initial readings were taken at 7.6 cm increments, the final reading at the first depth could not be taken accurately beneath the center of the tire track with the density gauge. The gauge is designed to take readings at depths greater than 5 cm so the initial readings at 7.6 cm should be accurate. However, following the wheel pass deformation beneath the tire resulted in less than 5 cm of soil between the surface and the location of the initial reading.

Analysis of the Grid Deformation

The coarse grid in the bottom 30.4 cm of each profile was not analyzed because there was virtually no deformation due to the wheel traffic at that depth. The initial area of the blocks in each row of the upper region of the profile were assumed to be equal (see Fig. 3). This area was calculated by multiplying the width between the points (7.6 cm) by the assumed vertical distance between rows. The initial position of each row of points was taken to be the average position of all points that were at least 25.4 cm from the centerline of the tire track. It was assumed that these remote points did not move in response to the wheel traffic. Once this initial position was determined for each row, the initial area of each block was calculated.

The final area was determined by the distance between the points after the wheel pass (see shaded block in Fig. 3). From the change in area of each block, a corresponding change in volume was defined by assuming a unit depth into the profile. This change in volume, expressed as a volumetric strain, is proportional to the change in density within the block as follows:

$$e_v = \frac{V_1 - V_2}{V_1} = \frac{D_2 - D_1}{D_2} \qquad [1]$$

TABLE 2. VOLUMETRIC SOIL STRAIN MEASURED IN RESPONSE TO POWERED WHEEL TESTS.

Soil condition 2
Distance from bin center, cm

Depth, cm	30.4–22.9	22.9–15.2	15.2–7.6	7.6–0	0–7.6	7.6–15.2	15.2–22.9	22.9–30.4
5.0–10.3	0.242	0.333	0.182	0.091	0.151	0.151	0.060	-0.152
10.3–20.6	-0.061	-0.092	-0.077	0.061	0.077	0.031	-0.031	0.031
20.6–29.5	-0.018	0	0.054	0.071	0.071	0.054	0.054	0.036

Soil condition 3
Distance from bin center, cm

(Location 1)

Depth, cm	35.4–27.8	27.8–20.2	20.2–12.6	12.6–5.0	5.0–2.6	2.6–10.2	10.2–17.8	17.8–25.4
8.7–15.5	0.016	-0.02	-0.02	0.051	0.133	0.121	0.063	0.016
15.5–22.9	-0.007	0.014	0.068	0.068	0.004	-0.039	-0.029	-0.007

(Location 2)

	27.8–20.2	20.2–12.6	12.6–5.0	5.0–2.6	2.6–10.2	10.2–17.8	17.8–25.4	25.4–33.0
9.6–15.7	-0.096	0.044	0.047	0.047	-0.018	-0.031	-0.018	0.048
15.7–23.2	-0.056	-0.088	-0.088	-0.035	-0.014	0.018	0.039	0.018

Soil Condition 4
Distance from bin center, cm
(Location 1)

Depth, cm	30.4–22.9	22.9–15.2	15.2–7.6	7.6–0	0–7.6	7.6–15.2	15.2–22.9	22.9–30.4
5.7–13.0	-0.022	0.065	0.076	0.076	0.130	0.141	0.098	0.076
13.0–23.2	0.016	0	0.109	0.258	0.211	0.070	0.016	0

(Location 2)

Depth, cm	30.4–22.9	22.9–15.2	15.2–7.6	7.6–0	0–7.6	7.6–15.2	15.2–22.9	22.9–30.4
6.0–13.7	0.062	0.031	0.041	0.125	0.219	0.146	0	-0.083
13.7–23.7	0.048	0.087	0.063	0.111	0.119	0.024	-0.064	-0.064

TABLE 3. COMPARISON OF FINAL BULK DENSITY AS COMPUTED FROM THE GRID DATA VS. MEASUREMENTS USING THE GAMMA DENSITY GAUGE.

Depth, cm	Computed final density, g/cc		Measured final density, g/cc	
Soil condition (below centerline)	Location 1	Location 2	Location 1	Location 2
15.2	1.23	*	1.20	1.26
22.9	1.20	—	1.15	1.17
30.4	1.20	—	1.18	1.20
(15.2 cm from centerline)				
7.6	1.54	1.28	1.14	1.22
15.2	1.08	1.18	1.16	1.23
22.9	1.15	1.18	1.15	1.22
30.4	1.15	1.18	1.16	1.21
Soil condition (below centerline)				
15.2	1.31	1.20	1.19	1.16
22.9	1.14	1.10	1.24	1.14
Soil condition (below centerline)				
15.2	1.29	1.44	1.14	1.15
22.9	1.39	1.25	1.17	1.14
(15.2 cm from centerline)				
7.6	1.19	1.24	1.20	†
15.2	1.24	1.13	1.21	—
22.9	1.23	1.12	1.16	—

*Measurements were not replicated for test number 2.
†Second replication was not at the same initial density.

where, e_v = volumetric strain
V_1 = initial volume of block
V_2 = final volume of block
D_1 = initial bulk density of block
D_2 = final bulk density of block.

Equation [1] was derived by Wood (1984). Values of volumetric strain for each soil profile are presented in Table 2 in the area of the profile for which they were calculated. The corners of each square are defined by the positions of the grid points. The error associated with measuring the distance between grid points resulted in an error in volumetric strain of $\pm$ 0.071. There was also some error introduced by not having the exact initial position of each grid point.

Values of final density were calculated using equation [1] and the initial density readings from the density gauge. These values are compared to the final gauge readings in Table 3. In general, there is good agreement between the two methods for the level of accuracy achieved in this experiment. A statistical t-test (α = 0.05) indicated no significant diference between the two methods of obtaining soil density.

CONCLUSIONS

An effective means has been demonstrated for making direct measurements of deformation within a soil profile due to surface wheel loading. Volumetric strain can be used to compute changes in soil bulk density provided initial density is known. The method offers the possibility of detailed characterization of two-dimensional soil deformation.

Final soil bulk density as computed from volumetric strain measurements were not significantly different from the gamma-ray density gauge readings. Thus the density gauge can be used to supplement direct measurement of soil deformation as well as to determine variations in initial soil bulk density within the bin.

Future research will be directed toward evaluation of two-dimensional models of soil stress due to surface wheel loading. Soil stress could be computed using measured soil strain and a stress-strain relationship. This approach may also be useful in differentiating between soil deformation due to dynamic load and that due to tractive thrust involving a pneumatic tire.

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