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Precompression stress and compression index depend on the property used to represent the soil deformation in the compression curve

Pressão de preconsolidação e índice de compressão dependem da propriedade usada para representar a deformação do solo na curva de compressão

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ABSTRACT

During linear deformation (h) in a soil sample, the variation of the void ratio with respect to deformation (dε/dh) and the respective variation of soil bulk density (dρ/dh) are identical only for a specific value of h. Consequently, if two compression curves are drawn for the same soil sample, one using ρ and the other using ε, there are differences in both the calculated precompression stress (σp) and compression index (Ic). In this study, we highlight the causes by a mathematical analysis and an experimental investigation, quantifying the differences in σp and Ic when using ε and ρ. σp and Ic were calculated for 103 compression curves of an ultisol and 193 of an oxisol. The σp (kPa) using ρ (σp_ρ) was greater than when using ε (σp_ε), and differences were rather independent of the soil type. The relations found by linear regression relating σp_ρ to σp_ε were σp_ρ=0.8186σp_ε+34.202 for the ultisol and σp_ρ=0.8878σp_ε+34.875 for the oxisol. In contrast, the used soil property (ρ or ε) as well as soil type affected Ic. Ic calculated using ρ was greater than when using ε in almost all (96%) of the cases for the ultisol, and in only 12% of the cases for the oxisol. For a wide range of ρ, evidence from this study indicated that the use of ρ overestimates σp when compared to the use of ε.

Key words: *void ratio, particle density, soil bulk density.*

RESUMO

À medida que uma amostra de solo sofre deformação linear (h), a variação do índice de vazios em relação à deformação (dε/dh) e da respectiva variação da densidade do solo (dρ/dh) são coincidentes somente para um único valor de h. Decorrente disso, verifica-se experimentalmente que, para a mesma amostra de solo, há diferenças, tanto na pressão de preconsolidação (σp) como no índice de compressão (Ic), se forem determinados a partir das duas curvas de compressão, uma a base da ρ e outra a base do ε. A análise matemática, seguida da investigação experimental deste estudo, evidencia as causas e quantifica as diferenças na σp e no Ic, devido ao uso do ε ou ρ. A σp e o Ic foram calculados em 103 curvas de compressão de um Argissolo e em 193 de um Latossolo. A σp (kPa) com o uso da ρ (σp_ρ) foi maior que a σp com o uso do ε (σp_ε), e as diferenças dependeram menos do tipo de solo. As relações encontradas por regressão foram σp_ρ=0,8186 σp_ε+34,202 para o Argissolo e σp_ρ=0,8878 σp_ε+34,875 para o Latossolo. Diferentemente, o Ic foi afetado pela propriedade usada (ρ ou ε) para descrever a deformação e pelo tipo de solo. O Ic calculado com o uso da ρ foi maior que quando calculado com o uso do ε em quase todos os casos (96%) no Argissolo e raramente (em 12% dos casos) no Latossolo. Para uma ampla faixa de ρ, as evidências deste estudo indicam que o uso da ρ superestima a σp em relação ao uso do ε.

Palavras-chave: *índice de vazios, densidade dos sólidos, densidade do solo.*

INTRODUCTION

The compression curve (*CC*) is widely used for obtaining the load-bearing capacity and susceptibility to compaction of soils, expressed by the precompression stress (*σp*) and the compression index (*Ic*), respectively (KELLER et al., 2011). To quantify changes in soil structure with the *CC*, some researchers use bulk density (*ρ*), CC_ρ, (DIAS JUNIOR & PIERCE, 1995; FRITTON., 2001; ASSOULINE et al., 2002) whereas others use the void ratio (*ε*), *CCε*, (GREGORY et al., 2006; CAVALIERI et al., 2008; KELLER et

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al., 2011; ROSA et al., 2011). Experimentally it is observed that there are differences between the *σp* and *Ic* values in the same soil sample estimated with both curves, CC_ρ and CC_ε (MOSADDEGHI et al., 2003; RÜCKNAGEL et al., 2010). There is evidence that the *σp* obtained with *ρ* (σp_ρ) is greater than the *σp* obtained with *ε* (σp_ε). MOSADDEGHI et al. (2003) presented the relation σp_ρ=1.3 σp_ε and RÜCKNAGEL et al. (2010) presented σp_ρ=1.08+7.73 σp_ε (kPa), both resulting in σp_ρ values higher than σp_ε.

The fact there are differences between σp_ρ and σp_ε indicates that differences between the values of *Ic* (Ic_ρ and Ic_ε) are also to be expected. Both for theoretical reasons, as well as for applications it is useful to know the causes and soil properties that determine the magnitude and direction of the differences. According to MOSADDEGHI et al. (2003) and RÜCKNAGEL et al. (2010), the cause of the differences is the non-linearity of the relationship between *ε* and *ρ*. However, these authors did not investigate mathematically the effect of this non-linearity on *σp* and *Ic*.

As *ε* and *ρ* are reciprocal and the relation between them depends on the (solid) particle density, the aim of this study was to analyze the effect of initial bulk density and particle density on the relation between *σp* and *Ic* with *ε* and *ρ*, theoretically, and experimentally in compression curves of an ultisol and an oxisol.

MATERIALS AND METHODS

Theory

Initially, two quantities were defined, bulk density (*ρ*, kg m^{-3}) and void ratio (*ε*, m^3 m^{-3}), as:

$$\rho = \frac{M_s}{V_t} \tag{1}$$

$$\varepsilon = \frac{V_v}{V_s} \tag{2}$$

M_s (kg) being the mass of solids, V_t (m^3) the total soil volume, V_v (m^3) the void volume (pores) and V_s (m^3) the volume of soil solids.

As will be shown in the following, the relationship between *ε* and *ρ* is defined solely by the particle density ρ_s (kg m^{-3}) given by

$$\rho_s = \frac{M_s}{V_s} \tag{3}$$

Multiplying equations (1) and (2) and combining with (3) yields

$$\rho\varepsilon = \frac{M_s}{V_t}\frac{V_v}{V_s} = \rho_s\frac{V_v}{V_t} \Leftrightarrow \varepsilon = \frac{\rho_s}{\rho}\frac{V_v}{V_t} \tag{4}$$

As $V_v = V_t - V_s$ it follows that

$$\frac{V_v}{V_t} = \frac{V_t - V_s}{V_t} = 1 - \frac{V_s}{V_t} = 1 - \frac{M_s/V_t}{M_s/V_s} = 1 - \frac{\rho}{\rho_s} \tag{5}$$

Substituting equation (5) in (4) we find:

$$\varepsilon = \frac{\rho_s}{\rho}\left(1 - \frac{\rho}{\rho_s}\right) = \frac{\rho_s}{\rho} - 1 \tag{6}$$

Equation (6) shows that *ρ* and *ε* are inversely proportional, the particle density being the proportionality coefficient.

Based on these definitions and relations, the effect of the use of *ε* and *ρ* in determining *σp* and *Ic* can be analyzed with the deformation of a soil sample as a function of the initial bulk density and the particle density. Being *H* (m) the height of a cylinder containing a soil sample and h_1 (m) the linear deformation when submitted to load (pressure), the resulting sample height h_2 (m) is given by:

$$h_2 = H - h_1 \tag{7}$$

Although h_2 is the height of the sample after a deformation h_1, in our case it is more convenient to use H-h_1, as it is our objective to analyze the relation of both *ε* and *ρ* with h_1.

At any time during the compression, the soil volume V_t is given by:

$$V_t = \pi r^2 (H - h_1) \tag{8}$$

and the volume of soil solids, V_s, which is not affected by compaction, is expressed by rewriting equation (3):

$$V_s = \frac{M_s}{\rho_s} \tag{9}$$

The void volume V_v is given by:

$$V_v = V_t - V_s = \pi r^2 (H - h_1) - \frac{M_s}{\rho_s} \tag{10}$$

from which the void ratio *ε* is obtained as:

$$\varepsilon = \frac{V_v}{V_s} = \frac{\pi r^2 (H - h_1) - \frac{M_s}{\rho_s}}{\frac{M_s}{\rho_s}} = \frac{\pi r^2 \rho_s (H - h_1)}{M_s} - 1 \tag{11}$$

Finally, the bulk density *ρ* is given by:

$$\rho = \frac{M_s}{V_t} = \frac{M_s}{\pi r^2 (H - h_1)} \tag{12}$$

Variations of *ε* and *ρ* as a function of h_1 can be calculated from equations (11) and (12) that reflect the relation described in equation (6):

$$\frac{d\varepsilon}{dh_1} = -\frac{\pi\, r^2 \rho_s}{M_s} \ (\text{m}^{-1}) \tag{13}$$

$$\frac{d\rho}{dh_1} = -\frac{M_s}{\pi\, r^2 (H - h_1)^2} \ (\text{kg m}^{-4}) \tag{14}$$

Equations (13) and (14) show that dε/dh_1 is a constant, unlike dρ/dh_1, which is a function of h_1. A direct comparison between the two derivatives represented in equations (13) and (14) does not make sense because they have different dimensions (units). To allow comparison, equation (12) is divided by the density of water, resulting in a relative density (ρ_r):

$$\rho_r = \frac{\rho}{\rho_a} = \frac{M_s}{\rho_a \pi\, r^2 (H - h_1)} \tag{15}$$

The variation rate of ρ_r as a function of h_1 is given by:

$$\frac{d\rho_r}{dh_1} = -\frac{M_s}{\rho_a \pi\, r^2 (H - h_1)^2} \ (\text{m}^{-1}) \tag{16}$$

Equations (13) and (16) have the same dimension and can be compared to find the values of h_1 and ρ that correspond to the same rate of variation, respectively, $h_{\rho x}$ (m) and ρ_x (kg m^{-3}):

$$\frac{M_s}{\rho_a \pi\, r^2 (H - h_{1,x})^2} = \frac{\pi\, r^2 \rho_s}{M_s} \tag{17}$$

$$\frac{M_s M_s}{\pi\, r^2 (H - h_{1,x}) \pi\, r^2 (H - h_{1,x})} = \rho_s \rho_a \tag{18}$$

$$\rho_x^{\ 2} = \rho_s \rho_a \Rightarrow \rho_x = \sqrt{\rho_s \rho_a} \tag{19}$$

In other words, ρ_x, the bulk density for which *d*ε*/dh*$_1$ and *d*ρ_r*/dh*$_1$ will be equal, is the geometric mean of particle and water density.

As dρ_r/dh_1 decreases with h_1 and dε/dh_1 is a negative constant, dρ_r/dh_1 will be less negative than dε/dh_1 when $\rho<\rho_x$. For $\rho>r_x$, the relation becomes inverse (Figure 1). This indicates that CC_ε is different from CC_ρ for all values of ρ except ρ_x. However, it does not allow concluding that the use of ρ will always overestimate σ_p when compared to the use of ε for the range of agricultural bulk densities, as observed by MOSADDEGHI et al. (2003) and RÜCKNAGEL et al. (2010).

The matter can be investigated experimentally, considering soils with different ρ_s and samples with different initial bulk density. The mathematical procedure should be the same for the description of both curves, CC_ε and CC_ρ in order to avoid differences caused by the mathematical models themselves (GREGORY et al., 2006; CAVALIERI et al., 2008; ROSA et al., 2011).

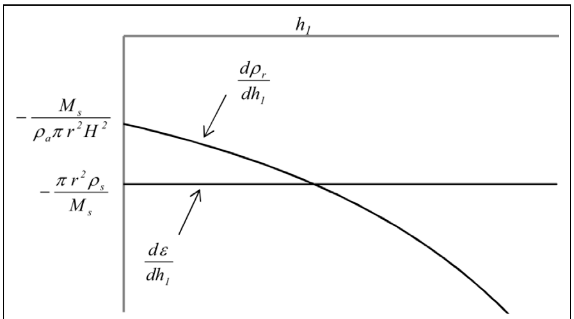

Figure 1 - Void ratio and bulk density variation rate (dε / dh_1 and dρ/ dh_1) as a function of sample deformation (h_1), as described by equations (13) and (16). Equations at the Y-axis represent the particular case of h_1 = 0 for equations (13) and (16).

Experiment

A study was performed with 103 samples of an ultisol and 193 samples of an oxisol, according to Soil Taxonomy developed by USDA (SOIL SURVEY STAFF, 2010). Samples were collected in experimental plots with different levels of soil compaction (no-till, no-till with additional traffic to enhance compaction and no-till with scarification to decrease compaction). Sampling was performed in these experiments at some depths to obtain a wide range in bulk density required for this study.

In the ultisol (0.10kg kg^{-1} clay, 0.65kg kg^{-1} sand and 0.25kg kg^{-1} silt), undisturbed samples were collected at depths of 0.05, 0.15 and 0.30m in stainless steel rings (0.057m in diameter and 0.03m in height). In the oxisol (0.12kg kg^{-1} sand, 0.24kg kg^{-1} silt and 0.64kg kg ^{1} clay), undisturbed samples were collected at depths of 0.07 and 0.25m in stainless steel rings (0.061m diameter and 0.03m height). Prior to the compression test, the samples were saturated with water by capillarity and submitted to the tension of 10kPa (both ultisol and oxisol) on a sand box (REINERT & REICHERT, 2006), and to 33, 100, 500 and 1500kPa (only the oxisol) in pressure chamber (KLUTE, 1986). At each pressure, the samples were weighed to determine the volumetric water content (θ, m^3 m^{-3}) and the degree of saturation (S=θ/ α, where α is the total porosity, m^3 m^{-3}) and were subjected to compression test.

The particle density ρ_s was determined in 25 samples of the ultisol and 48 samples of the oxisol by the volumetric flask method with modifications proposed by GUBIANI et al. (2006). For the ultisol, ρ_s was 2650kg m^{-3} (standard deviation 52kg m^{-3}) and for the oxisol 2720 kg m^{-3} (standard deviation 65kg m^{-3}).

Uniaxial compression tests were performed in a consolidometer, model Terraload S-450 (Durham

Geo-Enterprises). Successive loadings of 12.5, 25, 50, 100, 200, 400, 800 and 1600kPa were applied. Each loading was applied during five minutes, enough to achieve 99% of total deformation (SILVA et al., 2000). At the end of the test, the samples were oven-dried at 105°C until constant weight. Structure changes of the sample for each loading were represented by ε (equation 11) and ρ (equation 12).

Both σp and Ic were calculated with the procedure proposed by DIAS JUNIOR & PIERCE (1995). Although this procedure was originally described with a compression curve CC_ρ, it can also be used with a compression curve and CC_ε (CAVALIERI et al., 2008). In summary, σp corresponds to the value of load at the intersection of the secondary compression line (drawn based on three data points for ($\log_{10}\sigma$, ε) or ($\log_{10}\sigma$, ρ) at loadings of 12.5, 25 and 50kPa) with the virgin compression line (drawn based on the final four data points ($\log_{10}\sigma$, ε) or ($\log_{10}\sigma$, ρ) at loadings of 200, 400, 800 and 1600kPa]. Unlike the original method of DIAS JUNIOR & PIERCE (1995), which uses two data points ($\log_{10}\sigma$, ρ) at loadings of 800 and 1600kPa to draw the virgin compression line, in the present study it was decided to use the four data points due to the fact that the two final points alone would not represent well the observed tendency which is slightly sigmoid in its tail. In these cases, the use of only the two final data points like proposed by DIAS JUNIOR & PIERCE (1995) would make the projection of the virgin compression line to intercept the line of secondary compression in the domain $\sigma<\sigma_{50kPa}$, in disagreement with the definition of the virgin compression line as the line segment subsequent to the secondary compression line (DIAS JUNIOR & PIERCE, 1995; GREGORY et al., 2006; KELLER et al., 2011). The use of the four final data points avoid that two data point (at loadings of 800 and 1600kPa) would be excluded, and to ensure that the line of virgin compression would intercept the line of secondary compression within the domain $\sigma>\sigma_{50kPa}$.

Regardless of the curve shape, the choice of data points changes estimates for σp and Ic in the same direction (either an increase or a decrease, irrespective of using ρ or ε). Furthermore, the magnitude of change in σp_ρ and Ic_ρ is different of that in σp_ε and Ic_ε. However, the choice of the final data points only increases or decreases these magnitudes, because the cause of differences is the intrinsic non-linearity of the relationship between ρ and ε shown above. Although the experimental results are affected by the procedure used, they only particularize but do not invalidate neither the discussion nor the conclusions of this study. Finally, Ic was defined as the absolute value of the slope of the virgin compression line. More details of the procedure are described in DIAS JUNIOR & PIERCE (1995).

The σp calculated using ε was correlated to σp calculated using ρ by linear regression. The comparison of the calculated Ic using ε and ρ was made by comparison of the respective slopes of the virgin compression line.

RESULTS AND DISCUSSION

There was a large variation in values of ρ, ε and S for the used samples (Table 1), indicating structural differences of the soil and different water contents leading to a wide range of σp values. The values of σp (average ± standard deviation) were 112 (±30)kPa for the ultisol and 133 (±46)kPa for the oxisol.

For both soils, values of σp calculated based on ρ (σp_ρ) were higher than when calculated using ε (σp_ε) (Figure 2A, B). Differences between σp_ρ and σp_ε were 34kPa at maximum, and were higher in samples with a low σp. Linear and angular regression coefficients for σp_ρ as a function of σp_ε were similar for both soils (linear 34.2 versus 34.9kPa and angular 0.82 versus 0.89kPa kPa^{-1} for the ultisol and oxisol, respectively), indicating that the relation between σp_ρ and σp_ε is not (much) affected by soil type. Based on the 95% confidence interval, regressions were similar for σp_ε<40kPa and different for higher values, but with a small difference. Numerically, these regression coefficients are different from the coefficients

Table 1 - Descriptive statistics for the soil samples.

Property *	Mean	Standard deviation	Minimum	Maximum
	-------------------------Ultisol-------------------------			
ρ_i	1619	154	1206	1964
ρ_f	1917	94	1661	2178
ε_i	0.65	0.17	0.35	1.20
ε_f	0.39	0.07	0.22	0.60
S_i	0.55	0.12	0.15	0.80
	-------------------------Oxisol-------------------------			
ρ_i	1318	114	982	1557
ρ_f	1720	81	1403	1941
ε_i	1.08	0.19	0.75	1.77
ε_f	0.59	0.08	0.40	0.94
S_i	0.66	0.13	0.28	0.89

* initial (ρ_i) and final (ρ_f) bulk density (kg m^3), initial (ε_i) and final (ε_f) void ratio (m^3 m^{-3}), initial degree of saturation (S_i).

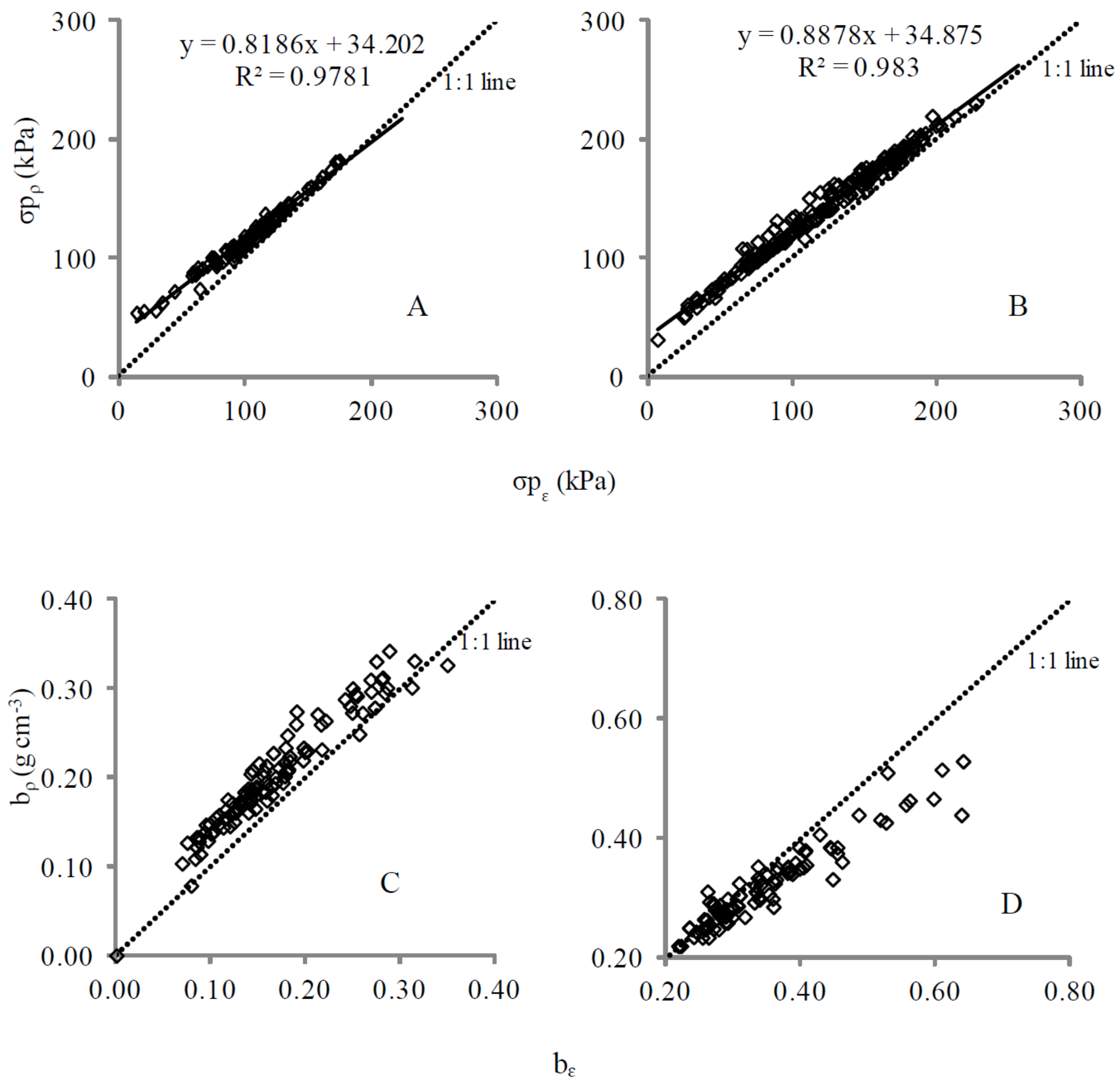

Figure 2 - Precompression stress calculated using bulk density (σp_ρ) versus using void ratio (σp_ε) for the ultisol (A) and the oxisol (B); and the relation between the absolute value of slope of the virgin compression line using bulk density (b_ρ) and using void ratio (b_ε) for the ultisol (C) and the oxisol (D).

presented by MOSADDEGHI et al. (2003), σp_ρ=1.3σp_ε and by RÜCKNAGEL et al. (2010), σp_ρ=1.08σp_ε+7.73, possibly due to the methodological differences in the calculation of σp. However, all experimental relations show σp_ρ to be greater than σp_ε.

The differences between σp_ρ and σp_ε ($\Delta\sigma p$=σp_ρ-σp_ε) decreased linearly with the initial bulk density (ρ_i) for both soils. For the ultisol, $\Delta\sigma p$=-0.039ρ_i +77.89 [R^2=0.7026] and for the oxisol $\Delta\sigma_p$=-0,051ρ_i+88.564 [R^2=0.592]. Based on these equations, $\Delta\sigma p$ would be negative for values of ρ_i greater than 1997kg m^{-3} for the ultisol and greater than 1736kg m^{-3} for the oxisol. These bulk density values are much higher than those found in these soils, indicating that the use of ρ will always overestimate σp when compared to employing ε.

The compression ratio *Ic*, which is the absolute value of the slope of the part of the compression curve (bulk density or void ratio as a function of applied load) that corresponds to plastic deformation, the so-called "virgin compression line", was affected both by the property used to describe the soil deformation as by the soil type (Figure 2C, D). The *Ic* calculated using ρ was higher than when using

ε in almost all cases (96%) in the ultisol and rarely (12% of cases) in the oxisol. This difference between both soils can be explained by the ρ ratio reached by the samples on the virgin compression line segment with the respective value of ρ_x (equation 19). For the ultisol, ρ_x equaled $\sqrt{(2650 \cdot 1000)}$=1628kg m^{-3} and for the oxisol it was $\sqrt{(2720 \cdot 1000)}$=1649kg m^{-3}. Note that the ρ_x values depend only on the particle density (2650kg m^{-3} and 2720 kg m^{-3} for the ultisol and oxisol, respectively), wherein one of the factors determines the difference between $d\varepsilon/dh_1$ and $d\rho/dh_1$.

In the ultisol, 93% of soil ρ were higher than its ρ_x (1628kg m^{-3}), indicating that in these cases, the rate of variation of ρ was greater than for ε (Figure 1). Consequently, in most cases, *Ic* calculated using ρ was higher than when using ε (Figure 2C, D). In contrast, in the oxisol, only 31% of the ρ were higher than its ρ_x (1649kg m^{-3}), resulting in a rate of variation of ε greater than that of ρ in 85% of the cases (Figure 1). Consequently, in most cases, the *Ic* calculated using ε was greater than when calculated using ρ (Figure 2C, D).

Based on this analysis, σp and *Ic* depends on the property used to describe the deformation of the soil. Consequently, the comparison of results of σp and *Ic* in several publications (GREGORY et al., 2006; CAVALIERI et al., 2008; KELLER et al., 2011; ROSA et al., 2011) is not suitable, because the differences in σp and *Ic* are partially caused by the soil property used and therefore may not accurately represent differences in the mechanical behavior of soils. Similarly, comparison of mathematical models that describe the compression curve based on ρ (DIAS JUNIOR & PIERCE, 1995; FRITTON, 2001; ASSOULINE et al., 2002) with those models that employ ε (GREGORY et al., 2006, CAVALIERI et al., 2008; KELLER et al., 2011) may also contains such errors. These problems can be avoided if all comparisons are made with σp and *Ic* calculated with the same mathematical model and soil property.

CONCLUSIONS

Precompression stress and the compression index differ between compression curves based on bulk density and void ratio due to the non-linearity of the relationship between these soil properties. The difference depends on the initial bulk density and the particle density. For a wide range of initial bulk densities, results with the two soils used in this study indicate that the use of bulk density overestimates the precompression stress when compared to the use of the void ratio.

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