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COMPARATIVE ANALYSIS OF SOME SOIL COMPACTION MEASUREMENT TECHNIQUES

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Abstract. There is a need to properly define soil compaction as one of the complex soil characteristics relevant to agriculture since it greatly influences plant growth and energy consumption.

The level of soil compaction may be described by many, well known, parameters, which also can be comparatively analysed according to its sensitivity and ability to describe soil reaction to the applied load.

This paper presents a specific analysis of soil compaction measurement methods based on laboratory testing. The sensitivity of usual compaction parameters such as tire sinkage, cone index and soil bulk density, as well as needle penetration were taken into consideration. The paper also includes the critical analysis of different measurement techniques and its possibility to be a source of valuable agricultural information.

Keywords: soil mechanics, soil compaction, cone index, sinkage, needle penetratrion

INTRODUCTION

Agricultural soil compaction is a complex phenomenon which depends on many parameters, but mainly on the action of agricultural machinery. The state of soil compaction also may be affected by the timing, and type of soil management, as well as by climate or plant.

It is very difficult to describe the level of soil compaction by using only one parameter. Such a parameter has to be sufficient to describe not only the influence of compacted soil on plant growth, but also its effects on energy input for tillage purposes, or on environmental conditions. In addition, since agricultural soil compaction has to be a part of total quality management in agriculture, the value which describes its level has to be easily measurable, reliable and sensitive enough to represent field conditions.

Many different methods and devices have been used for quantifying soil reactions to applied forces, but, penetration resistance and soil density measurement are the most used techniques.

Cone penetrations have been used for various applications, including prediction of vehicle tractive performance [3,12], prediction of draft force [4,5], as well as soil compaction caused by vehicle traffic [2,8,10]. Results of previous studies show that cone index considerably depends on soil type, soil moisture content and density [1,2,11], so, without adequate interrelation between mentioned parameters, usage of cone index as a measure of soil compaction could be limited.

Soil bulk density is often used as a measure of soil compaction. Several methods for soil bulk density measurement have been the subject of comparative analyses [7]. Comparative analyses of moisture and density neutron gauge and core sampling have always shown that values obtained with neutron probe were more related to the core sampling method, but generally, the methods were well correlated.

The analysis of certain soil compaction measurement methods has been the subject of many researches but the comparison of possible soil compaction measurement techniques, which is the objective of this study, and their evaluation, is still very actual. In addition, tire sinkage and needle penetration method is also analysed as a possible suitable measure of soil compaction value.

METHODOLOGY AND EQUIPMENT

Experimental work includes five types of agricultural tires and four types of soils. The following tires have been tested:

1. 16.9-38, Goodyear, Power Torque (R1), Rim 15", 6 PR
2. 16.9R-38, Goodrich, Power Saver Radial HT (R1), Rim 15", 6 PR
3. 18.4-42, Goodyear, Power Torque (R1), Rim 16", 10 PR
4. 18.4R-42, Goodrich, Power Saver Radial HT (R1), Rim 16", 10 PR
5. 24.5-32, Goodyear, Power Torque (R1), Rim 16", 10 PR
6. 245R-.32, Goodrich, Power Saver Radial HT (R1), Rim 16", 10 PR
7. 18.4-34, Goodyear, Power Torque (R1), Rim 16", 10 PR
8. 18.4R-34, Goodrich, Power Saver Radial HT (R1), Rim 16", 10 P
9. 11-28, Rumaguma, Bias (R1), 6PR.

The first eight listed tires were characterised by almost the same load capacity, the same lug angle, the same lug space, close to the same lug height and the same lug profile (R1).

Tests were carried out in large soil bins, with the exception of tire 11-28, under controlled soil and tire conditions using single-wheel tire tester as the basic device used for measuring traction values, as well as cone penetration and soil core sampling for soil compaction. Test with 11-28 tire was also run in the soil bin under controlled soil condition but needle penetration as a measure of soil compaction.

Vertical load was varied gradually during each of the run from 0 to 50 kN, inflation pressure varied from 69 to 138 kPa and slip varied from 0 to 30 %. During the tests, traction force, dynamic load, slip, tire inflation pressure and kinematics values were measured.

Four types of soil have been tested: two types of sandy loam (SL I) and (SL II), a loamy clay (LC) and a clay (C) with the global characteristics given in the Table 1, and initial conditions given in Table 2.

Table 1. Global characteristics of tested soils

	Property	SL I	SL II	LC	C
Soil texture	>2 mm	0.0	0.1	0.6	1.5
	0.05-2 mm	71.6	73.1	50.4	23.2
	0.002-0.005 mm	17.4	10.9	12.8	17.2
	<0.002 mm	11.0	16.0	36.2	59.6
Specific gravity		2.65	2.66	2.69	2.72

Soil preparation: Tilling, wetting, levelling and precompaction.

TIRE SINKAGE AS A MEASURE OF SOIL COMPACTION

Tire sinkage can be used as a measure of soil compaction because of its general sensibility to active force variation, which is illustrated in the Fig. 1abc.

Tire sinkage represents, basically, soil deformation along the vertical axle only, which, at first sight, does not give information about the influence of the horizontal active force. In accordance, the lines in Fig. 1a show expected

Table 2. Initial conditions of the soils

Property		SL I	SL II	LC	C
Penetration resistance* (kPa)	7.5 cm depth	1019	2315	-	1643
	10 cm depth	1023	2000	-	2005
Soil bulk density (g/cm^3)		1.58	1.69	1.38	1.22
Moisture content		7.83	10.06	24.0	19.5

*Average of 30 measured values.

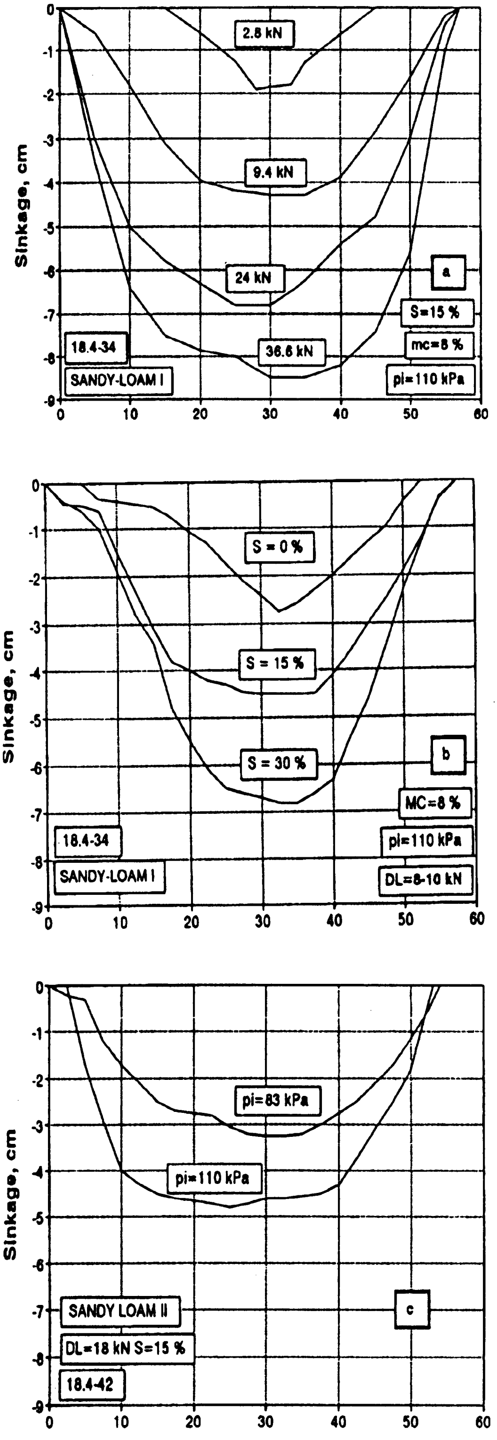

Fig. 1. Traffic line profile for: a - vertical load variation, b - slip variation, c - inflation pressure variation.

changes of tire shrinkage for different amounts of vertical load. However, the lines in Fig. 1b, where influence of slip on tire shrinkage is given, show that changes in traction force caused by changes of slip, affect significantly the amount of tire shrinkage.

In addition, the change in tire inflation pressure affects the amount of total ground pressure, and, as it is visible in the Fig. 1c, causes a change in tire sinkage. Generally speaking, tire sinkage reacts to variation of all basic active tire loading values, vertical and horizontal force and pressure, and may be used as a measure of soil reaction.

But, the values of tire sinkage have to fulfill some other conditions also, such as level of sensibility related to the other methods, easiness of measurement techniques, and possibilities to correlate with the other compaction parameters, in order to be taken as a measure of soil compaction.

Analyses of the obtained test data shows that the average increase of tire sinkage per unit increase of vertical load, for all tested tires in the range of 10 to 35 kN vertical load, the slip of 15 % and the inflation pressure of 110 kPa, is:

1.4 to 2.0 (mm/kN) for sandy loam I
0.6 to 1.1 (mm/kN) for sandy loam II
0.2 to 0.6 (mm/kN) for clay.

The average increase of tire sinkage per percent of slip increase for the range of slip from 0 to 15 %, 20 kN of dynamic load and 110 kPa of inflation pressure for all tested tires is:

1.5 to 2.1 (mm/% slip) for sandy loam I

and the average increase of tire sinkage for unit inflation pressure for the range of inflation pressure of ±28 kPa (±25 % of recommended inflation pressure), vertical load of 20 kN and 15% level of slip, is:

0.25 to 0.61 (mm/kPa) for sandy loam II.

It is possible to conclude that minimum three parameters should be previously known.

The first one is influence of moisture content changes on tire sinkage for a certain type of soil. Such dependencies, which did not take a part of this investigation, are quite possible to generate and to generalize from the laboratory or field testing.

The second is the influence of precompaction level on tire sinkage. For example, the precompaction level was the highest for clay type of soil and, in addition to relatively low moisture content, yielded the lowest sensitivity values, compared to two other soils. Knowing the clay characteristics, it can be concluded that small sinkage values as a reaction to vertical load increase were caused by higher level of precompaction in comparison to the two other soils.

The third influence on the obtained sinkage values is connected with the tire construction characteristics such as, carcass construction (or radial and diagonal stiffness), tire diameter and width and tire trade parameters, which can also be defined in advance for certain field and machinery characteristics.

The tire sinkage values react in the expected way to changes of the basic tire exploitation parameters (active loads), and it can be observed, that the level of sensitivity is reasonably high. In addition, sinkage is a relatively easy measurable quantity which does not require complicated or expensive measuring equipment.

SOIL BULK DENSITY AS A MEASURE OF SOIL COMPACTION

Figure 2abc, represents some of obtained data of soil bulk density at 0-5 cm depth, at traffic mid-line.

Analyses of all obtained data show that soil bulk density at the bottom of the tire traffic line is sensitive to the changes of basic traction parameters. The averaged reactions to changes of vertical load, slip and tire inflation pressure are the following:

a) The average of soil bulk density increase per unit increase of vertical load for all of tested tires in the range of 10 to 35 kN vertical load, 15 % slip and 110 kPa inflation pressure is:

7.0 to 33 10^{-4} (g/cm^3/kN) for sandy loam I
2.4 to 4 10^{-4} (g/cm^3/kN) for sandy loam II
2.0 to 5.2 10^{-4} (g/cm^3/kN) for clay;

b) The average increase of soil bulk density per percent of slip increase for the slip

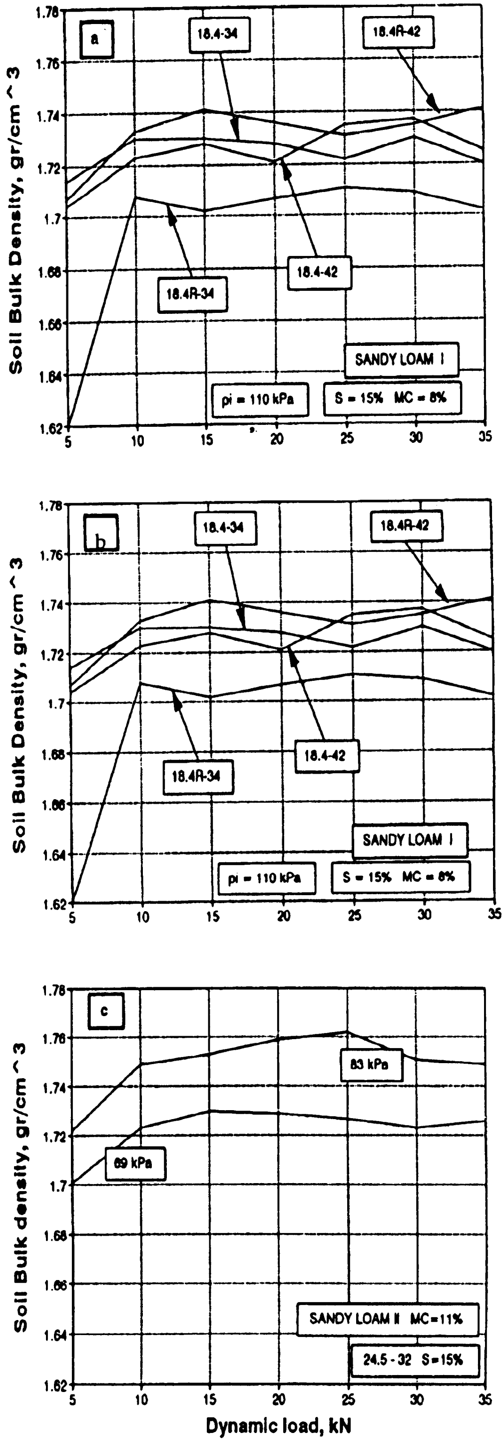

Fig. 2. Soil bulk density at a traffic mid-line on 0-5 cm depth: a - different tire size and carcass construction, b - slip variation, c - inflation pressure variation.

range from 0 to 15 %, dynamic load of 20 kN and 110 kPa inflation pressure for all tested tires is:

6.7 to 30 10^{-4} (g/cm^3/% slip) for sandy loam I;

c) The average increase of soil bulk density per unit of tire inflation pressure for the range of inflation pressure of ±28 kPa (±25 % of recommended inflation pressure), vertical load of 20 kN and level of slip of 15 % is:

3.2 to 11 10^{-4} (g/cm^3/kPa) for sandy loam II

6.1 to 14 10^{-4} (g/cm^3/kPa) for clay.

It may be concluded that the changes of soil bulk density are rather small in comparison to the global preciseness of the applied measurement technique (core sampling). Moreover, the sample taken from the bottom of the tire footprint area can be additionally loosened as a result of tire tread lugs action. Obtaining the sample from the deeper layer requires more time and efforts, so a more advanced measuring technique, such as neutron gauge or some similar device seems to be more suitable.

CONE INDEX AS A MEASURE OF SOIL COMPACTION

Figure 3ab, presents some of the cone index data obtained at 10 cm depth in the middle of the traffic line.

Similarly as for tire sinkage and soil bulk density, analysis of the cone index data shows that the cone index value at the bottom of the tire traffic line is sensitive to changes in the basic motion parameters.

The average cone index values for changes of dynamic load, slip and tire inflation pressure are the following:

a) The average of cone index increase per unit increase of vertical load for all of tested tires in the range of 10 to 35 kN vertical load, 15 % slip and 110 kPa inflation pressure is:

14 to 41 (kPa/kN) for sandy loam I

13 to 27 (kPa/kN) for sandy loam II

9 to 21 (kPa/kN) for clay;

b) The average increase of the cone index per percent of slip increase for the slip range of 0 to 15 %, 20 kN of dynamic load and 110 kPa inflation pressure for all tested tires is:

21 to 41 (kPa/% slip) for sandy loam I;

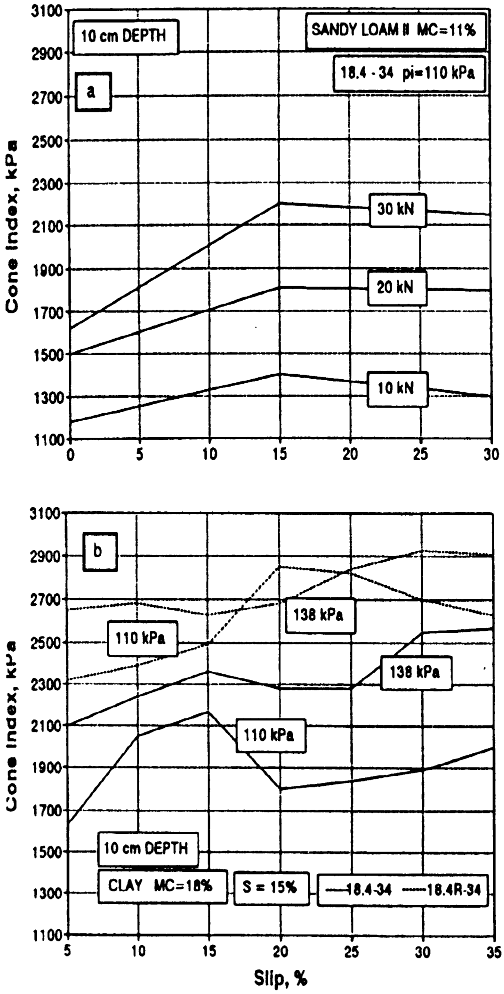

Fig. 3. Cone index values at the middle of traffic line on 10 cm depth: a - vertical load and slip variation, b - inflation pressure variation.

c) The average increase of the cone index value per unit inflation pressure for the range of inflation pressure of ±28 kPa (±25 % of recommended inflation pressure), vertical load of 20 kN and level of slip of 15 %, is:

6 to 10 (kPa/kPa) for sandy loam II

3 to 17 (kPa/kPa) for clay.

Although obtained average values to cone index reaction on the traffic conditions changes, may be considered as satisfactory according to the sensitivity of usually available measurement devices, the cone resistance readings from 10 cm depth in the traffic mid-line, should be critically discussed. For undisturbed soil, 10 cm depth is quite acceptable, but, for the measurement at the compacted traffic line, some influence of additional soil loosening caused by tire lugs action, may be expected.

The cone penetration technique is suitable for the purpose due to its easy application, though it requires additional work for the definition of many sides effects.

NEEDLE PENETRATION AS A MEASURE OF SOIL COMPACTION

Needle penetration to define state of compaction is not an often used technique. Some of the obtained needle penetration data are given in Fig. 4, for loamy-clay type soil with moisture content of 24 %, and 11-28 6PR, bias ply tractor tire.

The 4 mm diameter needle,was made to penetrate the soil to 45 cm depth, across the traffic line. The obtained needle penetration resistances were in the range of 0 to 250 N and, for analysis purposes, have been divided into five zones:

Zone 1: from 3^0 to 3^1 (1 to 3 N)
Zone 2: from 3^1 to 3^2 (3 to 9 N)
Zone 3: from 3^2 to 3^3 (9 to 27 N)
Zone 4: from 3^3 to 3^4 (27 to 81 N)
Zone 5: from 3^4 to 3^5 (81 to 243 N),

which are given on Fig. 4, for defined traction and soil conditions. The tests were run in the large soil bin and the tire was towed.

From the lines given in Fig. 4 it is visible that the tire sinkage follows an expected trend for both, inflation pressure variations and tire vertical load vibration. But the needle penetration resistances show some unexpected behaviour, mainly caused by hard pan existence at 35 cm depth. Existence of hard plow pan influences on penetrometer readings in top soil. So, as mentioned before, penetrometer readings as a measure of soil compaction need to be more investigated for soil compaction prediction.

CONCLUSIONS

The analysis of the sinkage, cone index, soil bulk density and needle penetration resistance as measurement techniques, for soil compaction

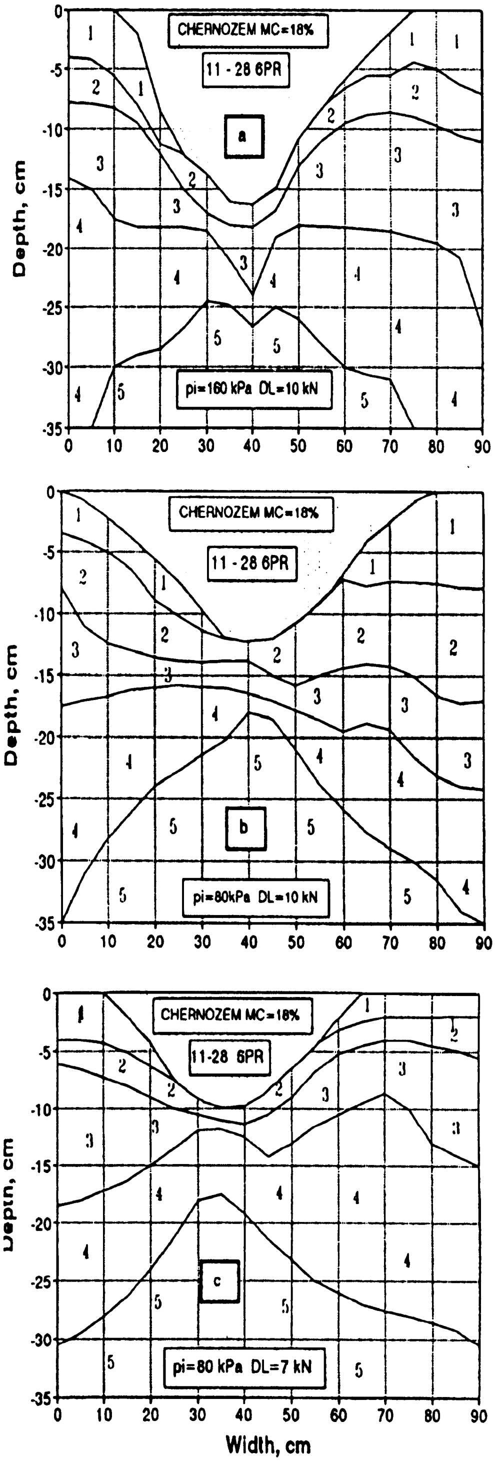

Fig. 4. Needle penetration data for: a - pi=160 kPa and DL=10 kN, b - pi=80 kPa and DL=10 kN, c - pi=80 kPa and DL=7 kN.

level determination in the top soil shows that all discussed parameters may be used as a measure of soil compaction.

The sinkage and cone index values present some advantage from the viewpoint of applicability, sensitivity and time consumption.

Knowing the possibilities to use GPS altitude measurement, radar, fifth wheel or some of the other continual measurement techniques for sinkage value evaluation, sinkage as a measure of soil compaction has some advantages related to cone index.

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