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Estimation of precompression stress in an Ultisol cultivated with sugarcane

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ABSTRACT: Compressive soil properties are typically used for the understanding of compaction process. As an alternative to laboratory tests, pedo-transfer functions have been used to estimate the mechanical behaviour of soil as a function of soil physical parameters. The impact of soil bulk density (BD) and gravimetric water content (w) was examined on soil strength and pedo-transfer functions were proposed to predict the precompression stress (σ_p) in an Ultisol cultivated with sugarcane. Undisturbed soil cores were sampled at the depths of 0-0.20 and 0.20-0.40 m, subjected to different water contents, and subsequently, compression tests were performed to determine σ_p. The data were subjected to analysis of variance and regression analysis. Bulk density and w affected σ_p positively and negatively, respectively. Approximately 70% of the variation of the σ_p could be explained as a function of BD and w through an accessible multiple regression model. Comparisons with other pedo-transfer functions showed that estimates of σ_p may be rather sensitive to soil management and textural classes. Variations imposed by soil management and cohesive character into depth suggest that independent models should be considered to characterise compressive behaviour of soil by horizon or layer.

Key words: compaction, soil compressibility, coastal tablelands

Estimativa da tensão de preconsolidação em Argissolo cultivado com cana-de-açúcar

RESUMO: Propriedades compressivas do solo são frequentemente utilizadas para entender o processo de compactação. Alternativamente a ensaios laboratoriais, funções de pedo-transferência têm sido usadas para estimar o comportamento mecânico em função de parâmetros físicos do solo. Este trabalho objetivou examinar o impacto da densidade (BD) e do conteúdo de água (w) na resistência do solo à compactação, bem como propor funções de pedo-transferências para predição da tensão de preconsolidação (σ_p) em um Argissolo cultivado com cana-de-açúcar. Amostras indeformadas foram coletadas nas camadas de 0-0,20 e 0,20-0,40 m e submetidas à diferentes conteúdos de água, e então, ensaios de compressão foram realizados e a σ_p foi estimada. Os dados foram submetidos à análise de variância e de regressão. A BD e o w afetaram positiva e negativamente a σ_p, respectivamente. Aproximadamente 70% da variação da σ_p foi explicada em função da BD e do w através de um acessível modelo de regressão múltipla. Comparações com outras funções de pedo-transferência mostraram que as estimativas da σ_p podem ser bastante sensíveis ao manejo e a classes de solo. Variações impostas pelo manejo e pelo caráter coeso em profundidade sugerem que modelos independentes sejam considerados para caracterizar o comportamento compressivo por horizonte ou camada.

Palavras-chave: compactação, compressibilidade, tabuleiros costeiros

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Introduction

Soil compaction due to agricultural traffic has become a major concern of modern agriculture (Horn et al., 2003; Lima et al., 2017). The stress applied by the machines reaches the soil through the tyre-soil interface due to the contact promoted by the wheels (Keller et al., 2015). When soil strength at a given depth is lower than the stress applied by the tyre, the soil undergoes changes due to a reduction in pore volume, resulting on soil compaction (Défossez & Richard, 2002; Stettler et al., 2014; Lima et al., 2018).

The resistance of soil to compaction is assumed as the precompression stress (σ_p) (Stettler et al., 2014; Schjønning & Lamandé, 2018), which can be obtained via the compression curve. The determination of σ_p is complex and time-consuming (Lima et al., 2016; Schjønning & Lamandé, 2018), and therefore, pedo-transfer functions have been used to estimate σ_p as a function of soil physical parameters, which can be easily obtained in the field (Schjønning & Lamandé, 2018). Water content (Oliveira et al., 2011; Severiano et al., 2013) and soil bulk density (Lima et al., 2015) are significantly correlated with σ_p. Although the literature provides various functions for the estimation of σ_p, soil management conditions, mineralogy and texture have limited generalised applications (Keller et al., 2015), and the functions have been developed for a given texture, management unit or soil class (Stettler et al., 2014).

To understand the mechanisms underlying the compressive behaviour of soil and to estimate σ_p as a function of readily measurable physical attributes in soils, the impacts of water content and soil bulk density on soil strength, proposing pedo-transfer functions to predict σ_p were examined in an Ultisol cultivated with sugarcane.

Material and Methods

The study was carried out during the period from December 2016 to February 2017, at an experimental area of Carpina Experimental Sugarcane Station (EECAC-UFRPE), located in Carpina, state of Pernambuco (7° 51' S, 35° 14' W), Northeast, Brazil. Mean annual rainfall is approximately 1,400 mm, with a mean annual temperature of 24 °C. The soil is classified as Yellow Argisol (Ultisol) with a cohesive characteristic, according to EMBRAPA (2013) and with sandy-loamy texture (EMBRAPA, 1997); physical soil characteristics are shown in Table 1.

The experimental area is conventionally cultivated with sugarcane. Prior to planting, soil preparation consisted of the use of a harrow disk, limestone incorporation, systematisation of the area and furrow opening with a spacing of 1.10 m. At the time of sampling, the experimental area was in its fourth productive cycle; for harvesting, conventional loaders, trucks and trailers were used, which moved in parallel through the inter-rows of the experimental field.

Table 1. Soil granulometry, particle density (D_p), plasticity (LP) and liquidity (LL) limits of the studied Ultisol

Layer	Sand	Silt	Clay	D_P	LP	LL
(m)	(g kg^{-1})			(Mg m^{-3})	(%)	
0-0.20	824	32	144	2.62	12.50	12.50
0.20-0.40	812	30	158	2.62	17.50	17.50

Undisturbed soil cores were sampled from 0-0.20 and 0.20-0.40 m, using metal rings of 0.0635 m in diameter and 0.025 m in height. In total, 60 cores were taken from 10 random sampling points (positions) in the experimental area. This procedure was adopted to obtain the maximum variability in soil bulk density. For each position, three samples were took at a depth of 0-0.20 m and others three samples at 0.20-0.40 m. Sampling was performed in the sugarcane inter-row with sufficient distance to the adjacent sampling plots. The collected material was protected by plastic film and placed in a box for transportation.

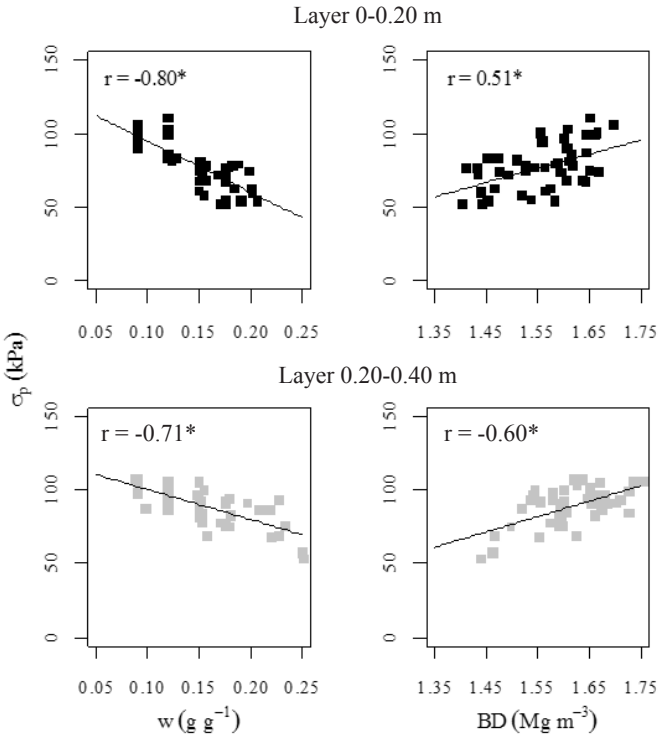
The undisturbed soil cores were saturated and separated into four groups of 15 samples each. For each group, different natural drying times were established (to obtain water content variability) and the samples were weighed to determine water content; subsequently, uniaxial compression tests were performed using a Bishop-type compression apparatus following the methodology described in NBR 1200790 (ABNT, 1990). Each sample was subjected to a successive vertical stress of 12.5, 25, 50, 100, 200, 400, 800 and 1,600 kPa per 2 min. After the test, the samples were oven-dried at 105 °C for 24 h to obtain soil dry mass.

Soil bulk density (BD) was calculated from the weight of the oven-dried soil and the total volume of the soil cores after each loading step. Gravimetric water content (w) was calculated using the wet mass and the dry mass of the soil, according to the procedure described in EMBRAPA (1997). The compression curve was analysed with the software package Compress 1.0; precompression stress (σ_p) was calculated via the Casagrande method.

Before proceeding to statistical fittings, the obtained values of σ_p, BD and w were examined via exploratory analysis using boxplot graphs. The points beyond the upper and lower limits of the boxplot were considered outliers and therefore removed from the dataset. Data were subjected to multiple linear regression analysis considering σ_p as the dependent variable. To verify differences between layers (i.e. σ_p between the 0-0.20 and the 0.20-0.40 m layers), σ_p was subjected to analysis of variance, and the means were tested by the least significant difference test (Fisher test) at 0.95 confidence intervals. All statistical and graphical procedures were performed through the R Software (R Core Team, 2017).

Results and Discussion

The σ_p was linearly and negatively correlated with water content (w), with linear correlation (r) coefficients of -0.80 and -0.71 for the 0-0.20 and the 0.20-0.40 m layer, respectively (Figure 1). In the analysis of the dispersion of σ_p as a function of w, it was observed that for larger w values, the values of σ_p were smaller. Inversely, the σ_p was linear and positively correlated (r of 0.51 and 0.60 for 0-0.20 and 0.20-0.40 m, respectively) with soil bulk density (BD), where for larger BD values, higher values of σ_p were obtained in both layers (Figure 1). In terms of absolute values, σ_p varied between 50 and 110 kPa for ranges of w and BD of 0.07 to 0.25 g g^{-1} and 1.40 to 1.75 Mg m^{-3}, respectively.



Pearson correlation coefficient. *p-value < 0.01 by t-test

Figure 1. Variation of precompression stress (σ_p) as a function of water content (w) and initial bulk density (BD) for a Ultisol cultivated with sugarcane

The combined effects of w and BD on σ_p, via the multiple linear regression model, explained 70 and 71% (R^2 of 0.70 and 0.71, respectively) of the variation of σ_p for the two layers (Table 2). In the model, the negative and positive effects of w and BD on σ_p were numerically designed by the regression fitting coefficients, which also express negative and positive values, respectively, within the model (Table 2). The behaviour of σ_p with the variation of w and BD is shown in Figure 2. The model explains that the combination of high values of w and low values of BD can result in lower resistance to compaction, i.e. the soil can support higher stress applied by traffic without compaction when w is low and BD is high.

Linear and negative variations of σ_p with w have been reported in several studies (Imhoff et al., 2004; Saffih-Hdadi et al., 2009; Lima et al., 2015). Imhoff et al. (2004) and Saffih-Hdadi et al. (2009) used multiple linear regression to explain the impact of w on σ_p. According to Imhoff et al. (2004) and An et al. (2015), the decrease of σ_p with the increase in w occurs because of decreased cohesion between the particles, which are continuously lubricated because of the high water content, interfering with the friction among particles and with the resistance to deformation. This process is shown in Figure 2, where with increasing water content, soil resistance to compaction, expressed as σ_p, decreases.

Table 2. Models for estimation of precompression stress (σ_p), in Yellow Argisol cultivated with sugarcane. Samples were taken at depths of 0-0.20 and 0.20-0.40 m

Layer (m)	Linear model	R^2
0-0.20	σ_p = 46.40 - 303.83***w + 49.25**BD	0.70
0.20-0.40	σ_p = -12.25 - 173.0***w + 79.62***BD	0.71

***p-value < 0.0001; **p-value < 0.001 by t-test; w - Water content (g g^{-1}); BD - Bulk density (Mg m^{-3})

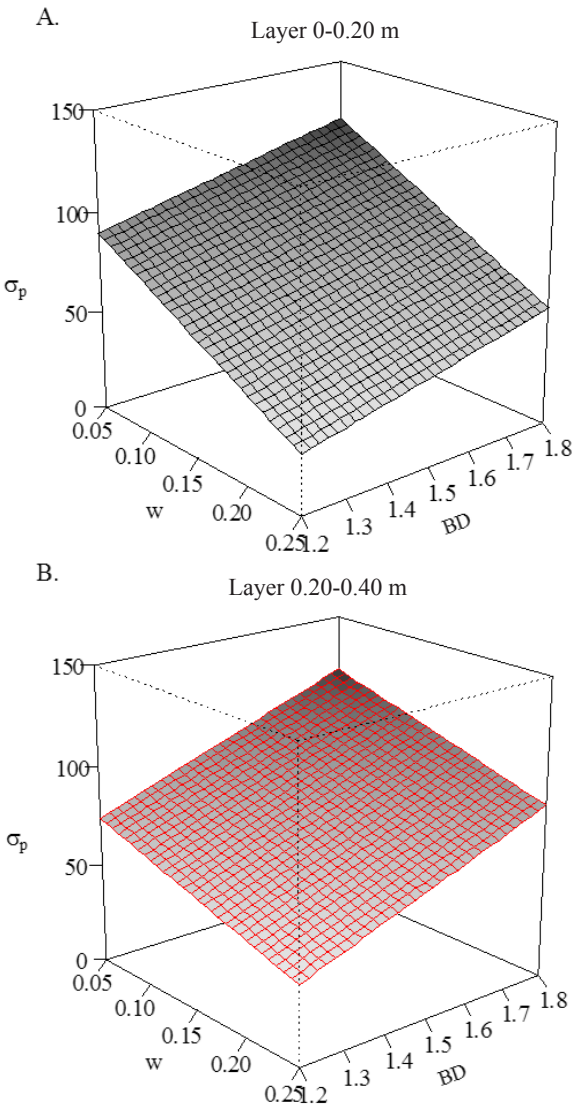


Figure 2. Variation of precompression stress (σ_p, kPa) as a function of water content (w, g g^{-1}) and soil bulk density (σ_p, Mg m^{-3}) for a Ultisol cultivated with sugarcane in soil layer 0-0.20 m (A) and 0.20-0.40 m (B)

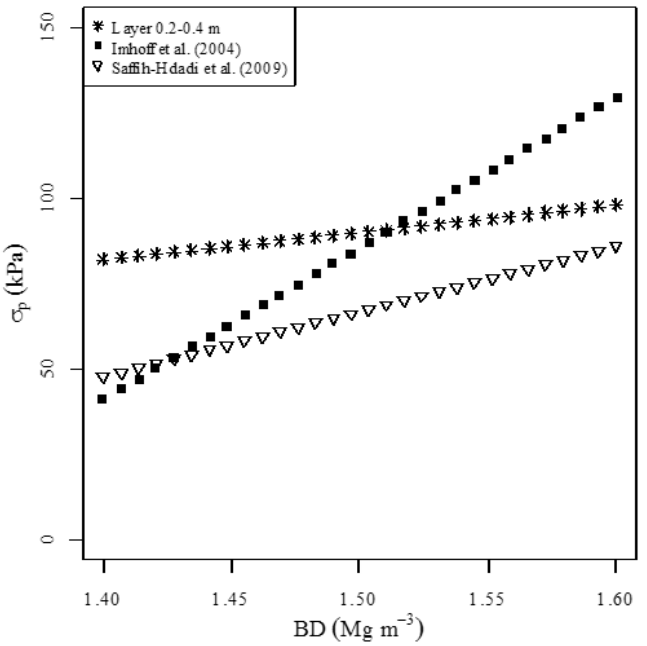
The linear and positive impacts of BD on σ_p have also been observed by Imhoff et al. (2004), Saffih-Hdadi et al. (2009), Lima et al. (2015, 2016) and Schjønning & Lamandé (2018). Imhoff et al. (2004) attributed the positive effect of BD to the increase of the frictional forces in the soil mass and explained that these forces impede the displacement and separation of the particles under stress, increasing the load-bearing capacity of the soil. Associated to this, the decrease in pore space, specifically of macropores (larger pores), also contributes to the increase in the resistance to compaction under larger BD, since the volume of pores with the expulsion of air in the compacting process decreases. Numerically, this process can also be verified through the behaviour of σ_p as a function of BD, as shown in Figure 2.

The model explains a large part of the variation of σ_p (around 70%), but still loses some information (30%) that may be associated to sampling errors, laboratory methodologies and estimation methods of σ_p (Silva & Lima, 2015, 2016), besides other physical and mechanical influences. For example, Pereira et al. (2007) and Braida et al. (2008) included the organic carbon content in their models, while Stettler et al. (2014),

Lima et al. (2018) and Schjønning & Lamandé (2018) used the matric potential to explain part of the variation attributed to soil moisture. According to Pereira et al. (2007), the organic carbon content may interfere with the soil water retention dynamics, affecting the cohesion and the friction between the particles under application of external stress. However, there is an attempt to simplify the models and to make them readily available (Schjønning & Lamandé, 2018), i.e. models which use few variables that are easily measured in the field. This assumption has justified the search for pedo-transfer functions that explain the soil compressive process as a function of soil moisture and pore space variables (Lima et al., 2018; Schjønning & Lamandé, 2018), which is the motivation of this study.

Although the results presented in Figure 2 have already been reported by other authors (Imhoff et al., 2004; Saffih-Hdadi et al., 2009; Lima et al., 2015), mineralogical, soil origin and management effects, reported by Giarola & Silva (2002) and Keller et al. (2015), can be seen in the absolute relation of the dependent variable (σ_p) as a function of the explanatory variables, i.e. the increase in σ_p for a corresponding variation in the explanatory variable (w or BD).

Figure 3 shows a simulation for σ_p as a function of BD, with fixed values of w (0.10 g g^{-1}) and clay content (15%, considering the values in Table 1), using the model given in Table 2, for the 0.20-0.40 m layer, and the equations given by Imhoff et al. (2004) and Saffih-Hdadi et al. (2009). It is possible to verify that the relations between σ_p and BD change according to the pedo-transfer function, even though they are proposed for the same clay content and simulated under the same water content. This work was conducted in Ultisol of Coastal Tablelands, while Imhoff et al. (2004) studied Oxisols, and the work of Saffih-Hdadi et al. (2009) was developed in French soils, where clay mineralogy is predominantly of the 2:1 type. This means that the cohesive character of the Ultisol of Coastal Tablelands, clay mineralogy and management factors may affect the physical-mechanical behaviour of the soil, which would impede the generalised use of the functions.



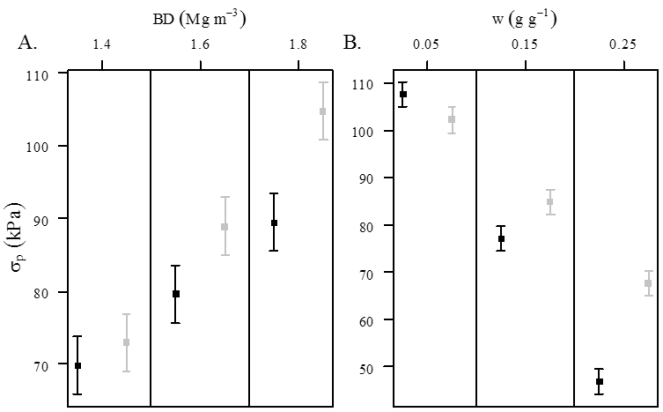
For the simulations, assumed values of water content (w) and clay were 0.10 g g^{-1} and 15%, respectively

Figure 3. Variation of precompression stress (σ_p) as a function of initial soil bulk density (BD) for a Yellow Argisol cultivated with sugarcane, according to the pedo-transfer functions proposed by Imhoff et al. (2004) and Saffih-Hdadi et al. (2009)

According to Giarola & Silva (2002), soils with cohesive character present a marked strength increase. The simulations presented in Figure 3 show that, even under low BD, the highest values of σ_p were obtained for the cohesive Ultisol, which could be associated to the increase in the cohesion of the particles from the cohesive character. According to EMPRAPA (2013), cohesive horizons can occur between 30 and 70 cm from the soil surface, which would be within the scope of the present study (at the 0.20-0.40 m layer).

Figure 4 shows a comparison between layers, i.e. a comparison of the prediction of σ_p using the fitted models for the layers of 0-0.20 and 0.20-0.40 m. The behaviour of σ_p is analysed as a function of BD (Figure 4A) and also of w, albeit separately (Figure 4B). It is possible to verify that, with increasing BD and w, significant differences in σ_p occur between the two layers, evidenced by the differences in the confidence intervals of the mean (0.95). The σ_p was higher in the 0.20-0.40 m layer, both in the BD and in the w as scenarios, showing that the lower layer (0.20-0.40 m) offered higher resistance to compaction under the same soil state conditions (i.e. w and BD).

Years of sugarcane cultivation in the experimental area may have caused the emergence of plough pans, which occur in the subsurface due to soil tillage operations and which may have artificially led to soil hardening (Keller et al., 2014) below the ploughing layer (about 0.20-0.40 m). The associated action of the plough pan and the cohesive layer may promote resistance to compaction at the subsoil level (Giarola & Silva, 2002; Keller et al., 2014), which, from the point of view of traffic planning, can be seen as a gain in soil strength, but may impede plant development. Unlike more uniform soils (e.g. Latosols), in Ultisol, the modelling per layers is justifiable, and it may evolve in future studies on models by horizons, as specified in the Terranimo model in soils of Europe (Stettler et al., 2014).



Horizontally overlapping intervals did not differ statistically at the 0.95 confidence level by the least significant difference test (Fisher test)

Figure 4. Confidence intervals (0.95) for the mean of the σ_p under scenarios as a function of (A) soil bulk density and (B) water content, estimated using the equations given in Table 2 for the layers 0-0.20 m (black colour) and 0.20-0.40 m (grey colour)

Conclusions

1. Bulk density and water content have positive and negative impacts, respectively on precompression stress (σ_p). Approximately 70% of the variation of σ_p can be explained using bulk density and water content in cohesive Ultisol through an accessible and simple regression model.

2. Comparisons with other models show that the estimates of σ_p can be rather sensitive to soil management and textural classes.

3. Variations imposed by soil management and cohesive character in depth suggest that independent models should be considered to characterise the compressive behaviour by soil horizon or layer.

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