Geoderma 262 (2016) 276–284

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Effect of wheel traffic on the physical properties of a Luvisol

M.-F. Destain [a,*], C. Roisin [b], A.-S. Dalcq [a], B.C.N. Mercatoris [a]

[a] ULg, GxABT, Biosystems Engineering Department, Belgium
[b] CRA-W, Belgium

ARTICLE INFO

Article history:
Received 29 April 2015
Received in revised form 11 August 2015
Accepted 18 August 2015
Available online 6 September 2015

Keywords:
Soil compaction
Precompression stress
Pore size distribution
Mercury intrusion porosimetry
Soil tillage
Beet harvesting

ABSTRACT

The effects of machine traffic were assessed on a Luvisol in a temperate climate area in Belgium. Soil samples were taken from topsoil (0.07–0.25 m) and subsoil (0.35–0.50 m), on plots under long-term reduced tillage (RT) and conventional tillage (CT). Cone index (CI), bulk density (BD) and precompression stress (Pc) were chosen as indicators of mechanical strength. Mercury intrusion porosimetry was used to characterise the soil microporosity structure. It was presented in two forms: (i) cumulative pore volume vs. equivalent pore radius r, from which four classes of porosity were defined: $r < 0.2$ μm, $0.2 \le r < 9$ μm, $9 \le r < 73$ μm and $r \ge 73$ μm and (ii) pore-size distribution (PSD). In the reference situation where there had been no recent passage of machines, the voids with $0.2 \le r < 9$ μm were the most important class in RT topsoil. The voids with $r \ge 73$ μm represented the main porosity class in the topsoil of CT. In the subsoil, for both tillage systems, the porosity was almost equally distributed between voids with $0.2 \le r < 9$ μm and voids with r greater than 9 μm.

Machine traffic was carried out when the soil water content was close to the optimum Proctor. Although unfavourable, these wet conditions often occur during the beet harvesting period in Belgium. The highest modifications in soil structure (increase in BD and Pc, reduction of macroporosity $r \ge 73$ μm) were observed in the topsoil of CT. More limited modifications were noticed in the soil structure of RT topsoil and subsoil layers but these latter are problematic in that the soil would no longer be loosened by subsequent tillage. These modifications could lead to soil consolidation as a result of wheel traffic year after year.

1. Introduction

Compaction of arable soils by agricultural machinery is a complex phenomenon and the understanding of the mechanisms involved in the stress transmission and deformation of soils still remains limited (Keller et al., 2013).

Soil compaction may be apprehended by modelling approaches, either analytical or numerical. Analytical solutions for stress transmission are based on the equations for stress propagation of Boussinesq (1885) and Frölich (1934), modified by Söhne (1957). These simple equations require few parameters and have been widely applied in agricultural soil mechanics (Horn and Fleige, 2003; Keller and Lamandé, 2010; Lamandé and Schjønning, 2011; D'Or and Destain, 2014). Numerical approaches involve the finite element method (FEM) which has been used to the study of deformation processes under wheel loads (Gysi et al., 2000; Defossez and Richard, 2002). It seems that up to now, the main obstacle to the development of enhanced FEM models is the lack of adequate quantitative description of the relevant soil properties (Keller et al., 2013). In particular, FEM methods require an accurate description of the non-linear stress–strain relationships of the different layers of the soil. These are generally obtained with static loading although the compaction created by agricultural machinery is a dynamic, short-term process.

Experimental approaches of soil compaction are traditionally based on measurement of macroscopic soil properties such as bulk density (BD), cone index (CI), and precompression stress (Pc). The measurement of BD by core sampling has been widely used over several decades and is considered as accurate if precautions are taken against sample disturbance (Campbell, 1994). Cone index is affected by several factors, namely soil texture, BD, moisture content, and organic matter content (Quraishi and Mouazen, 2013). Despite his lack of specificity, this method has been widely used since it permits to identify easily zones of equi-resistance by two-dimensional plotting (Roisin, 2007) or to draw probabilistic maps of compaction risks (Carrara et al., 2007).

Precompression stress (Pc) is considered by several authors to be a robust indicator of soil compaction (Dexter, 1988; Lebert and Horn, 1991; Cavalieri and Arvidsson, 2008) and is usually measured in laboratory conditions by confined uniaxial compression tests (oedometer tests) (Horn and Lebert, 1994). This method presents good sensitivity but Pc is affected by historic effects such as over-consolidated zones due to repeated passages of machines (Hanquet et al., 2004).

More recent approaches investigate the effect of machine traffic on soil microstructure by using microtomography systems or mercury intrusion porosimetry (MIP). These methods permit to obtain a better description of soil strength and deformation that would also facilitate the

* Corresponding author.
E-mail address: mfdestain@ulg.ac.be (M.-F. Destain).

http://dx.doi.org/10.1016/j.geoderma.2015.08.028
0016-7061/

development of enhanced models accounting for the dynamics of soil pore systems (Verveckaite et al., 2007; Peth et al., 2010; Dal Ferro et al., 2014). MIP enables to assess the stress effect of tillage or vehicular traffic on soil over a wide range of pore sizes (Lipiec et al., 2012). It is thus possible to study the eventual modification of the pore system configuration due to traffic that could affect soil hydraulic properties and carbon sequestration. Indeed, the saturated hydraulic conductivity which represents the soil infiltration mainly through macropores is reduced when the proportion of large pores decreases, while soil carbon concentration is enhanced in the presence of macropores.

The aim of this study was to determine the effects of agricultural machinery on soil structure by using experimental techniques at two different scales. The impact of traffic on soil physical properties was quantified by macroscopic measurements including cone index (CI), bulk density (BD) and precompression stress (Pc) and by microstructure characterisation performed thanks to MIP. The study concerned two kinds of soil tillage, conventional tillage (CT) and reduced tillage (RT). CT is a deep primary cultivation method performed by a plough, whereas RT is carried out with a spring-tine cultivator.

2. Materials and methods

2.1. Soil location and soil description

A field experiment was conducted on an Orthic Luvisol developed from loess in an experimental field at Gentinnes (50°35′N, 4°35′E) in Belgium. The local climate is temperate with mean rainfall of 852 mm and yearly average temperature of 10.5 °C. Experimental treatments were established in 2003 in order to compare conventional tillage (CT) with reduced tillage (RT) in a field of 2.45 ha. CT was performed with mouldboard ploughing to a depth of 0.27 m depth while RT consisted in using a spring-tine cultivator to a depth of 0.10 m. Wheat (*Triticum aestivum* L.) was grown in rotation with sugar beet (*Beta vulgaris* L.). At the beginning of the experiments, in October 2012, sugar beet was implemented in lines spaced from 0.50 m. The experiment was performed to analyse the effect of beet harvesting machines on the soil structure.

Soil granulometry is given in Table 1. The soil is characterised by a somewhat greater proportion of clay and lower organic carbon content in the subsoil (0.35–0.50 m) than in the topsoil (0.07–0.25 m). From the soil water retention curves (SWRC) (Fig. 1), the volume of water available for plants (suction comprised between −33 kPa and −1500 kPa or 2.5 ≤ pF < 4.2) is somewhat higher in the topsoil than in the subsoil, while the non-available water (suction < −1500 kPa or pF ≥ 4.2) is higher in the subsoil (Table 2).

The optimum Proctor which is the gravimetric water content (ratio of the mass of water to the dry weight of the soil sample) at which the soil becomes most dense and achieves its maximum bulk density (BD) is 18.5 ± 0.5% in the topsoil and 16.8 ± 1.5% in the subsoil.

2.2. Measurements

Measurements were taken in October 2012 in a ‘reference line’ where there had been no recent passage of machines and in a ‘passage line’ after the passage of beet harvesting machines, according to the scheme given in Fig. 2. The beet harvester covered six rows at the same time and was followed by the beet loader. In the passage line, there were thus successive passages of sowing machines (in April), beet harvest and beet loader (in October). The mean stresses applied by each of these machines at the soil interface were computed by dividing the weight on each wheel by the mean contact surface. The highest vertical stresses were applied by the beet loader and were about 150 kPa repeated three times due to the presence of three axles. During the trials, the gravimetric water content was 18.5 ± 0.6% in the topsoil and 16.5 ± 0.6% in the subsoil. As these values were close to the optimum Proctor, the soil susceptibility to compaction was high. These unfavourable conditions are often encountered during the beet harvesting period in Belgium.

Soil samples were taken in order to measure dry bulk density (BD) and precompression stress (Pc) and to characterise the soil porosity by mercury intrusion porosimetry (MIP), in the reference and the passage lines, both in the topsoil and the subsoil. Furthermore cone index (CI) measurements were performed along the reference line and the passage line.

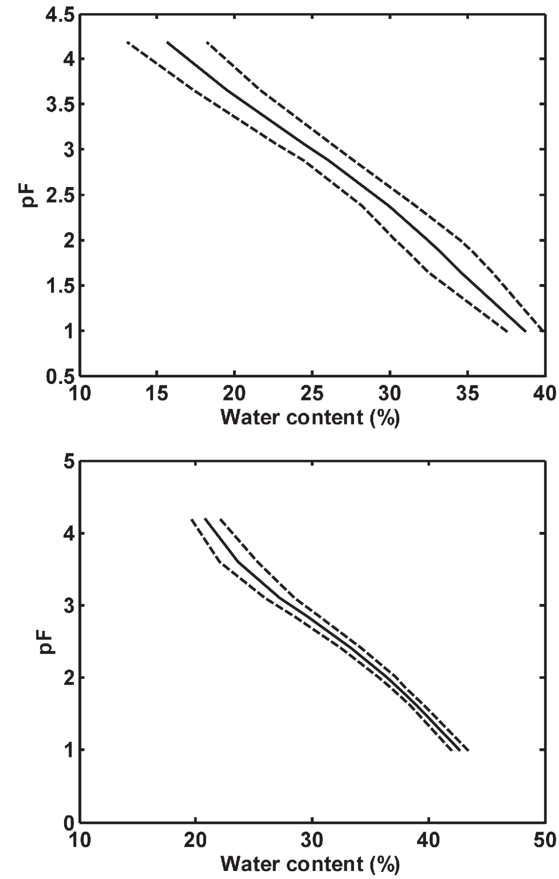

Fig. 1. Soil water retention curves for the Orthic Luvisol at Gentinnes. Topsoil (above) and subsoil (below). Mean values (continuous line) and mean ± standard deviation (dashed line).

Table 1
Granulometry of the Orthic Luvisol at Gentinnes.

Depth (m)	Particle size distribution (%)			SOC (%)
	Clay (<0.002 mm)	Silt (0.002–0.02 mm)	Sand (>0.02 mm)	
Topsoil (0.07–0.25)	17.70 ± 2.88	75.67 ± 2.28	6.63 ± 0.69	7.5 ± 2.89
Subsoil (0.35–0.50)	20.52 ± 1.92	74.17 ± 1.08	5.31 ± 0.97	<5.30

SOC = soil organic content.

2.3. Measurement of the cone index

CI was measured using a fully automated penetrometer (30° angle cone with a base area of 1 cm^2) mounted on a small vehicle, as described by Roisin (2007) (Fig. 3). Two adjacent areas of 0.80 × 0.80 m^2 were investigated centred on the reference and passage lines, the spacing between cone penetration locations being 0.05 m in both directions. At each node, data were collected every centimetre from the surface down to a depth of 0.45 m. The data were presented in a cartographic format and the structural homogeneity of the arable layer beneath the investigated areas was assessed by computing the dimensionless