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Soil compressibility and penetrability of an Oxisol from southern Brazil, as affected by long-term tillage systems☆

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Abstract

The precompression stress value defines the transition from the reloading curve to the virgin compression line in the stress–strain curve, which can be used to quantify the highest load or the most intense predrying previously applied to the soil. Thus, in soils with well-defined structured soil horizons, each layer can be characterized by such mechanical strength. Penetration resistance measurements, on the other hand, can be used to determine total soil strength profiles in the field. The effect of long-term tillage systems on physical and mechanical properties was determined in undisturbed and remolded samples collected at 5 and 15 cm depth, 6 months after applying no-till (NT), chisel plow (CP), and conventional tillage (CT) treatments, along with the application of mineral fertilizer and poultry litter. The compressibility tests were performed under confined conditions, with normal loads varying from 10 to 400 kPa after a defined predrying to −6 or −30 kPa. Penetration resistance was determined in the field, after seeding, in three positions: seeding row (SR), untrafficked interrow (UI), and recently trafficked interrow (TI). No-till system showed greater soil resistance to deformation than tilled treatments, as determined by the higher precompression stress and lower coefficient of compressibility. When original soil structure was destroyed (remolded samples), smaller differences were found. The application of extra organic matter (poultry litter) resulted in a reduction of precompression stress in undisturbed samples. Penetration resistance profiles showed greater differences among tillage treatments in the upper layer of the untrafficked interrow, where NT system showed the higher values. Smaller differences were found in the seeding row (with lower values) and in recently trafficked interrow (with higher values), showing that even traffic with a light tractor after soil tillage reduced drastically the effect of previous tillage by loosening up the soil. On the other hand, the tool used to cut the soil and to open the furrow for seeding, incorporated in the direct seeding machine, was sufficient to realleviate surface soil compaction.
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Keywords: Soil tillage; Precompression stress; Penetration resistance

1. Introduction

The mass of various machines used in agricultural operations has increased by a factor of 3–4 during the last three decades, while the number of field operations can be greater than 10 per year (Horn, 1995). As a consequence, increasing interest in surface and subsoil compaction has been focused in order to protect the soil against detrimental effects on physical, chemical, and biological soil properties and processes in deeper layers, which cannot be easily realleviated by tillage implements or inexpensive practices (Håkansson and Reeder, 1994).

From basic soil mechanics, the normal stress on any plane is, in general, the sum of the stresses transmitted

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by solid particles (effective) and the pressure of the fluid in the void space (neutral). The effective stress (σ') for saturated soils is given by the expression proposed by Terzaghi:

$$\sigma' = \sigma - u \quad (1)$$

where σ denotes total normal stress and u denotes fluid pressure in the pore space.

In unsaturated soils, air and water in the pore space also affect the stress transmission (Bishop, 1961). Thus, the corresponding expression for the effective stress in all situations is defined as:

$$\sigma' = \sigma - u_a + \chi(u_a - u_w) \quad (2)$$

where u_a denotes pressure in the gas and vapor phase and u_w denotes pressure in the pore water. The values of the χ parameter are unity for saturated soils, when the equation is reduced to a two-phase system as proposed by Terzaghi, and zero for dry soils (pF 7). The intermediate values will depend primarily on the saturation degree (Bishop, 1961). Another special case arises when u_a is equal to atmospheric pressure, which reduces the effective stress equation to (Skempton, 1961)

$$\sigma' = \sigma - \chi(u_w) \quad (3)$$

Especially for long-term loading, this equilibration will occur between internal and external pore air pressures in uniaxial confined test. Although this type of equation is well-known since many decades, the calculation of the effective stress is mostly not considered in the calculation of the precompression stress because neither the pore water pressure changes during the stress application were determined, nor values of the χ factor were calculated. Depending on soil type and processing conditions, saturation degree and χ factor present different behavior, but in overall terms the relation can be considered as being 1:1 in high saturation degree (Horn and Baumgartl, 1999).

The simultaneous registration of soil settlement and pore water pressure during stress–strain tests under confined conditions allows studying the relationship between soil deformation and water suction during soil compressibility determination in a multi-step device. Fazekas and Horn (2005) found that increasing time of each loading step increased soil settlement and reduced pore water pressure and precompression stress values. Longer time intervals allowed the remaining water to redistribute in the whole soil sample and result in a new equilibrium state of pore water pressure (since part of water can be lost during the test) in the reduced pore volume and new pore size configuration. It can be also concluded from their findings that the more negative the pore water pressure, the higher is the effective stress, which in itself shows a clear dependency to the loading time and the corresponding stresses applied.

In soils with markedly differentiated soil horizons or layers, each layer has a well-defined mechanical strength value which can be quantified by its precompression stress. If the applied stress does not exceed this value, the soil horizon reacts elastically, while exceeding it results in further plastic deformation (Horn et al., 1995). Furthermore, deeper soil horizons will be also subjected to an additional soil compaction as long as their internal strength is smaller than the remaining stress applied. Soil tillage systems affect mechanical behavior of soil layers. Horn (1986, 2004) determined that soils under a long-term conservation tillage induced changes in physical properties compared with conventionally tilled soils, being more resistant and thus less susceptible to deformation. Differences in precompression stress, shear strength, and hydraulic conductivity were found at 10–15 cm after approximately 3 years, at 30–35 cm after 5–6 years, and at 55–60 cm the same trend started after around 7 years (Horn, 2004). He also concluded that, under climatic conditions prevailing in northern Germany, better functioning pore systems can be obtained under a continuously applied system of conservation tillage, but these findings could only be maintained if during all tillage operations the internal soil strength is never exceeded by the applied mechanical stress.

Penetration resistance measurements can be used to determine total soil strength profiles in the field, being suitable in detecting strength and structural discontinuities associated with wheel tracks and size of structural units (Lowery and Morrison, 2002). Since this determination is highly influenced by soil water content and suction, measurements in the field should be done preferably when soil water content is uniform in the whole profile, i.e. when the water content is at field capacity, which is obtained 3–5 days after a rainfall with high precipitation. Shafiq et al. (1994) determined that penetration resistance increased with the increase in degree of compaction and this increase was more pronounced when compaction was induced at higher antecedent soil water contents. Greater penetration resistance was found in upper layers in no-till compared with conventional tillage systems (Burch et al., 1986; Francis et al., 1987) and chisel plow (Stewart and Vyn, 1994). When additional load (12 Mg axle load) was applied before tillage, significant differences in penetration resistance were restricted to depths of less than 35 cm in any of the tillage system (Stewart and Vyn, 1994). Genro et al. (2004) found higher penetration

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