A study to determine the correlation between characteristics diameters and air-entry value of fine-grained soil

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ABSTRACT
Historically, there has been only minor research carried out to correlate characteristic soil particle diameters with the air-entry value (AEV) for sand materials. It was found that the AEVs were strongly related to characteristic grain size diameters, specifically D_{30} and D_{50}. The current research undertakes a similar study to determine correlation(s) between characteristic diameters and AEV for clay and silt material. The purpose was to determine whether it would be possible to estimate a grain size distribution for a given soil water characteristic curve (SWCC) or vice versa. This study demonstrates that there are not correlations for clay soils, most likely due to the electrostatic nature of clay particles. Because the SWCC is a measure of pore-space distribution and is not necessarily related to the grain-size distribution of the soil, there are considerable difficulties with the prediction of the AEV in clay soils when using grain size distributions alone. This difficulty is due to the presence of the diffuse double layer and its interaction with the pore-water that changes the effective pore diameter. This interaction thereby affects the corresponding SWCC by drastically reducing the predicted pore-size distribution. This paper presents the findings and suggests a path forward for confirming the hypothesis.

RÉSUMÉ
Historiquement, seules des recherches mineures ont été menées pour corréler les diamètres caractéristiques des particules de sol avec la valeur d'entrée d'air (AEV) pour le sable. Il a été constaté que les AEV étaient fortement corrélés aux diamètres caractéristiques, en particulier D30 et D50. La recherche actuelle entreprend une étude similaire pour déterminer la ou les corrélations entre les diamètres caractéristiques et l'AEV pour les matériaux argileux et limoneux. Le but était de déterminer s'il serait possible d'estimer une distribution granulométrique pour une courbe caractéristique de l'eau du sol (SWCC) donnée ou vice versa. Cette étude démontre qu'il n'y a pas de corrélations pour les sols argileux, probablement en raison de la nature électrostatique des particules d'argile. Étant donné que le SWCC est une mesure de la distribution de l'espace poreux et qu'il n'est pas nécessairement lié à la distribution granulométrique du sol, il existe des difficultés considérables avec la prédiction de l'AEV dans les sols argileux lors de l'utilisation des distributions granulométriques seules. Cette difficulté est due à la présence de la double couche diffuse et à son interaction avec l'eau interstitielle qui modifie le diamètre effectif des pores. Cette interaction affecte ainsi le SWCC correspondant en réduisant considérablement la distribution prédite de la taille des pores. Cet article présente les résultats et suggère une voie à suivre pour confirmer l'hypothèse.

1 INTRODUCTION

Unsaturated soil problems are commonly encountered in many environmental and geotechnical applications. The soil water characteristic curve (SWCC) is the relationship between matric suction and volumetric water content. The SWCC is the most fundamental concept in analyzing unsaturated problems such as seepage, shear strength, volume change, air flow, and heat flow (Fredlund, Rahardjo and Fredlund 2012).

Retention of water in soils is controlled by the capillarity of soil particles where water is retained in the soil pores and the surface tension of water. The air-entry value (AEV) is the highest negative pore pressure (matric suction) that the soil can withstand while still being saturated. Beyond this value, the pores will be drained by the penetration of air into the pore spaces. The SWCC is strongly dependent on the pore size which is created by the arrangements of soil particles in the soil structure. The smaller the pore size, the higher the capillary water rises; thus, higher suction is required to drain finer pores of water (Fredlund, Rahardjo and Fredlund 2012).

Due to the relationship between grain size distribution (GSD) and the pore size distribution (PSD), GSD is typically used as a means to predict the SWCC. Past research that utilized the GSD to predict a corresponding SWCC are presented by Arya and Paris (1981), Fredlund (2000), Perera, et al. (2005), and Vanapali and Catana (2005).

Sakaki et al. (2014), attempted to determine an empirical relationship between AEV and characteristic particle diameters (D_{10}, D_{20}, D_{30}, …, D_{90}). Sakaki et al. (2014) found that measured AEVs are highly correlated to smaller particle diameters (D_{10} to D_{50}) and less with particle diameters larger than D_{50}. The authors explained the reason was due to AEV is influenced by the largest pores where the smaller particles tend to fall into the larger pores, thereby reducing the characteristic pore volume. Therefore, although larger pores are formed by larger particles, the overall pore sizes are influenced by the smaller particles filling the pores between larger particles. For the sands examined by Sakaki et al. (2014), the AEVs showed the highest correlation to D_{30} and D_{50}.

The limitation of Sakaki et al. (2014) is that the correlations were only applicable to coarse grained (sand) materials. To expand on their research, this study was conducted to determine the correlations between AEV and characteristic particle diameters of fine-grained soils.

2 METHODOLOGY

SWCC and GSD data of 25 fine-grained soils were acquired from published literature presented in Nguyen (2022). Linear regression analysis was then performed on the soils reported in the literature to determine the correlations between AEV and characteristic particle diameters (D_{10}, D_{20}, D_{30}, …, D_{90}) of the collected soils. A coefficient of determination, R^2, 95% prediction interval, and residual value plot were used to determine the accuracy of these correlations. The 95% prediction interval was calculated using the following equations:

$$y_0 \pm t_{(1-\alpha/2,n-2)} \times Syx\sqrt{(1+\frac{1}{n}+\frac{(x_0-\bar{x})^2}{SSx})} \qquad (1)$$

where y_0 is the predicted value of the response when the predictor is x_0, $t_{(1-\alpha/2,n-2)}$ is the t-multiplier, α is the threshold value for statistical significance, n is the sample size, Syx is the standard error of estimate, $\bar{x}$ is the mean of the sample, and SSx is the sum of squared deviations from the mean of the sample. The t-multiplier value, Syx, SSx, and R^2 were determined using the built-in feature of Excel.

The residual value was determined by subtracting the predicted value from the measured value. The closer the residual value to zero, the smaller the differences between the measured and predicted values.

3 RESULTS AND DISCUSSIONS

Linear regression results showed that there was no correlation between the AEV and all characteristic particle diameters. As an example of the determined result, Figure *1* shows the linear regression analysis between D_{50} and AEV of the published fine-grained soils. As shown in Figure *1*, the prediction interval AEV based on D_{50} was determined to be between 10 – 2,000 kPa. R^2 value for this relationship was determined to be 7%. Figure *2* presents the residual value plot which shows considerable scatter around the horizontal zero line indicates large differences between the measured and predicted AEV. These factors all indicate that the determined relationship between D_{50} and AEV is also poorly correlated. Other relationships between other characteristic particle diameters and AEV all demonstrated similar results to D_{50} and AEV relationship with large prediction interval, low R^2 value, and large scatter on the residual value plots.

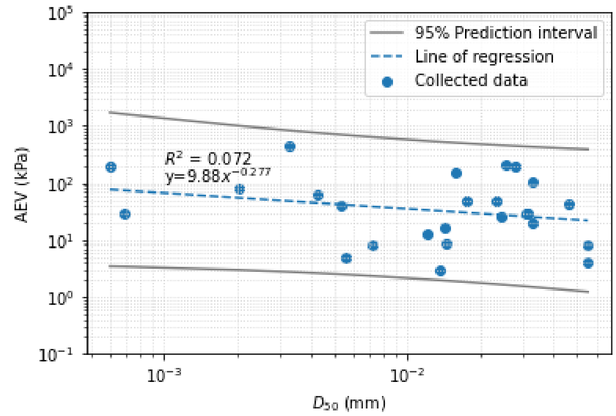

Figure 1: Linear regression of D_{50} and AEV relationship of published fine-grained soil

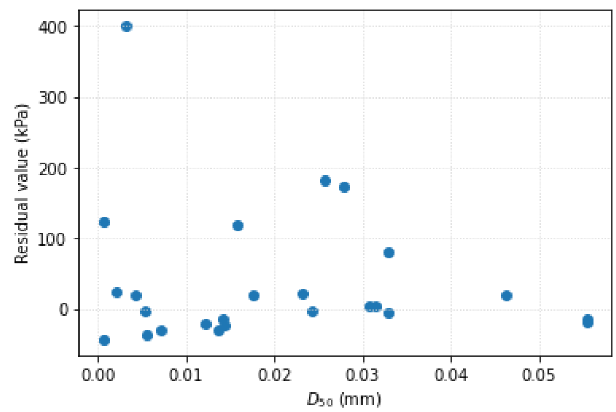

Figure 2: Residual plot of D_{50} and AEV relationship for fine-grained soil

The lack of relationship between AEV and characteristic particle diameters for fine-grained soils is due to the electrostatic nature of clay particles. According to Bhattacharjee (2016), when the clay particles are suspended in an electrolyte, a layer of counter-ions is strongly bonded on the clay's surface; this layer is termed as the Stern layer. Outside of this layer, the electrostatic attraction from the clay's surface is still active but decreases with distance. Due to this process, another layer, consisting of both cations and anions, grows beyond the Stern layer. This layer is known as the Gouy-Chapman layer. These two layers form what is commonly known as the double diffusive layer (DDL).

The DDL was found to affect the hydraulic conductivity and swelling in clay soils (Xu, Liao and Li 2008). Therefore, the DDL has effect on the pore-water interaction which is also affected by the PSD. The DDL would essentially affect the PSD, the water capacity of the soil and its ability to transmit pore-water under a given pressure change which is represented by the SWCC.

Further investigation was conducted on published fine-grained soils data and is given in Nguyen (2022). The published data was divided into their respective classifications of silt and clay. A linear regression analysis was once again conducted on soils classified as silt. It was expected that a correlation might be discovered as silt particles do not exhibit electrostatic properties.

Figure *3* presents the linear regression analysis of the D_{80} and AEV relationship. The prediction interval was much narrower to the line of regression, with values ranging between 2 – 200 kPa. The R^2 value for this relationship was determined to be approximately 97%. Figure *4* shows the residual value plot for the relationship between D_{80} and AEV. The residual values are effectively zero, indicating a small difference between the recorded and predicted values. These factors all indicate that there is a good correlation between D_{80} and AEV for silt dominant fine-grained soils which expressed as:

$$AEV = 0.0014x^{-3.177} \quad (1)$$

Although the linear regression analysis indicates a strong correlation, it is important to note that the relationship is statistically insignificant due to the small data set. The effect of the coefficient of uniformity, C_u, was not analyzed because some published data lacked sufficient information needed to calculate C_u.

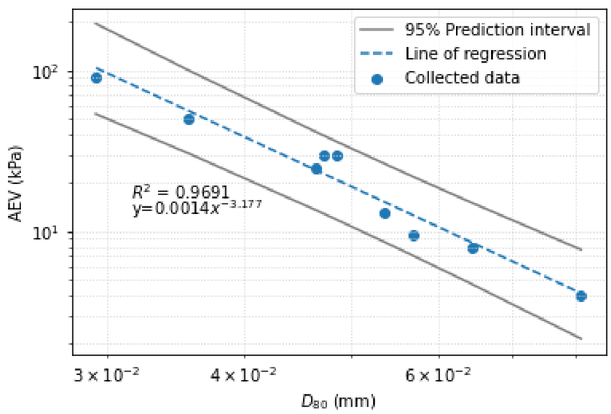

Figure 3: Linear regression D_{80} and AEV relationship of silt classified soils

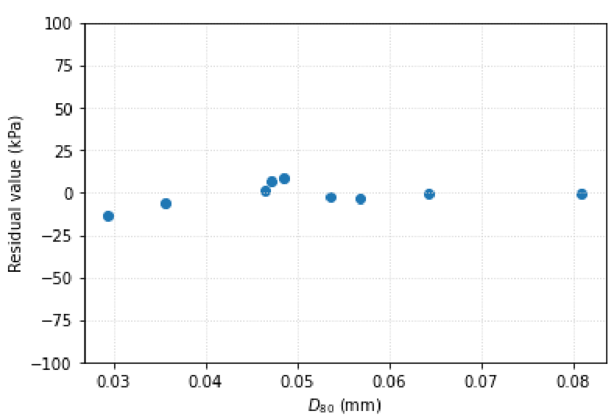

Figure 4: Residual plot of D_{80} and AEV relationship for silt classified soils

Sakaki et al. (2014) determined that D_{30} and D_{50} correlated well to the AEV for sand material. Sakaki et al. (2014) explained that the smaller particles had a greater influence on the AEV due to smaller particles tend to fall into bigger voids. This reduces the influence of larger voids on the AEV. The D_{80} and AEV relationship for silt dominant fine-grained soils determined in this research suggested the opposite. Meaning that larger particles have a greater influence on the AEV. A possible explanation is that, for a silt soil, there is a likelihood that C_u range would be small. A small Cu would suggest that the if the material is predominately silt, then the particle sizes would be relatively uniform and there would be little room for other particles to fill the voids of "larger" particles. In this instance, then the assumption that large voids control capillarity would be valid. This assumption is confirmed in the companion paper to this study (Nguyen and Elwood 2022), which shows that D_{30} better represents the AEV for a silty fine sand. In this case, the finer soils were able to move into the relatively large voids created by the larger sand particles. Because the voids are effectively filled, then the capillarity would be controlled by the reduced overall pore space.

4 CONCLUSION

Data of 25 fine-grained soils were collected from published literature to conduct linear regression analysis to determine the relationship between AEV and characteristic particle diameters. The results presented in this study showed that there were no correlations between characteristic diameters and AEV for fine-grained soils. The reason for this is most likely due to the charged clay particles that creates the DDL which affects the pore-water interaction and the PSD. As the SWCC is highly dependent on the PSD, the DDL would have a considerable effect on the SWCC. It is recommended for future research that a third variable of zeta potential should be considered and compared. The zeta potential would most likely explain the change in effective pore size affected by the DDL as it determines the electrostatic repulsion of adjacent particles. If the zeta potential is high, the particles will remain dispersed and vice versa. Understanding this factor is crucial in establishing the relationship between particle diameters to AEV of fine-grained soils (Hanaor, et al. 2011).

When the researched soils were divided into their respective classification of silt and clay, a relationship between D_{80} and AEV was discovered for silt dominant fine-grained soils. However, this relationship is currently statistically insignificant due to the small number of data points reported. More data on silt soils is needed to confirm the D_{80} and AEV relationship. This result showed a contradiction to existing research which stated that smaller particles have more influence on the AEV. A possible explanation was that due to the likelihood of silt soils having a small C_u range which indicated a small difference between large and small particles.

5 REFERENCES

Arya, Lalit M., and Jack F. Paris. 1981. "A Physicoempirical Model to Predict the Soil Moisture Characteristic from Particle Size Distribution and Bulk Density

Data." *Soil Science Society of America* 1023-1030.

Bhattacharjee, Sourav. 2016. "DLS and zeta potential–What they are and what they are not?" *Journal of Controlled Release* 337-351.

Bruch, Philip G. 2008. *Laboratory study of evaporative fluxes in homogeneous and layered soils.* PhD Thesis, Saskatoon: University of Saskatchewan.

Cai, Guoqing, Annan Zhou, Runze Xu, and Chengang Zhao. 2020. "Soil water retention behavior and microstructure evolution of lateritic soil in the suction range of 0-286.7 MPa." *Acta Geotechnica 15, no. 12* 3327-3341.

Chen, Yonghui, Bingyi Li, Yuntao Xu, Yunpeng Zhao, and Jie Xu. 2019. "Field study on the soil water characteristics of shallow layers on red clay slopes and its application in stability analysis." *Arabian Journal for Science and Engineering 44, no. 5* 5107-5116.

Fredlund, D.G., H. Rahardjo, and M.D. Fredlund. 2012. *Unsaturated Soil Mechanics in Engineering Practice.* John Wiley & Sons.

Fredlund, Murray Delwyn. 2000. "The Role of Unsaturated Soil Property Functions in the Practice of Unsaturated Soil Mechanics." Saskatoon.

Hanaor, Dorian, Marco Michelazzi, Cristina Leonelli, and Charles C Sorrell. 2011. "The effects of carboxylic acids on the aqueous dispersion and electrophoretic deposition of ZrO 2." *Journal of the European Ceramic Society* 32: 235-244.

Hashem, Elham Bani. 2013. *Volume change consideration in determining appropriate unsaturated soil properties of geotechnical applications.* PhD Thesis, Phoenix: Arizona State University.

Jamie, M., H. Guiras, K. Ben Hamouda, M. Hatira, and S. Olivella. 2008. "A study of the slope stability in unsaturated marly clay soil." *Studia Geotechnica et Mechanica 30, no. 1-2* 95-106.

Kassab, A., Kamal Mohamed Hafez Ismail, Waleed Hamdy Elkamash, and Azza Hassan. 2021. "Shear strength behavior of unsaturated clay." *Life science Journal 18, no. 5.*

Marcotte, B. A., and I. R. Fleming. 2019. "The role of undrained clay soil subgrade properties in controlling deformations in geomembranes." *Geotextiles and Geomembranes 47, no .3* 327-335.

Nguyen, Minh. 2022. *An interative program to back analyze grain-size distribution from a predetermined soil-water characteristic curve.* M.Sc Thesis, Saskatoon: University of Saskatchewan.

Nguyen, Minh, and David Elwood. 2022. "An iterative method to estimate grain-size distribution from woil water characteristic curve." *GeoCalgary 2022.* Calgary.

Park, Kevin D. 2005. *Evaluation of a geosynthetic capillary break.* PhD Thesis, Saskatoon: University of Saskatchewan.

Peranić, Josip, Željko Arbanas, Sabatino Cuomo, and matej Maček. 2018. "Soil-water characteristic curve of residual soil form a flysch rock mass." *Geofluids.*

Perera, Y. Y., C. E. Zapata, W. N. Houston, and S. L. Houston. 2005. "Prediction of the Soil- Water Characteristic Curve Based on Grain-Size-Distribution and Index Properties." *Advances in Pavement Engineering .* 1-12.

Pham, Hung Q. 2005. *A volume-mass constitutive model for unsaturated soils.* PhD Thesis, Saskatoon: University of Saskatchewan.

Pham, Hung Q., and Delwyn G. Fredlund. 2008. "Equations for the entire soil-water characteristic curve of a volume change soil." *Canadian geotechnical journal 45, no. 4* 443-453.

Rahardjo, Harianto, Alfrendo Satyanaga, Haneena Mohamed, Sabrina Chui Yee Ip, and Rishi Suryankant Shah. 2019. "Comparison of soil-water characteristic curves from conventional testing and combination of small-scale centrifuge and dew point methods." *Geotechnical and Geological Engineering 37, no. 2* 659-672.

Reina-Leal, Carlos R., Ceasar S. Ramirez, and Julio E. Colmenares. 2019. "Influence of the organic matter content on the woil water retention characteristics of reconstituted kaolinitic clay." *Japanese Geotechnical Society Special Publication 7, no. 2* 439-444.

Saadeldin, Ramy, and Amr Henni. 2016. "A novel modeling approach for the simulation of soil-water interaction in a highly plastic clay." *Geomechanics and Geophysics for Geo-Energy and Geo-Resources 2, no. 2* 77-95.

Sakaki, Toshihiro, Mitsuru Komatsu, and Manabu Takahashi. 2014. "Rules-of-Thumb for Predicting Air-Entry Value of Disturbed Sands from Particle Size." *Soil Science Society of America* 454-464.

Smethurst, J. A., Derek Clarke, and William Powrie. 2011. "Seasonal changes in pore water pressure in a grass-covered cut slope in London Clay." *In Stiff Sedimaentary Clays: Genesis and Engineering Behaviour: Geotechnique Symposium* 337-351.

Swanson, D. A., G. Savci, G. Danziger, R. N. Mohr, and T. Wiskopf. 1999. "Predicting the soil-water characteristics of mine soils." *Tailings and Mine Waste, vol. 99* 345-349.

Tadza, Mohd Yuhyi Mohd. 2011. *Soil-water characteristic curves and shrinkage behaviour of highly plastic clays: an experimental investigation.* PhD Thesis, Ann Arbor: Proquest LLC.

Vanapalli, S. K., A. Wright, and D. G. Fredlund. 2000. "Shear strength behavior of a silty soil over the suction range from 0 to 1000000 kPa." *Proceedings of the 53rd Canadian Geotechnical Conference.* Montreal. 15-18.

Vanapalli, S. K., D. G. Fredlund, D. E. Pufahl, and A. W. Clifton. 1996. "Model for the prediction of shear strength with respect to soil suction." *Canadian geotechnical journal 33, no. 3* 379-392.

Vanapalli, Sai K., and M. Cevat Catana. 2005. "Estimation of the Soil-Water Characteristic Curve of Coarse-grained Soils Using One Point Measurement and Simple Properties." *International Symposium on Advanced Experimental Unsaturated Soil Mechanics.* 401-410.

Vanapalli, Sai Krishna. 1996. *Simple test procedures and their interpretation in evaluating the shear strength of an unsaturated soil.* PhD Thesis, Saskatoon: University of Saskatchewan.

Wong, Jonathan, and David Elwood. 2018. "Cone Penetration Testing in Unsaturated Soil with Matric Suction Measurement."

Xu, C., X. Y. Liao, and Z. B. Li. 2008. "Influence of Solution Characteristics on Swelling and Hydraulic Performance of Geosynthetic Clay Liners." In *Geosynthetics in Civil and Environmental Engineering*, by C. Xu, X. Y. Liao and Z. B. Li, 58-63. Berlin, Heidelberg: Springer Berlin Heidelberg.

Xu, Xu-tang, Wen-bin Jian, Neng-sen Wu, Xiang Xu, and Lian-jin Shao. 2020. "Void ratio-dependent water retention model for a deformable residual clay." *Internation Journal of Geomechanics 20, no. 8* 04020131.

Zhang, Xiwei, Maria Mavroulidou, and Michael J. Gunn. 2017. "A study of the water retention curve of lime-treated London clay." *Acta Geotechnica 12, no. 1* 23-45.

Zhao, Gui-tao, Wei-lie Zou, Han Zhong, Dong-xing Wang, and Xie-qun Wang. 2021. "Evolution of woil-water and shrinkage characteristics of an expansive clay during freeze-thaw and drying-wetting cycles." *Cold Regions Science and Technology 186* 103275.