Chapter 8
A Preliminary Proposal for the Structural Classification of Soil Pore Space

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Abstract This study presents a preliminary proposal of a structural classification system of soil pore space seeking to group soils with similar air availability curves. The function that relates soil air content to water suction is herein called the air availability curve. The proposed system approach is similar to that of textural classification and allows classifying soil according to types of soil structural families based on nine possible sub-areas (from A to I) represented in a classification triangle, herein called the structural triangle. Besides family types, it is also necessary to predict the family orders according to different ranges of variation for the effective soil porosity. Both family type and order are obtained by parameterization of the moisture retention curve. 467 samples were classified according to the proposed methodology, which confirmed that the structural families grouped soils with similar air availability curves. This result shows the potential usefulness of the proposed methodology for pedologic knowledge and for the development of pedotransfer functions of the soil water properties.

Keywords Air availability • Available water • Brazilian soils • Classification triangle • Effective air • Parameters of van-Genuchten model • Pedotransfer function • Pore size distribution • Residual water • Soil classification • Soil's void space

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• Structural classification • Structural family • Textural classification • Water retention curve

8.1 Introduction

Soil pore spaces are filled with water by suction *s* (in centimeters of water column), defining a saturation volumetric fraction equal to θ/Φ where θ is the volumetric water content and Φ is the soil porosity. In turn, suction can be understood as being a measure of the size of the hydrated pores, in terms of their equivalent diameter *d*, through the capillarity equation:

$$d = \frac{4\sigma}{\rho g s}, \tag{8.1}$$

where σ and ρ are, respectively, the surface tension and the specific mass of the water, and *g* is the acceleration due to gravity. So, the plot of "$(\Phi - \theta)/\Phi$" versus "*s*" can be considered a representation of the distribution, as a cumulative function of volume, of the pore size within the soil pore space volume. This distribution is close to zero for the greatest hydrated pore diameter *d* (with the smallest suction s) and increases to the limit of 1.0 with the increase in suction and decrease in size of the pores filled up with water.

The similarity between the construction of the pore size distribution mentioned above and the particle size distribution curve allows the development of a structural classification of the pore space that is similar to the soil textural classification. Because of this similarity this study proposed a structural classification system of soil pore space based on the $(\Phi - \theta)$ curve (and not on the θ curve), herein called the soil air availability curve, as a function of water suction. We expect that the soil grouping by similar air availability curves allowed by the system may contribute to pedologic knowledge and the description of the dynamic processes that occur in soil pore spaces. This classification system is termed as structural because it refers to volume distribution inside the soil void space, which is a direct consequence of soil structure, a classical pedological term that, instead, generally refers to geometric and physical features of the soil solid matrix.

8.2 Material and Methods

8.2.1 Representation of the Pore Size Distribution Curve

For the modeling of the various dynamic processes that occur in soil pore spaces, it is important to obtain an accurate representation of the pore size distribution curve, which, in turn, depends on the representation of the moisture retention curve *θ(s)*. To this end, we adopted the van Genuchten (1980) model, which relates *s* (cm) to θ ($cm^3\ cm^{-3}$):

$$W(s) = \frac{\theta(s) - \theta_r}{\Phi - \theta_r} = \left[1 + (\alpha s)^{1/(1-m)}\right]^{-m}, \tag{8.2}$$

$$s \geq 0, \theta_r \leq \theta \leq \Phi, 0 < m < 1, \alpha > 0,$$

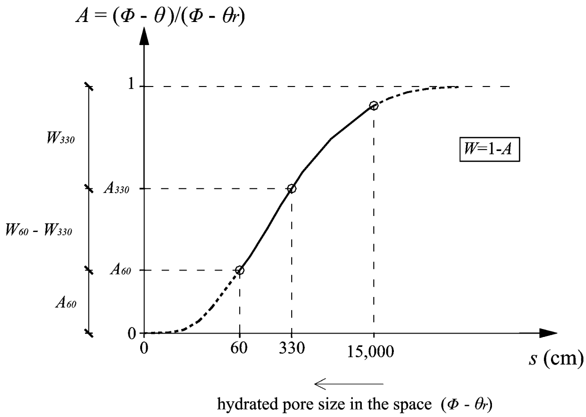

Fig. 8.1 Pore size distribution curve within the effective pore space ($\Phi - \theta_r$). For the structural classification the pore space was arbitrarily divided in three fractions: A_{60}, ($W_{60} - W_{330}$) and W_{330}. In the classification system, the curve was applied only in the suction range 60–15,000 cm (*bold line*)

where θ_r ($cm^3\ cm^{-3}$), α (cm^{-1}) and m (non-dimensional) are considered as fitting parameters, and Φ is the soil saturation moisture (or porosity) determined in laboratory. This model was chosen due to its wide use (Tomasella et al. 2000, 2003; Cornelis et al. 2005; Vereecken et al. 2010) and because its parameters can be used to fit the non-saturated hydraulic conductivity curve (van Genuchten 1980; Schaap and van Genuchten 2006). However, a high accuracy for W ($0 \leq W \leq 1$) is not expected when θ is in a very wet range (close to saturation) or very dry range (close to the residual moisture θ_r), as reported in the literature (van Genuchten 1980; Coppola 2000; Schaap and van Genuchten 2006). Therefore, Eq. 8.2 will only be applied for the intermediate range of suction, 60 cm $\leq s \leq$ 15,000 cm. It also is advantageous that θ_r may be fitted as a negative number (Dourado Neto et al. 2000). However, Ottoni and Ottoni Filho (2011) indicate that there is not a significant improvement in accuracy in the determination of the moisture retention curve if θ_r is more negative than $-0.30\ cm^3cm^{-3}$, for which reason we arbitrarily set $\theta_r \geq -0.30\ cm^3cm^{-3}$.

For the classification of an undisturbed soil sample relative to its pore space structure, the function

$$A(s) = \frac{\Phi - \theta(s)}{\Phi - \theta_r} = 1 - W(s) \tag{8.3}$$

represents the pore size distribution in terms of cumulative volumetric fraction, assuming an effective pore space between $\theta = \Phi$ ($A = 0$) and $\theta = \theta_r$ ($A = 1$) (Fig. 8.1). Effectively, this procedure allows building a parameterized and standardized pore space structural classification system that is similar to the textural classification, as shown later on.

8.2.2 Distribution Curve Parameterization Protocol

To determine function $A(s)$ (Eqs. 8.2 and 8.3) with approximately equal accuracy in its entire range (60 cm $\leq s \leq$ 15,000 cm), the three fitting parameters (θ_r, m and α)

are calculated using, correspondingly, only three experimental points of the moisture retention curve, called (s_i, θ_i), $i = 1, 2, 3$, following the protocol below:

- s_1 is the suction the closest to 60 cm, in the range of 30 cm $\leq s \leq$ 80 cm; s_2 is the suction the closest to 330 cm, in the range of $250 \leq s \leq 500$ cm, and s_3 is the suction the closest to 15,000 cm, in the range of 9,000 cm $\leq s \leq$ 18,000 cm.
- Parameters θ_r, m and α will be determined according to the procedure described by Ottoni (2009), which requires that the residuals (observed θ_i – calculated θ_i) be null, $i = 1, 2, 3$. If this is not possible, the RETC software (van Genuchten et al. 1991), with modifications to allow $\theta_r \geq -0.30$ cm^{3}cm^{-3} (Ottoni and Ottoni Filho 2011), will be used for the calculation of the three parameters. This ensures a minimization of the residuals (observed θ_i – calculated θ_i, $i = 1, 2, 3$), which would not be assured if all the water retention data points were used.

8.2.3 Definition of the Structural Families

The air availability curve "$\Phi - \theta(s)$" is the element to be grouped and classified in structural families. The values of A_{60} [$A(s = 60$ cm)], A_{330} and $A_{15,000}$ are calculated using the values of Φ, θ_r, m and α in Eqs. 8.2 and 8.3. Volumetric fractions A_{60}, $A_{330} - A_{60}$ (which is equal to $W_{60} - W_{330}$) and $1 - A_{330}$ (which is equal to W_{330}) add up to 1.0 (Fig. 8.1) and allow the determination of the structural family type of the sample when they are plotted in the pore space structural classification triangle (Fig. 8.2), here called the structural triangle.

By analogy with the textural triangle, fraction A_{60}, called the "effective air", is similar to that of sand, as it tends to be high in sandy soils. The fraction A_{60}, to a certain extent, can be interpreted as being a measure of soil aeration capacity. Fraction W_{330} tends to be high in clayey soils, as these soils usually have great affinity to water and high microporosity. W_{330} is called the "less available water fraction" and it is qualitatively similar to clay in the textural triangle. Finally, $W_{60} - W_{330}$, the "more available water fraction", is similar to the silt fraction. In fact, it is known that silty soils tend to have great water availability for plant use in the low suction range of microporosity, generally being quite appropriate soils in terms of water retention for irrigated agriculture. Although the normalized moisture $W_{15,000}$ is not used for classification purposes, it is useful in the system for the determination of θ_r. Figure 8.2 defines nine types of structural families, from type A to I, relative to plotting areas of fractions A_{60}, ($W_{60} - W_{330}$) and W_{330}. From Eq. 8.2:

$$\left(W_{60}^{-1/m} - 1\right)^{1-m} = (60/330)\left(W_{330}^{-1/m} - 1\right)^{1-m} \tag{8.4}$$

Equation 8.4 allows the calculation of m if W_{60} and W_{330} are known. The representation of the lines of equal m values in the structural triangle is shown in Fig. 8.2, reinforcing the thesis that this triangle can be viewed as a tool of graphical representation of the pore space structure. After determining the value of m,

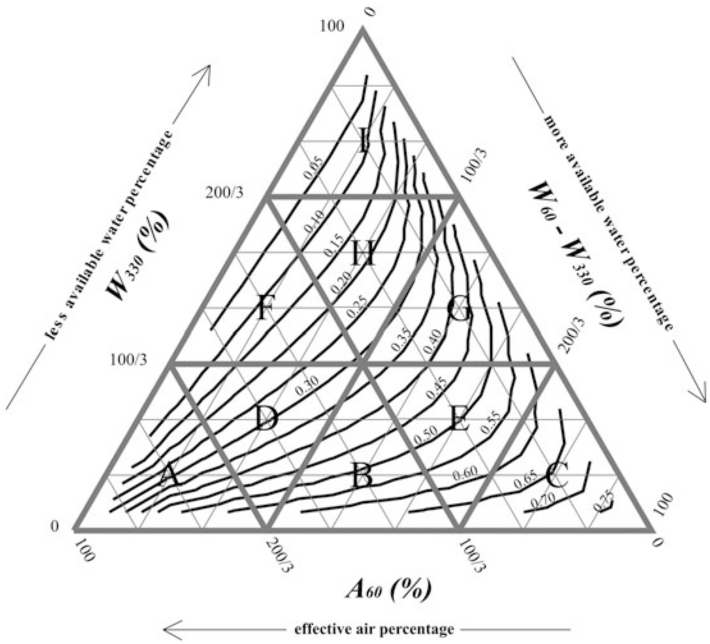

Fig. 8.2 Nine types of structural families (from A to I) defined in the pore space structural classification triangle, or simply, structural triangle. The lines of equal parameter m values are also shown

parameter α is calculated by solving Eq. 8.2 for the known value of W_{60} (or W_{330}). Thus, the pair (W_{60}, W_{330}) determines the pair (m, α).

From Eqs. 8.2 and 8.3, the air availability curve is:

$$\Phi - \theta(s) = (\Phi - \theta_r)\left\{1 - \left[1 + (\alpha s)^{1/(1-m)}\right]^{-m}\right\} = (\Phi - \theta_r)f(s)_{m,\alpha} \qquad (8.5)$$

Thus, for the perfect definition of the structural families, it is also necessary to group the soil samples in $(\Phi - \theta_r)$ value ranges. These ranges indicate the various "i" orders of the families. A soil is considered to be in the family of order i ($i \geq 1$) when

$$0.05\,(i - 1) < (\Phi - \theta_r) \leq 0.05\,i \qquad (8.6)$$

Equations 8.5 and 8.6 justify the classification of a structural family using the notation iX, where the integer number i (Arabic) represents the family order and X is the family type (from A to I). Order i groups similar values of $(\Phi - \theta_r)$ and type X groups similar (m, α) pair values. Thus, a soil can be graphically regarded in a three-dimensional space as a point with height $(\Phi - \theta_r)$ above the point where the soil is plotted in the structural triangle.

8.2.4 The Studied Soils

Samples (467) of Brazilian soils, most of them classified as Latosols and Argisols, were classified into structural families. The samples were selected by Ottoni (2009) based on the study by Tomasella et al. (2003). The database contains water contents for five suction values (60 cm, 100 cm, 330 cm, 1,000 cm and 15,000 cm) and porosity (or saturation moisture). Soil descriptions and data determination methodology can be found in Tomasella et al. (2003).

8.3 Results and Discussion

8.3.1 Parameterization of the Distribution Curve

For all samples, $s_1 = 60$ cm, $s_2 = 330$ cm and $s_3 = 15{,}000$ cm, and the three parameters, θ_r, m and α, were determined according to Ottoni (2009), by making the residuals (observed θ_i – calculated θ_i) null, $i = 1, 2, 3$. θ_r values were nearly always positive, with the exception of 47 soil samples, for which the minimum θ_r was -0.183 cm^{3}cm^{-3}. The maximum absolute residual in all cases for the validation points ($s = 100$ cm and 1,000 cm) was 0.0044 cm^{3}cm^{-3} (Ottoni 2009), which confirms the good reliability of Eq. 8.2 to represent the water retention curves.

8.3.2 Structural Families

The calculation of fractions A_{60}, $(W_{60} - W_{330})$, and W_{330} (from Φ, θ_r, m and α) led to the plotting of the 467 soil samples in the structural triangle (Fig. 8.3a). The corresponding textural triangle plot is also shown for comparison (Fig. 8.3b). The analysis of the two figures reveals two tendencies: (a) there were few soils in the silty classes (or with silt percentages over 50 %) and few soils with high $W_{60} - W_{330}$ fractions (more available water percentages over 33 %), which confirms the expectation that the materials from those textural classes tend to retain large amount of readily available water for plant use; (b) there was a large number of soils in the heavy clay class and a much smaller number in the "corresponding" class (class I) of Fig. 8.3a. This can be attributed to the "hybrid" tendency of some clayey latosols to behave hydrodynamically as soils of sandy texture (Tomasella et al. 2000), with great "effective air" ($\Phi - \theta_{60}$), which might explain the predominance in the number of samples plotted in classes D and F in Fig. 8.3a. The effective air fractions (A_{60}) of samples in these two classes are greater than those of class I.

A qualitative comparative analysis of Fig. 8.3a, b indicates a correlation between the textural and structural behavior of the soil samples, which is assumed when

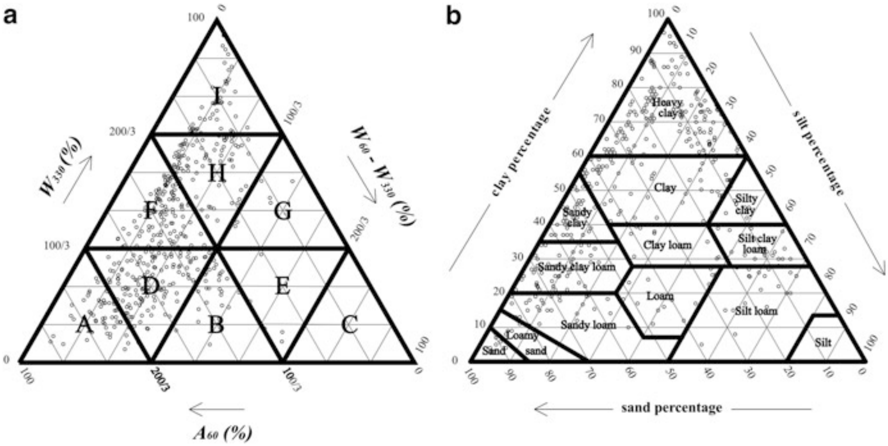

Fig. 8.3 Studied soils plotted in the (**a**) structural and (**b**) textural triangle

one uses pedotransfer functions to estimate water retention from granulometric data (Tomasella et al. 2000, 2003). This result shows the potential use of the proposed pore space classification system as a tool in the construction of pedotransfer functions.

In the soils studied, 13 orders of structural families were identified, from order 3 (0.10 $cm^3cm^{-3} < (\Phi - \theta_r) \leq 0.15\ cm^3cm^{-3}$) to order 15 (0.70 $cm^3cm^{-3} < (\Phi - \theta_r) \leq 0.75\ cm^3cm^{-3}$). Among the family types of highest sample incidence, in decreasing order, were classes D, F and H, totaling 70 % of the samples. The most frequent orders were 6, 7, 5, 8, and 9, in decreasing number of soils, totaling 68 % of the samples. The only family type which did not have any soil sample was C.

8.3.3 *Air Availability Curve Grouping*

Figure 8.4 shows the ($\Phi - \theta_r$) curves for soils in families 5A, 9A, 5 F and 9 F, as an example. The classification system was conceived to group similar air availability curves, as shown in Fig. 8.4. The similarity observed among ($\Phi - \theta$) curves for soils of the same family was confirmed for all families of the 467 samples investigated. One can see that the shape of the curves in 5A and 9A are similar to each other, as their soils correspond to the same class in the structural triangle. What distinguishes the two groups of curves is the scale of values (vertical axis), because they are of different orders. The same analysis applies to the elements of families 5 F and 9 F shown in Fig. 8.4. The curves were plotted only in the suction range allowed by the system (60 cm to 15,000 cm). If they were extrapolated to the zero suction, they would all tend to zero ($\Phi - \theta = 0$), asymptotically to the horizontal axis. As the elements of class A have a greater effective air fraction (A_{60}) than those of class F,

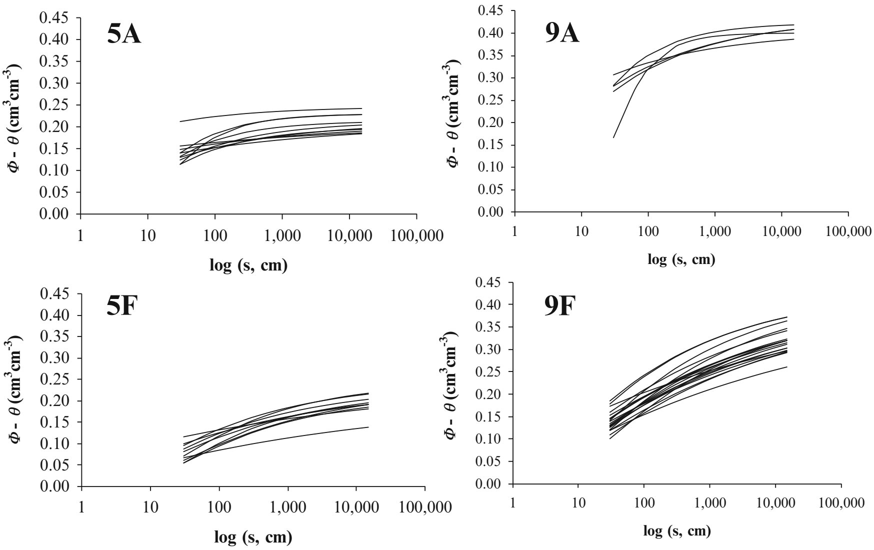

Fig. 8.4 Air availability curves for soil samples of families 5A, 9A, 5F and 9F

the effective air values ($\Phi - \theta_{60}$) of 5A soils tend to be greater than those of 5 F, which is also observed for soils in 9A and 9 F (Fig. 8.4).

8.4 Conclusions

The proposed classification system showed to be able to group soils with similar air availability curves, which lends it to potential use as an instrument of pedologic investigation and for the modeling of processes that occur in pore spaces. The proposed classification system needs to be better evaluated taking into account soils of various pedologic origins. So, we consider that we are presenting a preliminary version of the system, which may be somewhat altered with respect to pragmatic aspects of the structural family definition and nomenclature.

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