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SOIL PHYSICAL PROPERTIES AS AFFECTED BY REPEATED WHEELING

F. E. Berisso

Institute of Technology, School of Biosystems and Environmental Engineering, Hawassa University, Hawassa Ethiopia

Abstract

A field experiment was carried out in the spring of 2015 to analyse the effect of field traffic on soil physical properties. A tractor used for wheeling and the experiment had a randomized block design with four replicate plots. Control and four repeated wheeling were used as treatments. Intact cores of 100 cm^3 were collected from and used for determination of soil mechanical and physical properties. The inflicted compaction was significantly increased bulk density at 10 and 20 cm depths, whereas the saturated hydraulic conductivity was reduced. At -6 and -30 hPa, the air-filled porosities were consistently lower for compacted soil than for control soil; whereas for most soil the values were higher than value proposed as the critical lower limit for plant growth. Our study hence documents that commonly used agricultural machinery may compact the soil to 0.3 m and even deeper with effect on important soil functions.

Key words: soil compaction, bulk density air –filled porosity, saturated hydraulic conductivity.

INTRODUCTION

In recent years, a growth in agricultural economy of Ethiopia has increased the dependence of agricultural operations on modern machineries such as tractors and combines harvesters. An increasing number of farmers are purchasing these machineries and associated drudgeries with farm operation are eased. On the other hand, high costs of these machineries, combined with timeliness of agricultural operations, force the owners to hire these equipments and operate even in wet soil condition, which increases high risk of soil compaction.

Compaction is a major problem affecting agricultural soil structure and this consequently leads to a reduction to crop production. Direct cause and effect relations appear to exist between the use of machinery and soil compaction, between soil compaction and a plant root environment, and between a plant root environment and crop production (HAMZA AND ANDERSSON, 2005). Compaction by wheel traffic, cultivation equipment, animals or natural processes can affect soil water movement by increasing bulk density and decreasing porosity and infiltration (ARVIDSSON, 2001). These changes can result in less soil water storage, poor nutrient movement, slowed gas exchange and restricted root growth, all of which can cause a reduction in crop yields (LIPIEC AND HATANO, 2003).

Due to these deleterious effects, soil compaction has received greater attention from different stakeholders, including public authorities and international policy makers, especially in developed countries. For instance, the European Union (EU) proposed an EU Soil Framework Directive to protect soil against threats that undermine its capacity to perform environmental, economic, social and cultural functions (COMMISSION OF THE EUROPEAN COMMUNITIES, 2006). Soil compaction has also been the subject of many studies, which are reported in books, research articles and review papers. Many international series of field experiments and projects have also been initiated at different times in order to address compaction effects on soil and crop yield, for example the Working Group on Soil Compaction by Vehicles with High Axle Load in 1980 (HÅKANSSON ET AL., 1987) and the POSEIDON project in 2009 (WWW.POSEIDON-NORDIC.DK).

Compared with these numerous studies and efforts worldwide, there are few reports from Ethiopia. Moreover, most of the data concerns the primitive agriculture or few estate farms alone. For instance, TADDESE ET AL. (2002) conducted study in primitive agriculture and reported higher bulk density in heavily grazed than in nongrazed medium grazed plots. TESHOME AND KIBRETE (2009) characterized soils of soil in one of the estate farms in terms of their physical and hydraulic properties and reported variation in soil bulk density. They attribute the observed differences entirely to soil management classes by disregarding the effect of agricultural machinery.

In Ethiopian context, there are a lack of studies that focus on the effect stresses due to agricultural machinery on soil compaction. The aim of this project was to analyse how soil compaction during field traffic effects soil pore structure and associated transport processes. The project was focused on immediate effect of agricultural machinery on water flow, soil air filled porosity, and bulk density. It was hypothesize that soil compaction affects the structure and functioning of soil pores.

MATERIALS AND METHODS

New compaction experiment was established in spring 2015 at Hawassa University Farm, which is located 260 km from capital city Addis Ababa. The field has been used for maize growth for many year and then used as experimental site for agronomy crops since 2007. Some physical and mechanical characteristics of the soil are shown in Tab. 1. Also listed is the soil water content during field sampling. Methods used to determine these properties are briefly described below.

Tab. 1. – Soil water content at sampling, soil texture, cohesion and angle of internal friction of the soils

Depth [m]	Water content [cm^3 cm^{-3}]	Clay <0.002 mm [g g^{-1}]	Silt 0.002-0.02 mm [g g^{-1}]	Sand 0.02-0.2 mm [g g^{-1}]	Cohesion kPa	Angle of internal friction (^{0})
0.10	0.36	0.17	0.21	0.62	54.0	36.1
0.20	0.34	0.19	0.24	0.57	54.2	34.5
0.30	0.37	0.20	0.24	0.56	58.0	33.8

Traffic experiment and machinery

The experiment had four replicate plots and wheeling was carried by a tractor, which was commonly used in the farm for tillage and harrowing operations. The front and rear wheel loads of the tractor were 750 and 3250 kg, respectively. The inflation pressure of the front tyres was of the tractor was 150 kPa, whereas that of the rear tyres 250 kPa. Wheeling was done by driving the tractor on the same track and the experiment had two treatments: 1) control treatments, which was not exposed to experimental traffic; 2) four repeated wheeling in single track by driving the tractor back and forth twice.

Field measurement and soil sampling

Penetrometer resistance was measured to a depth of 35 cm in the track before and immediately after wheeling. The outer area of the front and back tyres (footprint) was marked with sand while the tractor was stationary and photographed. The area was determined from image analysis of the footprint and used as an input in the *Soilflex* model by KELLER ET AL. (2007). Rut depth was measured after each wheeling at three different location of each plots.

After wheeling, access pits was carefully opened in each plot, and horizontal planes was sequentially prepared for sampling intact cores of 100 cm^3 at 10, 20 and 30 cm depth. Six replicate cores were collected from each plot and used to characterize physical and mechanical properties of the soil by a range of standard measurements in the laboratory as indicated below. Bulk soils of 1 kg were collected from each sampling plots at three depths (10, 20 and 30 cm) and used for determination of soil textural class.

The complete stress state in the soil profile beneath the machinery was predicted using the *SoilFlex* model presented by (KELLER ET AL., 2007). Soil deformation (change in soil volume, rut depth) was calculated according to the (O'SULLIVAN AND ROBERTSON, 1996) model, which is included in the SoilFlex.

Laboratory analyses

Prior to the experiment, all soil cores were carefully trimmed with a sharp-edged knife, covered with fine nylon cloth. Two replicate cores, at field moisture contents, were used to determine initial mechanical properties of the soil. The precompression stress and other mechanical properties (see Tab. 2) were derived by fitting Gompertz equation to stress-strain curve obtained from uniaxial confined compression test with odometer.

Soil cores used for measurement of saturated hydraulic conductivity (two replicate for each treatments) were saturated bottom with a distilled water containing 0.01 M $CaCl_2$. The saturation was done in three steps within 24 hours and the samples were kept in distilled water for a week in order to assure fully saturation. Samples used for measurement of water retention were transferred to sandboxes, where they sequentially drained to -6 and -30, hPa matric potentials. The cores were weighed at each matric potential and after oven-dried (105 ºC) for 24 hours. Bulk density (BD) was calculated from weight of oven-dried soil and total volume of the soil cores. Total porosity (θs) was calculated from BD and particle density (2.65 gm.cm^{-3} was used in this study). Gravimetric water content (w) was calculated as a difference between the weight of the samples at a given matric potential and at an oven dry. Volumetric water content at a given matric potential (θ) was calculated from w and BD. Air-filled porosity (ε_a) was calculated as a difference between θs and θ.

Tab. 2. – Soil parameters used for the simulations

Parameter	Symbol (unit)	Soil depth		
		10 cm	20 cm	30 cm
Specific volume[a] at p = 1 kPa	n (-)	2.335	2.382	2.383
Compression index[b]	λ_n (ln (kPa^{-1}))	0.114	0.131	0.130
Swelling index[a]	κ (ln (kPa^{-1}))	0.0040	0.0042	0.0026
Slope of the ‘steeper recompression line’[a]	κ‘ (ln (kPa^{-1}))	0.0214	0.0235	0.0020
Separation between yield line and virgin compression line[a]	M (-)	0.92	1.22	0.8600
Initial bulk density	ρ (Mg m^{-3})	1.31	1.33	1.36

[a] The soil depth refers to the midpoint depth of a sample of 3.8 cm height

[b] Calculated from oedometer tests by assuming s2 =s3 = 0.5 s1 (Koolen and Kuipers, 1983; Keller et al., 2007)

The saturated hydraulic conductivity, K$_{sat}$, was measured using constant head method as described by Kulte and Dirksen (1986). The measurements of average value of water discharge (Q), soil length (L), cross-sectional area of the soil sample (A), and hydraulic head (H), were used to determine the Ksat using (Equation 1).

$$q = K_{sat} \frac{\Delta H}{L} \tag{1}$$

Where q is Darcy flux density and given by q=Q/A. K$_{sat}$ was then calculated as:

$$K_{sat} = \frac{QL}{AH} \tag{2}$$

Before analyses, the bulk samples were kept in the laboratory at room temperature (25 °C) and used for the analysis of soil textural class. The standard sieve-hydrometer method was used for this purpose.

Statistical analysis

In new compaction experiment, statistical analysis of all variables was performed using the MIXED procedure in SAS by assuming the effect of treatment and blocks as fixed and random, respectively. The Kenward and Roger method was used for calculating the degrees of freedom in the statistical tests (Kenward and Roger, 1997). The normality of residuals was tested after fitting a linear mixed model to the data in order to ensure that the normality assumption of the model was satisfied.

RESULTS AND DISCUSSION

Predicted soil stress

Predicted mean normal stresses under front and rear wheels after four repeated wheeling are shown in Fig. 1. Research finding from Scandnevian (e.g. Keller, 2004; Keller et al., 2012) have been shown the occurrence of plastic deformation (irreversible compaction) when the vertical stress exceeds 50 kPa at water contents close to field capacity and this value has been suggested as a critical threshold for sustainable traffic in the field (Schjønning et al., 2012). It can be note from Fig. 1 that the predicted vertical stress of front and rear wheels were exceeded this value at depths shallower than 25 and 50 cm, respectively. Based on this, one can assume that soil deformation has actually took place to approximately that depth during wheeling event.

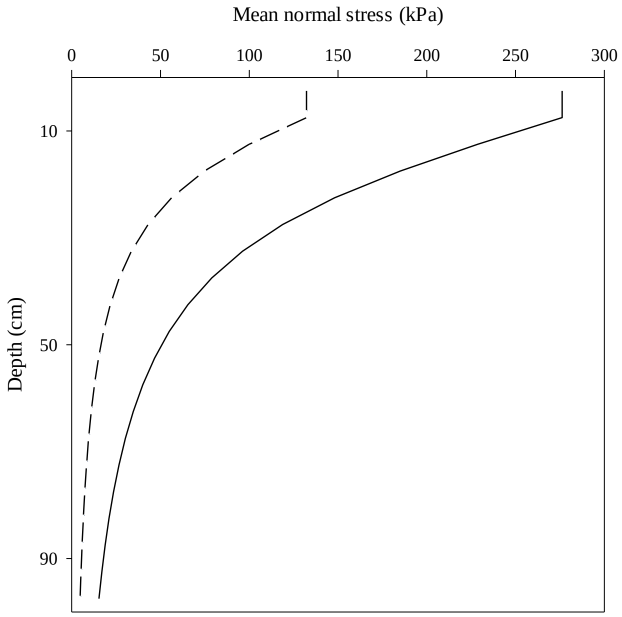

Fig. 1. – Calculated mean normal stress under the center line of the wheel rut (dotted line for front wheel; solid line for rear wheel)

Penetration resistance

Four repeated wheelings, during field experiment, had increased the penetration resistance of the soil at all depths down to 30 cm (Fig. 2), whereas significant differences were observed from 10-30 cm depth. In general, the penetration resistance was sharply increased from 0-10 cm depth for both control and wheeled plots. Similar trends were reported by ANSORGE AND GODWIN (2006),who measured penetration resistance immediately after wheel passes. However, such measurements should not be taken as a conservative estimate of compaction effect.

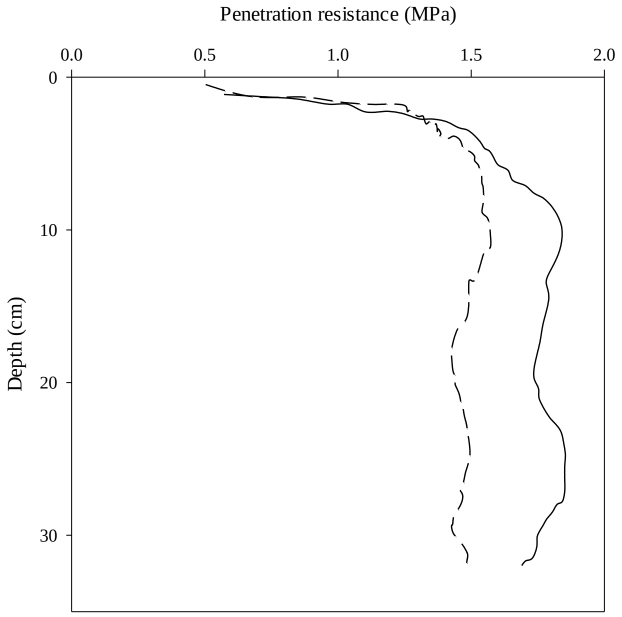

Fig. 2. – Penetration resistance measured before (dotted line) and after (solid line) four repeated wheelings

In control plots, this increase could be attributed to the residual effect of traffic from previous management or repeated traffic imposed during annual agricultural operations. Since there were no tillage activities during the time of wheeling, which can partially or fully alleviate compaction from preceding traffic, natural regeneration must occur by biological and abiotic activities in this soil, which might require much more time. However, no such activities were observed during sampling event.

Measured soil physical properties

Bulk density, air-filled porosity at -6 and -30 hPa, and saturated hydraulic conductivity for both control and compacted soils are shown Tab. 3. Results of the statistical analysis are also included in the figure. In general, four repeated wheelings increased the bulk density at all sampling depths, whereas significant differences were observed in the two upper sampling depth (Tab. 3).

Tab. 3. – Bulk density, air-filled pore space at -6(e_{a6}) and -30 (e_{a30}) hPa and saturated hydraulic conductivity for compacted and control treatments. The values shown are least squares means observed in four replicate blocks. P-values show the results of the linear mixed model tests on the differences between control and compacted treatments.

Depth (cm)		BD	Air filled porosity $m^3 m^{-3}$		Saturated hydraulic conductivity cm day^{-1}
			ε_{a6}	ε_{a30}	
10	Control	1.28	0.06	0.11	182
	Compacted	1.35	0.04	0.09	74
	P-value	<0.01	<0.01	<0.01	<0.01
20	Control	1.33	0.08	0.14	166
	Compacted	1.36	0.04	0.12	124
	P-value	0.02	0.04	0.01	0.04
30	Control	1.36	0.07	0.17	143
	Compacted	1.37	0.05	0.15	123
	P-value	0.08	0.09	0.62	<0.01

Several researchers obtained similar results. For instance, from nine different six experiments in Sweden on soils with clay contents ranging from 19 to 256 g kg^{-1} of soil, Arvidsson (2001) observed significant increase in bulk density up to 50 cm depth in the compacted plots as compared to the control one. Despite this changes, bulk density observed in this study, both in compacted and control plots, was lower than the typical minimum bulk density at which root-restricting conditions occur according to USDA-NCRS (1996; cit. Kaufmann et al., 2010) for sandy clay loam (1.70 $g.cm^{-3}$) soil.

The air-filled porosity values, ε_a, measured at -6 and -30 hPa were lower in the compacted treatment than in the control treatment at all four soil depths (except at 30 cm depth). Our observed reductions in volume of ε_a at both matric potentials are similar to the findings of Berisso Et al. (2013). For soils from compacted treatment, the εa_6 values were below 10 % (0.1 m^3 m^{-3}), the value which has been proposed as the critical lower limit for plant growth (Grable and Siemer, 1968). The low ε_a values in control soils indicate that the Hawassa soil was generally less dense and favourable for crop growth.

The function of soil pores can be evaluated from their ability to conduct water. At all three depths, the saturated hydraulic conductivity was lower in compacted than in control treatments at (Tab. 3). The finding is in agreement with Horton et al. (1994), who reported a reduction in saturated hydraulic conductivity from 1437 to 224 cm day^{-1}in a no-till treatment and from 1892 to 291 cm day^{-1} in a chisel plough treatment due to field traffic.

In general, for both soils from compacted and control plots, the saturated hydraulic conductivity values of the Hawassa soil were considerably higher than

8.6 cm day^{-1}, which was established by MCQUEEN AND SHEPHERD (2002) as the critical limit for adequate hydraulic conductivity for crop growth. However, the saturated hydraulic conductivity values for compacted soil at 0.3 m depth was rather low compared with the extreme precipitation events in recent days. This situation inevitably increases the risk of surface ponding, which eventually leads to soil erosion and leaching of agro chemical to receiving water bodies.

Estimated and measured soil compaction

For soil considered in this study, the mean normal stresses (σ_m) were calculated from the principal stress components, and converted to total rut depth using O'SULLIVAN AND ROBERTSON, (1996) model. The calculated values are plotted against measured values in Fig. 4. Different researchers made similar attempts: for instance GUPTA AND RAPER (1994) used the major principal stress (σ_1) and predicted changes in bulk density across the wheel rut. In another study, BERISSO ET AL. (2013), predicted changes in total porosity from mean normal stress and reported good agreement between measured and predicted values. The results in these studies confirmed the validity of different component of stresses to predict volume change in the soil during deformation.

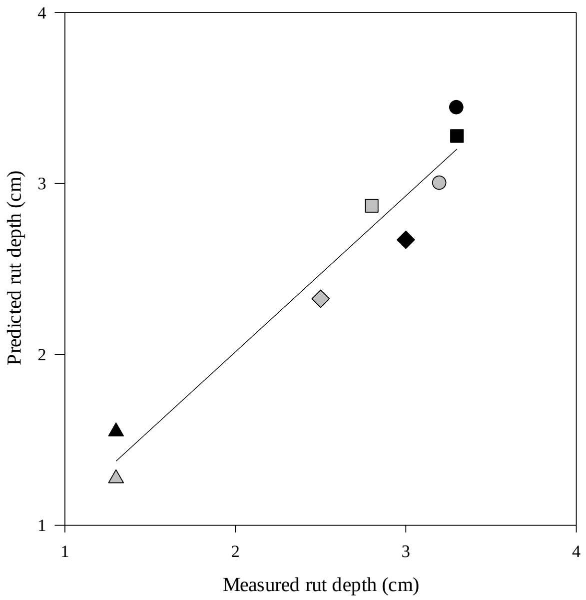

Fig. 3. – Measured and predicted rut depth for soils collected at 0 (circle), 10 (rectangle), 20 (diamond), and 30 (triangle) cm from center of wheel rut after two times (gray shaded) and four times (black shaded) wheeling

CONCLUSIONS

This study provides clear evidence that the top 0.3 m of agricultural soils may be mechanically compacted by traffic with heavy machinery. Our results further document that the compaction had immediate and negative effects on soil bulk density, air filled porosity and saturated hydraulic conductivity of the soil. The documented low hydraulic conductivity in the compacted soil may increase the risk of preferential convective flow of water in periods with high precipitation and may carry contaminants to receiving water bodies.

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Corresponding author:

Feto Berisso., Institute of Technology, School of Biosystems and Environmental Engineering, Hawassa University, Hawassa Ethiopia