Important factors in the prediction of the soil-water retention curves of different unsaturated soils

Facteurs importants dans la prévision des courbes de rétention du sol-eau des différents sols non saturés

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ABSTRACT: The soil–water retention curve, SWRC, is a key function in analyses of the hydro-mechanical behavior of unsaturated soils. A number of equations have been suggested to represent analytically the primary boundary drying SWRC and almost all the equations suggested can be derived from a single generic form. The van Genuchten (1980) equation, VG, is one of the most commonly used in literature for predicting the SWRC. There are several published database tables which allow estimate the VG coefficients for different non-deformable soils based on soil texture. This paper discusses factors important in the prediction of the SWRC and presents some examples of predicted SWRC for different databases. The non-uniqueness of the fitted SWRC coefficient sets is also discussed in the paper, and the extrapolation of model values outside the range of input data should be avoided. The large variability of soil types and the lack of physical meaning of the fitted SWRC coefficients did not allow quantifying the variation of the VG coefficients with the particle-size distribution of the soils analyzed in this study.

RÉSUMÉ: La courbe de rétention du sol-eau, SWRC, est des fonctions essentielles dans les analyses du comportement hydromécanique des sols non saturés. Un certain nombre d'équations ont été suggéré pour représenter analytiquement la limite primaire séchage SWRC et presque toutes les équations suggérées peuvent être dérivées d'un seul formulaire générique. Le van Genuchten (1980), VG, équation est l'un des plus couramment utilisés dans la littérature pour prédire le SWRC. Il y a plusieurs tables de base de données publiée, permettant d'estiment les coefficients de VG pour différents sols indéformable, basées sur la texture du sol. Cet article discute des facteurs importants dans la prédiction de la SWRC et de comparer les coefficients VG obtenus pour différentes bases de données. Le non-unicité des ensembles de coefficients SWRC équipées est également abordée dans le livre, et l'extrapolation des valeurs du modèle en dehors de la plage des données d'entrée doit être évitée. La grande variabilité des types de sols et de l'absence de signification physique de de coefficients SWRC équipée que certaines équations utilisées pour prédire le SWRC séchage principale pourraient ne pas suffire pour décrire certaines données expérimentales.

KEYWORDS: unsaturated soil, soil-water retention, soil texture, soil hydraulic properties.

1 INTRODUCTION

Knowledge of the constitutive relationships between volumetric water content and suction called the soil–water retention (or characteristic) curves, SWRC, is essential when modeling unsaturated flow in practical applications, including clay liners in waste containment and compacted clay cores in earth dams (Bicalho et al. 2000). Typically the SWRC is highly nonlinear and exhibits a marked hysteresis, with the wetting curve differing from the drying curve. There are infinite scanning SWRC between the boundary curves (i.e., the primary boundary SWRC on drying and wetting conditions).

The SWRC is related to size and connectedness of pore spaces; hence strongly affected by particle size, shape, surface texture, and size distribution. A number of equations have been suggested to represent analytically the primary boundary drying SWRC and almost all the equations suggested can be derived from a single generic form. Most of the equations represent the general sigmoidal shape of the primary boundary drying SWRC (i.e., van Genuchten 1980, McKee and Bumb 1987, and Fredlund and Xing 1994). However, determining the fitting coefficients of these equations remains laborious and time consuming.

The van Genuchten (1980) equation, VG, is one of the most commonly used in literature for predicting the primary boundary drying SWRC equation. This paper discusses important factors in the prediction of the SWRC and presents some examples of predicted SWRC for different soils and regions. The non-uniqueness of the fitted SWRC coefficients sets is also discussed in the paper.

2 PREDICTING THE SWRC

The empirical VG equation describes a continuous SWRC function, and it is defined by:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1+(\alpha h)^n\right]^m} \quad (1)$$

where θ, θ_r and θ_s are the actual, residual and saturated volumetric water contents respectively, h (m) is the soil suction head, α (m^{-1}), n, and m are the fitting coefficients directly dependent on the shape of the SWRC. A common simplification is to assume that $m = 1 - 1/n$ (Mualem, 1976). The effect of the VG fitting coefficients on the shape of the SWRC is illustrated in van Genuchten (1980) and Leong and Rahardjo (1997).

It may be recalled that θ_s, commonly termed in geotechnical engineering as a dimensionless variable called soil porosity, has a physical basis. The soil porosity (e.g. θ_s) is defined as the ratio of the soil void volume to the soil total volume and represents a basic property of the soil. Therefore it should not be considered an adjustable fitting parameter to create the ideal data sets in predicting the primary boundary drying SWRC of a soil.

The fitting parameters are adjusted and correlated, mainly, with the soil grain-sized distribution. There are several published database tables which allow estimate the fitting coefficients for different SWRC equations and non-deformable soils based on soil texture. Some of these databases are discussed in this study: UNSODA (Schaap et al. (2001) and HYPRES (Wosten et al. 1999).

3 DATABASE INVESTIGATED

Schaap et al. (2001) developed a computer program (Rosetta) that implements five pedotransfer functions (PTFs), which are empirical relationships between the soil hydraulic properties and more easily obtainable basic soil properties available, for hierarchical estimation of the SWRC and unsaturated hydraulic conductivity. The extensive database published by Schaap et al. (2001) with values of the VG equation fitting coefficients for different sedimentary soils (about 2134 soil speciments) of temperate climate regions was determined by different experimental methods, and present incomplete information of the geotechnical properties of the soils.

Knowledge of the soil texture, saturated hydraulic conductivity (K_s) and VG coefficients is required for evaluating the correlation of the fitting VG coefficients with the soil texture. Thus, a subset of 554 soil specimens of different soils of the database UNSODA published by Schaap et al. (2001) with the required information was separated and examined herein. These soil specimens were separated according to the measured particle size ranges to evaluate the influence of the amount of fines (silt and clay-size material) in predicting the SWRC of the investigated soils. The SWRC depends far more on the fine particles (particle sizes smaller 74 μm, i.e., 200 mesh sieve) than on the large. Thus, the soil specimens were separated by the percent by weight of fines fraction (% Fines) into 10 (ten) subgroups with: 0-10%; 10-20%; 20-30%; 30-40%; 40-50%; 50-60%; 60-70%; 70-80%; 80-90%; 90-100% fines.

Suitability of the predict models appeared to be influenced by soil texture (i.e., coarse or fine soil) rather than by measured size ranges (Nemes et al. 1999). Thus, the investigated data were also separated by soil texture classes into 5 (five) subgroups according to Soil Geographical Database of Europe (Nemes et al. 1999, Wosten et al. 1999): coarse, medium, medium-fine, fine, and very fine. The separation of surface soils and subsoils was not used because it did not have this information in the evaluated experimental data. The VG coefficient set obtained in this study for each soil texture class using the database UNSODA published by Schaap et al. (2001) were then compared to the VG coefficient set obtained by Wosten et al. (1999) for different soil and region (HYPRES database) with the same soil texture class.

4 RESULTS AND DISCUSSIONS

4 .1 *Saturated hydraulic conductivity*

No other property of importance in geotechnical engineering shows as much variability in a given database as does the hydraulic conductivity. Thus the variation of the mean K_s values with the corresponding amount of fines ranges, for the subgroups of the subset data investigated in this study is shown in Figure 1. It is observed a relatively little change in the mean K_s values for the investigated subset data. The mean K_s values range from 3.65 x 10^{-5} cm/s to 1.62 x 10^{-6} cm/s, which correspond to typical saturated hydraulic conductivity values of silt sands, fine sands (Fetter, 1994).

At low fines contents (% fines < 20%), fines particles fit into the voids between sand particles, so the mean K_s values decrease with increasing the amount of fines as shown in Figure 1. A similar trend is still observed for sands containing amount of fines ranging from 20% to 40% (transition state), although within this range there is a greater scatter in the K_s values. At a certain amount of fines content, the fines fully occupies the voids, and the increase in fines content results in sand particles floating inside the fines matrix. In this case, the permeability of the mixture is defined by the permeability of the fine soil and independent of the %fines. Figure 1 suggests fines filling the voids between the sand particles for % fines > 40% for the investigated experimental database. The large scatter observed in the experimental data in the higher range of amount of fines (% fines > 40%) are indicators of the variability of the type of fines in the investigated database.

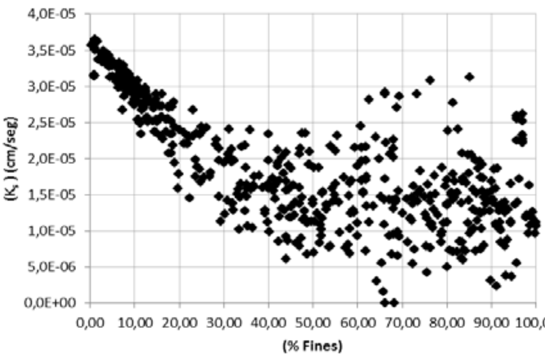

Figure 1. Variation of K_s(cm/s) with % Fines for the investigated subset of 554 samples of different sedimentary soils of the database published by Schaap et al. (2001)

Bicalho et al. (2002) investigated the influence of clayey fractions on the one-dimensional compression of clay and sand mixtures and observed that the sandy fraction (quartz) is inert in a clay-sand mixture, and the clay-sand mixture compressibility is controlled by the clay fraction for mixtures containing clay content greater than 30 percent. This percentage is expected to be even smaller for the permeability property, since it is not necessary to lose contact between the grains in order for the clay matrix to dominate the behavior of the clay-sand mixture.

4 .2 *SWRC (primary boundary drying)*

Two classification approaches have been use to define the hypothetical SWRC obtained for the mean values of the VG coefficient set obtained for the investigated database (Schaap et al. 2001), one based on measured size ranges (ten subgroups defined by fines content) and the other on the soil texture classes (five subgroups).

Figure 2 presents the hypothetical SWRC obtained for the VG coefficient set (median values) obtained for the ten different subgroups of the first classification adopted in this study. In geotechnical engineering practice and the petroleum literature, it is customary to plot suction as a function of the degree of saturation, S (equal to the volumetric water content divided by soil porosity). If the volume of the soil specimens remains constant as soil suction is increased the use of S or θ to quantify the amount of water in the soil provide essentially the same information, and can be interpreted in a similar manner (Fredlund 2004). Soil suctions are plotted as a function of degree of saturation (Figure 2) and volumetric water content (Figure 3). When plotting soil suctions as a function of volumetric water content the influence of the amount of fines in the two boundary curves (i.e, %fines = 0-10% and %fines = 90-10%) is clearly shown (Figure 3). An air entry value (AEV) < 1kPa for %fines < 10% is shown in Figure 3. Fredlund (2004) recommends to extent the soil suction scale lower than 0.1 kPa for some coarse-grained soil.

The results show large changes in the predicted SWRC for unsaturated silt sands. The data demonstrates the effects of the amount of fines in predicting the SWRC of unsaturated silty sands and the varied slopes of the relationships resulting from variable pore size distributions. It is observed that for a suction in the order of 10^2 (cm H_2O) the difference in the degree of saturation of the upper limit curve for the lower limit curve is approximately 52%. When the suction increases to 104 (cm H_2O) this difference reduces to approximately 17%.

The VG coefficients set used for defining each primary boundary drying SWRC are the median values of each sub-group of the adopted classification. They are assumed constants for a given subgroup. It was used the median, or the number found at the exact middle of the VG coefficient set values of each subgroup of the investigated database. The mean value has the disadvantage of being affected by any single value being too high or too low compared to the rest of the sub-group data.

The database published by Schaap et al. (2001) assumes that θ_r is about zero for most soils. Though a residual content is observed in most soils, some publications suggest that water will continue to drain slowly through film flow or flow through small grooves in soil grains (Simms and Yanful 2005). The VG coefficient θ_s, that is, the soil porosity varied from 0.25 to 0.82 (median values ranged from 0.37 to 0.66) for the analyzed soils. Soil porosity can range between 0 and 1, typically falling between 0.3 and 0.7 for soils (Nimmo 2004).

Because large pores fill or empty at suction near zero, a medium that has many large pores will have a SWRC that drops rapidly to low θ at high suction values. Conversely, one with very fine pores will retain much water even at highly suction values, thus having a SWRC with more gradual changes in slope (Nimmo 2004). The results are consistent, such that the upper limit SWRC (% fines > 90%) has a more gradual changes in slope and the lower limit SWRC (% fines <10%) has the majority of pores drained over a relatively low suction (a low air-entry value pressure, AEV). The soil specimen begins to desaturate when subjected to an applied soil suction greater than the AEV. It is verified that the soils with lower percentage of fines have more pronounced retention curves, with better defined stretches. Soils with higher percentages of fines have smoother curves. According to Barbour (1998), the decrease in grain size leads to an increase in the AEV and smoothes the slope of the curve.

Jhorar et al. (2002) recommended fitting at most three VG coefficients (α, n, θ_s) while fixing the value of the other three coefficients. Seaman et al. (2009) observed that n, θ_r and θ_s were the most sensitive coefficients, and α was found to be the least in predicting SWRC and movement through a coarse-textured soil profile using VG equation.

The different experimental methods used to determine the data obtained from the UNSODA database published by Schaap et al. (2001), the great variability of different soils and regions of the data, the lack of complete information of the geotechnical properties of the soils and the lack of physical meaning of the adjustment VG coefficients did not allow to define a function that quantifies the variation of the VG coefficients with the particle-size distribution of the soils analyzed in this study.

The following tendencies were observed in this study: the mean and median values of α are not related to the grain size and soil texture; The mean and median values of the VG coefficient n are related to the particle-size for % Fines<20%. Thus, VG coefficient α is not the air entry value or bubbling pressure and should not be interpreted as such (Leong and Rahardjo 1997).

It is verified that K_s and VG coefficient n have the same decreasing trend for % Fines < 20%. The value of K_s is determined by the permeability of the fine soil and the VG coefficient n appears to become an adjustment parameter for % Fines > 20%. The behavior of n for median values was similar to the behavior obtained for the mean values. The VG coefficient n ranged from 1.0145 to 10 for the investigated soils.

In the second classification approach the database published by Schaap et al. (2001) were separated according to the criteria suggested by Wosten et al. (1999). It is verified that 79% of the soil specimens are classified as coarse and medium texture classes, 19% as medium-fine and fine and only 1% as very-fine texture. One percent of the data does not fit into any textural classification suggested by Wosten et al. (1999). Silty soils are not considered in database HYPRES evaluated by Wosten et al. (1999). Therefore, these soil specimens were disregarded in this study. The five different hypothetical retention curves obtained by the second textural classification with the median values of the VG coefficient set are presented in Figure 4.

The SWRC obtained with the VG coefficient set suggested by Wosten et al. (1999) are smoother and have about the same air-entry value pressure values when compared to the same textural class of retention curves obtained with the UNSODA database (Schaap et al., 2001); The air-entry value pressures do not differ greatly between the limit subgroups: "0 to 10% fines" and "90 to 100% fines". Results tended to be sensitive to the packing porosity and more research is suggested in this case.

The median values of the VG coefficients obtained in this study for predicting de SWRC for the UNSODA database (Schaap et al. 2001) approximate the values suggested by Wosten et al. (1999) for corresponding textural classification (Tables 1 and 2), despite the variations observed in the hypothetical SWRC obtained for the two databases considered.

However, it is important to note that a similar predicted SWRC, but with different VG coefficients α and n, can be obtained (i.e., α=2.715 and n =1.2; α=2.6 and n =1.22, and α=2.3 and n =1.3). Hence, the non-uniqueness of the fitted SWRC coefficient set and the lack of physical meaning of the fitted SWRC coefficients suggest that the extrapolation of model values outside the range of input data should be avoided since the adopted VG coefficient set can be far from the real set.

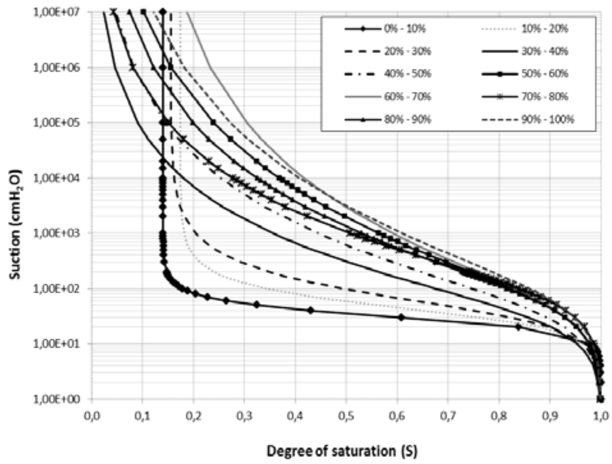

Figure 2. The hypothetical SWRC obtained for the first classification (median values of the VG coefficient set) of the database published by Schaap et al. (2001)

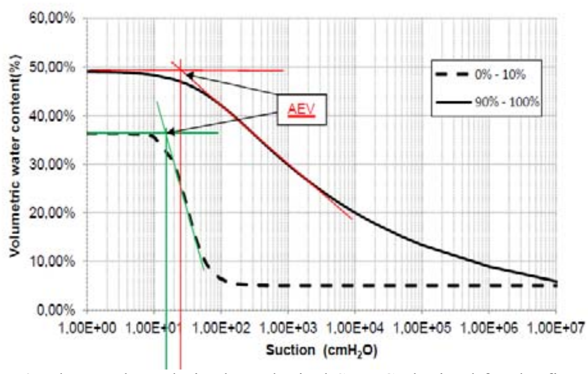

Figure 3. The two boundaries hypothetical SWRC obtained for the first classification (median values of the VG coefficient set) of the database published by Schaap et al. (2001)

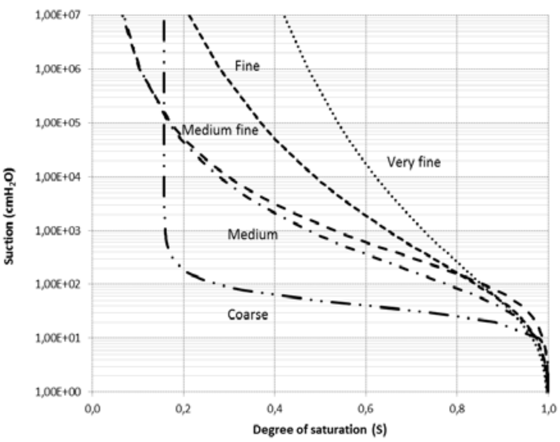

Figure 4. The five different hypothetical retention curves obtained for the second textural classification (median values of the VG coefficient set) of the database published by Schaap et al. (2001)

Table 1. Comparative VG coefficient n, median values, for two different databases: A (Schaap et al., 2001) and B (Wosten et al. 1999)

Soil texture classes	*VG coefficient n*	
	A	*B*
Coarse	2,70	1,52 -1,38
Medium,	1,25	1,17-1,18
Medium-fine	1,27	1,22-1,25
Fine	1,13	1,09-1,10
Very fine	1,10	1,07

Table 2. Comparative VG coefficient α (cm^{-1}), median values, for two different databases: A (Schaap et al., 2001) and B (Wosten et al. 1999)

Soil texture classes	*VG coefficient* α (cm^{-1})	
	A	*B*
Coarse	0,03	0,04
Medium,	0,02	0,02-0,03
Medium-fine	0,01	0,01
Fine	0,03	0,02-0,04
Very fine	0,07	0,02-0,03

5 CONCLUSIONS

The paper presents and discusses some examples of predicted SWRC for different soils and regions. Two classification approaches have been use to define the predicted SWRC: one based on measured size ranges defined by fines content and the other on the soil texture classes. The mean values of the saturated hydraulic conductivity for the data evaluated in this study correspond to typical permeability values of fine sand and silt sand. No dependence was observed between the content of fines (silt and / or clay fraction) and the coefficients of the van Genuchten equation (1980) for the data evaluated. When the percentage of fines is such that it fills all voids of the coarser particles, the classification exclusively by texture should not be used to estimate the adjustment VG coefficients. The variation in permeability with the fines content can be used to define the content of fines this happens. The large variability of soil types and the lack of physical meaning of the fitted SWRC coefficients did not allow quantifying the variation of the VG coefficients with the particle-size distribution of the soils analyzed in this study. And, the non-uniqueness of the fitted VG coefficient set shows the limitation of the use of VG equation for predicting the SWRC.

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7 REFERENCES

Barbour S.L. 1998. Nineteenth Canadian Geotechnical Colloquion: The Soil-Water Characteristic Curve: A Historical Perspective. *Canadian Geotechnical Journal,* 35, 873-894.

Bicalho K.V., Znidarcic D., and Ko H-Y. 2000. Air entrapment effects on hydraulic properties. Geotechnical Special Publication, ASCE 99:517–528.

Bicalho K. V. Cavassani M. R. P. and Castello, R. R. and Polido U. F. 2002. Características de Compressibilidade de Argilas Arenosas Moles. *8 Congresso Nacional de Geotecnia.* Lisboa. 1, 303- 312.

Fredlund D. G. (2004) Use of soil–water characteristic curves in the implementation of unsaturated soil mechanics. In: de Campos J, Marinho FAM (eds) Unsaturated soils, 3, 887–902.

Fredlund D. G. and Xing A. 1994. Equations for the soil-water characteristic curve. *Canadian Geotechnical Journal* 31, 521-532.

Jhorar R.K., W.G.M. Bastiaanssen, R.A. Feddes, and J.C. Van Dam. 2002. Inversely estimating soil hydraulic functions using evapotranspiration fluxes. *J. Hydrol.* 258, 198-213.

Leong E. C., and Rahardjo, H. 1997. A review on soil-water characteristic curve equations. *J. Geotech. Geoenviron. Eng.,* 123 (12), 1106–1117.

McKee C. R. and Bumb A. C. 1987. Flow testing coalbed methane production wells in presence of water and gas. SPE Formation Evaluation, 1200-12006.

Mualem Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porus media. Water Resource 12, 513-522.

Nemes A., Wo J.H.M., Lilly A. and Oude Voshaar J.H. 1999. Evaluation of different procedures to interpolate particle-size distributions to achieve compatibility within soil databases. Geoderma 90, 187–202.

Schaap M. G. Leij F. J. van Genuchten, Th. 2001. Rosetta a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology* 251, 63-176.

Simms P.H. and Yanful E.K. 2005. A pore-network model for hydromechanical coupling in unsaturated compacted clayey soils. *Canadian Geotechnical Journal* 42, 499–514.

van Genuchten M. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci 44, 892-898.

Wosten, J.H.M. Lilly, A. Nemes A. and Bas C. L 1999. Development and use of a database of hydraulic properties of European soils. *Geoderma* 90, 169–185.