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A study on the air permeability as affected by compression of three French soils

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ABSTRACT

Soil air permeability is one of the most important parameters which govern the aeration in agricultural soils and thus has a significant effect on the plant growth and crop production. Therefore, it appears important, when analysing the effect of soil compaction due to agricultural machinery, to correlate air permeability with soil capacity parameters such as air-filled porosity, degree of saturation, water content, etc. In the present work, the relationship between air permeability, soil capacity parameters and vertical stress was analysed by performing confined uniaxial compression tests accompanied by air permeability measurements. Three French soils having different textures were studied. Tests were performed on remoulded and undisturbed soils, at various initial dry bulk densities and water contents. For the remoulded soils, the air permeability has been found strongly correlated with the applied vertical stress for sandy loam; by contrast, no obvious correlation could be established for clay. As far as the undisturbed soils are concerned, the air permeability could be correlated with the air-filled porosity for sandy loam and silty–clayey loam but also no evident correlation could be established for clay. Examination of an existing model predicting the air permeability from the air-filled porosity using one tortuosity/connectivity parameter showed that this parameter varies in a small range for sandy soils and in a larger range for clayey soils.

1. Introduction

Prevention of soil degradation is an important issue in the context of intensive agriculture and forest exploitation. Compaction by traffic has been identified as a major process that affects the production and the environment by changing the soil structure and the physical properties of soils. It changes the mechanical strength, water and gas transports and thus affects the root and shoot growth. It changes also soil nitrogen and carbon cycles and increases soil erosion due to water flow (Soane and van Ouwerkerk, 1994). Quantifying the soil damage by compaction is therefore of importance when establishing strategies for farming and forest management on a local scale and for environmental protection measures on a larger scale. The evaluation of the soil compaction effects on soil physical properties is generally based on the consideration of the changes in soil mechanical strength, aeration and hydraulic properties (Hemmat and Adamchuk, 2008; Horn et al., 1995; Kozlowski, 1999; Lipiec and Hatano, 2003; Schäfer-Landefeld et al., 2004). Different approaches have been proposed to assess soil degradation due to compaction using relations between soil compaction parameters and soil capacity parameters such as air-filled porosity, degree of saturation, water content, etc.: (i) Håkansson (1990) described the soil compactness in terms of relative soil porosity variations; (ii) Koolen and Kuipers (1989) examined the soil sensitivity to compaction and proposed various compaction criteria in terms of variations of soil strength parameters such as the pre-compression pressure; (iii) Horn et al. (2007) and Mosaddeghi et al. (2007) investigated the relationships between applied stress and soil air permeability; (iv) Håkansson and Lipiec (2000) analysed soil compaction using relations between soil capacity parameters and air permeability. Note that after Horn and Kutilek (2009), a capacity parameter defines a general status, while an intensity parameter includes dynamic aspects over time and space. Goss and Ehlers (2010) presented their disagreement about these definitions, arguing that both intensity and capacity properties can vary in both space and time. In the present work, the term "capacity parameter" is adopted and it defines a general status, i.e., the composition of a given volume but not the internal structure and function (as proposed by Horn and Kutilek, 2009); at the same time, it is admitted that the capacity parameters can vary with time (following Goss and Ehlers, 2010).

Laboratory studies on air permeability have shown its dependency on various soil parameters related to the capacity parameters, such as the degree of saturation (Juca and Maciel, 2006; Seyfried and Murdock, 1997), the water content (Sanchez-Giron et al., 1998) and the air-filled porosity (Moldrup et al., 2003; Olson et al., 2001). In general, the air permeability is lower at a higher degree of saturation

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with a lower air-filled porosity. Based on the experimental data of compacted silty soil, Delage et al. (1998) concluded that air-filled porosity is the unique parameter affecting the air permeability. Moon et al. (2008) found that the air permeability of compacted soils depends on the compaction energy as well as the moisture content at moulding; the lowest value of air permeability being at the optimum moisture content (maximum dry unit weight). Studies on undisturbed and repacked soils have shown significant effects of the soil structure and pore-space characteristics on the air permeability (Dörner and Horn, 2006; Moldrup et al., 2001; O'Sullivan et al., 1999; Tuli et al., 2005). It has been found that the air permeability was greatly reduced for repacked soils. As far as the anisotropy is concerned, the air permeability measured in the vertical direction has been found higher than in the horizontal direction due to the presence of biopores and vertical cracks. For further analysis about the air permeability dependency on the water and air contents, Tuli et al. (2005) fitted the experimental data to the model proposed by Mualem (1976) and analysed the fitting parameters. Similar studies were performed by Seyfried and Murdock (1997), Moldrup et al. (2001, 2003), Kamiya et al. (2006), and Dörner and Horn (2006), showing that it is appropriate to evaluate the changes in soil pore structure based on the measurement of air permeability.

In addition to the soil capacity parameters, the effect of applied stress has been also reported by various authors. Mosaddeghi et al. (2007) noted that cyclic loading is not always accompanied by significant irreversible strain but it could decrease the air permeability by one order of magnitude. The effects of stress state on air permeability were also reported by Horn et al. (1995) and Sanchez-Giron et al. (1998). Other factors affecting air permeability have been also observed: the matric suction (Samingan et al., 2003) and the wetting/drying process (Kamiya et al., 2006). Even if the matric suction can be related to the capacity parameters (i.e. degree of saturation), it is usually considered as a stress parameter (see Gens and Alonso, 1992). On the whole, it has been observed that the air permeability coefficient decreases when the stress increases or when the matric suction decreases; the relationships between air permeability coefficient and suction showed hysteresis in the drying and wetting processes.

It can be concluded that air permeability has been recognised as one of the most appropriate parameters for soil compaction assessment. Nevertheless, examination of the studies mentioned above shows that the conclusions made by the authors were based on the results obtained on either one soil or a limited range of water content and porosity. The present work aims at analysing the effects of soil capacity parameters on air permeability for three French soils of various textures, with a large range of water content and porosity. Air permeability was measured in an oedometer cell using the technique developed by Yoshimi and Osterberg (1963) and Delage et al. (1998). Emphasis was put on the effects of various parameters: soil type (sandy loam, silty clay loam and clay), vertical stress (15–800 kPa), initial dry bulk density (0.98–1.66 Mg m^{-3}) and initial water content (14.0–40.5%). A comprehensive analysis of the obtained data was made and allowed identifying the most relevant parameters which affect the soil air permeability.

2. Materials and method

The studied soils were taken from three sites in France: (i) Le Breuil; (ii) Avignon; and (iii) Epernay. Le Breuil is an experimental forest site located in the Morvan (47°18′ N, 4°4′ E, centre of France) where monospecific plantations have been conducted for thirty years (oaks, beech, spruce and Douglas fir); it involves a sandy loam (Dystric Cambisol). The Avignon site is a sugar beet field (43°55′ N, 4°53′ E, south of France). The soil is calcareous with a silty clay loam texture (Calcaric Cambisol). The Epernay site is an experimental site managed by the CIVC-Technical Institute for Champagne Wine (49° N, 3°56′ E, east of France) and the soil involved is calcareous with a clay texture (Calcaric Cambisol). Some physical and chemical properties of the studied soils are presented in Table 1. The soil properties were determined following the French Standard for Geotechnical Engineering: the particle density was determined using water pycnometer on soil sieved at 2 mm; the Atterberg limits were determined on soil sieved at 0.4 mm; and the blue value was determined using the methylene blue absorption method on soil sieved at 0.5 mm. The organic carbon content is 82.8 g kg^{-1} for the Le Breuil soil, 10.2 g kg^{-1} for the Avignon soil and 16.8 g kg^{-1} for the Epernay soil. Soil texture was classified following FAO-UNESCO (1974) system (after Jones et al., 2003) and USDA classification that are based on the particle size distribution. According to FAO classification, the texture of the tested soils varies from medium to fine. This classification was in good agreement with the plasticity indexes and the blue values, i.e., the finer the soil texture the higher the plasticity index and the larger the blue value. Note that the physical and chemical properties of the soils presented in Table 1 were determined from a mixture of soil taken from a layer of 60 cm in thickness. The variability of these properties within the depth (in the range of 0–60 cm) was therefore not considered in this study.

Remoulded samples were tested for the topsoil layer (0–30 cm) depth which is frequently tilled whereas undisturbed samples were tested for the subsoil layer (30–60 cm depth) where compaction is persistent. For the preparation of remoulded samples, the topsoil was air-dried, crushed and passed through a 2-mm sieve. It was then wetted by spraying distilled water to achieve the desired water content and then stocked in a hermetic box for 24 h for water homogenization. Finally, the soil was poured directly into the oedometer cell and manually compacted.

For the preparation of undisturbed samples, a core sampler of 70-mm high, 150 mm in inner diameter and 1 mm in thickness, was pushed vertically into the subsoil layer (30–60 cm depth) in the field. The soil cylinders were then wetted by spraying distilled water to achieve the desired water content and then covered by a plastic film for 24 h for water homogenization. Finally, the soil specimen (70 mm in diameter and 20 mm in height) was trimmed directly from the cylinder and inserted into the oedometer cell. When a drying process was involved, the soil cylinder was air-dried for 2 h, and then covered by plastic film for 6 h. The procedure was repeated until the desired water content was achieved. This drying process allowed the soil to be prevented from any dry-cracking during the preparation. Finally, as for the wet samples, the soil specimen was prepared by trimming and inserted into the oedometer cell.

The experimental setup developed by Delage et al. (1998) was used for the measurement of soil air permeability. The soil sample was installed in an oedometer cell. The basis of the cell was connected to a tank of large volume ($V = 3120$ cm^3) and a U-shaped manometer. When measuring the air permeability, an initial low value of air pressure was applied in the tank ($p = 6$ kPa, that corresponds to a

Table 1
Some physical and chemical properties of studied soils (determined from a mixture of soils taken from the depth of 0–60 cm).

Site	Le Breuil	Avignon	Epernay
Particle density (Mg m^{-3})	2.56	2.71	2.68
Liquid limit (%)	58	31	49
Plastic limit (%)	51	20	29
Plasticity index (%)	7	11	20
Organic carbon content (g kg^{-1})	82.8	10.2	16.8
Methylene blue absorption (g 100g^{-1})	0.4	2.3	7.4
Particle size distribution (g g^{-1}):			
Clay (<2 μm)	0.19	0.34	0.47
Silt (2–50 μm)	0.23	0.51	0.33
Sand (50–2000 μm)	0.58	0.15	0.20
USDA classification	Sandy loam	Silty clay loam	Clay
FAO classification	Medium	Medium fine	Fine
FAO taxonomy	Dystric cambisol	Calcaric cambisol	Calcaric cambisol