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A method for predicting soil susceptibility to the compaction of surface layers as a function of water content and bulk density

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ABSTRACT

Identifying the vulnerability of soils to compaction damage is becoming an increasingly important issue when planning and performing farming operations. Soil compaction models are efficient tools for predicting soil compaction due to agricultural field traffic. Most of these models require knowledge of the stress/strain relationship and of mechanical parameters and their variations as a function of different physical properties. Since soil compaction depends on the soil's water content, bulk density and texture, good understanding of the relations between them is essential to define suitable farming strategies according to climatic changes. In this work we propose a new pedotransfer function for 10 representative French soils collected from cultivated fields, a vineyard and forests. We investigate the relationship between soil mechanical properties, easily measurable soil properties, water content and bulk density. Confined compression tests were performed on remoulded soils of a large range of textures at different initial bulk densities and water contents. The use of remolded samples allowed us to examine a wide range of initial conditions with low measurement variability. Good linear regression was obtained between soil precompression stress, the compression index, initial water content, initial bulk density and soil texture. The higher the clay content, the higher the soil's capacity to bear greater stresses at higher initial water contents without severe compaction. Initial water content plays an important role in clayey and loamy soils. In contrast, for sandy soils, mechanical parameters were less dependent on initial water content but more related to initial bulk density. These pedotransfer functions are expected to hold for the soils of tilled surface layers, but further measurements on intact samples are needed to test their validity.

1. Introduction

Soil compaction is one of the major causes of soil degradation in modern agriculture and forestry. The overuse of machinery has been identified as the main reason contributing to soil compaction. Due to its persistence, subsoil compaction can be considered as a long-term degradation, although compaction also concerns surface layers. Compaction affects soil physical fertility adversely, in particular by impeding the storage and supply of water and nutrients. This leads to decreased porosity, increased soil strength and hence soil resistance to root penetration and plant emergence, and decreased soil water infiltration and holding capacity. These adverse effects also reduce fertilization efficiency and crop yields, increase waterlogging, runoff and soil erosion with undesirable environmental problems (Soane and van Ouwerkerk, 1994). Thus, knowing the changes in soil compaction with changes in water content and bulk density is essential when planning farm operations at appropriate water contents (Arvidsson et al., 2003), or when decreasing soil bulk density by increasing its organic matter content through the retention of crop and pasture residues or appropriate soil tillage (Hamza and Anderson, 2005).

Recently, soil protection with respect to soil compaction has led to great concern in Europe. Identifying the vulnerability of soils to compaction damage is becoming an increasingly important issue both in the planning and execution of farming operations at field scale and in planning environmental protection measures at larger scales. Numerous studies have been performed to formulate soil compaction assessment methods. Horn and Fleige (2003) and Horn et al. (2005) chose precompression stress (σ_p) as an indicator of soil resistance to compaction and applied, at various scales ranging from farm to country and continent, the pedotransfer functions that link the precompression stress and soil physical parameters. Jones et al. (2003) proposed a classification method for subsoil

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vulnerability to compaction based on available soil properties such as texture and bulk density and on soil moisture data at critical traffic time. This classification method, initially developed for local field conditions, was then extended to the scale of Europe.

At large scales, modeling and spatialization are helpful means for assessing soil vulnerability to compaction. The most readily available spatial information on soils in most countries is soil survey data and the corresponding climatic data. However, it should be noted that most models (Bailey and Johnson, 1989; Défossez et al., 2003; Keller et al., 2006; Larson et al., 1980; O'Sullivan and Robertson, 1996; van den Akker, 2004) require knowledge of the stress/strain relationship, and its variation with different soil physical properties. The stress/strain relationship provides two relevant mechanical parameters: precompression stress (σ_p) and the compression index (C_c). Precompression stress is an indicator of a soil's load support capacity; the slope of the virgin compression line, namely the compression index, represents an indicator of soil susceptibility to compaction. Confined compression tests are usually used to determine these soil mechanical parameters in the laboratory. A short loading time of between 5 and 45 min is usually used for laboratory oedometer tests as the loading duration by vehicles in agricultural fields is generally short (0.5 s). Different models have been developed to evaluate soil sensitivity to compaction for decision-making. One approach based on the notion of precompression stress consists in estimating soil bearing capacity with respect to compaction. It allows building a map of permissible machinery ground pressure that a soil can bear without permanent subsoil deformation. Horn et al. (2005) and van den Akker (2004) applied this approach for the Netherlands and Europe. A second approach aims at evaluating compaction intensity, i.e. the increase in soil dry bulk density. Obviously, this approach requires the use of both precompression stress and compression index, and is particularly applicable for surface layers where deformation cannot usually be avoided but can be reduced, as compaction intensity depends on soil type and physical parameters (Canarache et al., 2000; Défossez et al., 2003; Gupta and Larson, 1982; Imhoff et al., 2004; Kirby, 1991; O'Sullivan et al., 1999; Salire et al., 1994; Smith et al., 1997). This paper deals with this second approach for which both precompression stress and the compression index of surface layers are required.

The variation of precompression stress and the compression index with different physical parameters has been widely studied. In geotechnical engineering, the compressibility characteristics of a soil are usually correlated with different geotechnical properties, such as liquid limit, the plasticity index and shrinkage limit (Giasi et al., 2003; Sridharan and Nagaraj, 2000). In agronomy and forestry, various regressions have been proposed to link precompression stress and the compression index to numerous soil properties. More studies on the relation between the precompression stress (σ_p) and soil physical properties can be found in the literature, in contrast to studies on the relation between the compression index (C_c) and soil physical properties. The soil physical properties studied most are the texture, structure and hydric state of soil. Texture is formed by soil clay, silt and sand content (Gupta and Larson, 1982; Imhoff et al., 2004; Lebert and Horn, 1991; McBride, 1989; Smith et al., 1997). Its structure is commonly characterized not only by initial bulk density, but also by other variables more difficult to measure related to the soil's internal structure at aggregate scale (Alexandrou and Earl, 1998; Canarache et al., 2000; Imhoff et al., 2004; Lebert and Horn, 1991; McBride, 1989; Rücknagel et al., 2007; Salire et al., 1994). Hydric state is characterized by initial water content (Alexandrou and Earl, 1998; Canarache et al., 2000; Défossez et al., 2003; Imhoff et al., 2004; Lebert and Horn, 1991; McBride, 1989; Mosaddeghi et al., 2003, 2006; O'Sullivan et al., 1999). In most of these studies, mechanical tests were performed on intact samples that lead to considerable variations in soil properties. This may explain the contradictory effects of texture, water content and porosity on the mechanical properties observed by numerous authors (Arvidsson and Keller, 2004).

This paper considers a simplified description of soil mechanical strength: structure via bulk density, hydraulic stress via water content and mechanical stress via external stress. This standpoint is driven by the objective of achieving compaction assessment by using accessible parameters. However, it fails to describe the physical processes acting on soil mechanical strength, i.e. the interaction between hydraulic, mechanics and structure in unsaturated soils. These interactions have been studied and modeled for several decades using the concept of effective stress and the theory of critical-state for geotechnical applications (Fredlund and Rahardjo, 1993). Different authors have applied these concepts to analyze and model the mechanics of cultivated soils (Richards, 1992; Wulfsohn et al., 1996; Peng et al., 2004), but these concepts cannot satisfactorily describe important characteristics of cultivated soil mechanics, such as the effect of soil structure anisotropy and time dependent processes (Peng and Horn, 2008).

The present work is based on the hypothesis that soil water content and bulk density are the main easily accessible parameters affecting soil mechanical strength. Oedometer tests were carried out on remolded soils with a wide range of textures at different initial bulk densities and water contents. The main objective of working on remolded samples was to cover a wide range of variation for both initial water content and initial bulk density. Ten representative French soils taken from cultivated fields, a vineyard and forests were considered. The identified σ_p and C_c were then correlated with initial soil water content, initial bulk density and texture. Finally, a new and simple method of assessing the susceptibility of French soil to compaction based on accessible parameters is proposed.

2. Material and methods

2.1. Soil properties

The soils studied were taken from the top soil of cultivated fields, forests and a vineyard from ten sites in France. The sites vary for soil type, carbon content, crops and management (Table 1) while the soils varied significantly for texture: clay content ranged from 31 to 683 g kg^{-1}; sand content from 55 to 895 g kg^{-1} and organic carbon from 8.5 to 22 g kg^{-1}. Soil textures were classified according to the FAO Classification System (FAO-UNESCO, 1974) (Fig. 1). The soils' physical properties were determined as per the French Standard for Geotechnical Engineering. Particle density was determined using a water pycnometer on soils passed through a 0.3 mm sieve; Atterberg limits (liquid limit, plastic limit) were determined for soils passed through a 0.4 mm sieve.

Soil was sieved at 2–3 mm; the aggregates obtained were saturated. The saturated aggregates were placed in a hermetic box on a plastic grid above a desiccant (silicagel). Every 15 min, a portion of soil sample was weighed, placed in a container and then immersed in petrol for 12 h. The soaked aggregates were spread on filter paper to let the excess petrol run off. The volume of the displaced petrol corresponded to that of the soil (Archimedes' principle). The dry mass of the aggregates was determined after 24 h of oven-drying at 105 °C. The density of the aggregates was then calculated based on the dry mass and the volume of aggregates determined previously. Five replicates were made per soil.

We measured the relationship between matric potential Ψ and gravimetric water content w in the laboratory by using Richard's press method (Klute, 1986) on small aggregates. Two aggregate