A simple method of estimating soil-water characteristic curve using point pedotransfer functions

L. Zou i) and E.C. Leong ii)

i) PhD Student, School of Civil & Environmental Engineering, Nanyang Technological University, Blk N1, 50 Nanyang Avenue, Singapore.

ii) Associate Professor, School of Civil & Environmental Engineering, Nanyang Technological University, Blk N1, 50 Nanyang Avenue, Singapore.

ABSTRACT

The soil-water characteristic curve (SWCC) is an essential property in unsaturated soil mechanics. The test methods to determine SWCC are mainly adopted or adapted from either soil science or agriculture. Determining the SWCC is very labour intensive and time-consuming. Hence, many pedo-transfer functions (PTFs) for SWCC were developed in soil science and agriculture. The PTFs can be grouped into point and parametric PTFs. The point PTFs give the water contents at several suctions while the parametric PTFs give the values of the parameters in SWCC equations. The suctions commonly used in point PTFs are 4 (or 3), 10, 33, 100 and 1500 kPa. In this paper, a simple method is proposed to estimate unimodal SWCC using an ensemble of point PTFs. The proposed method is illustrated using six coarse-grained and six fine-grained soils from literature. The results show that the proposed method is able to estimate a unimodal SWCC with good accuracy.

Keywords: Soil-water characteristic curve, pedotransfer function, fine-grained soil, coarse-grained soil

1 INTRODUCTION

The soil-water characteristic curve (SWCC) is an essential property in unsaturated soil mechanics. The SWCC can be determined either directly by laboratory tests or indirectly by pedotransfer function (PTF) using routinely measured soil properties, such as grain-size distribution (GSD), index properties and dry density or void ratio.

The tests that directly measure the SWCCs are not easily accessible and are often extremely time-consuming and labour intensive. Many indirect methods of estimating the SWCC using routinely measured physical properties, such as, GSD, index properties and dry density or void ratio, have been proposed (e.g., Arya and Paris, 1981; Rawls et al., 1982; Saxton et al., 1986; Tomasella and Hodnett, 1998; Scheinost et al., 1997; Mayr and Jarvis, 1999; Minasny et al., 1999). Such methods are commonly referred to as pedotransfer functions (PTFs).

Point PTFs assume that the water content at a particular suction is dependent on the soil texture (sand, silt, clay and organic contents and or) soil structure (dry density or void ratio). The most common method used to develop point PTFs is to employ multiple linear regression to determine the relationship of water content at one particular suction with other soil properties (Minasny et al., 1999). Table 1 to Table 5 summarize the regression coefficients of point-estimation PTFs for point PTFs at suctions of 4 (or 3), 10, 33, 100 and 1500 kPa, respectively. In Table 1 to Table 5, $S_a$, $S_i$, $C_l$ and $O_C$ represent sand, silt, clay and organic contents, respectively, and $\rho_d$ is dry density, which is defined as the ratio of the mass of the soil solids, $M_s$, to the total volume of soil, $V$.

Pedotransfer functions can be divided into three types: point, parametric and physico-empirical PTFs. Point PTFs estimate water content at a particular suction level using GSD or other physical properties of the soil. The parametric PTFs assume that the SWCC can be adequately described by a SWCC equation and relate the parameters in the SWCC equation with GSD and other physical properties of the soil. The physico-empirical PTFs can be considered as a subset of point PTFs as physico-empirical PTFs also estimate the water content at a particular suction level. The approaches that can be used to determine the SWCCs are summarized in Figure 1.
Point PTFs estimate the soil water content at one suction level. Point PTFs were mainly developed to determine the available soil water for plants and crops (Minasny et al., 1999). The most common suction levels used in point PTFs are at 10, 33 kPa (corresponding to field capacity) and at 1500 kPa (corresponding to permanent wilting point). In some point-estimation PTFs, 4 (or 3) kPa and 100 kPa were also used. For coarse-grained soils, the water content at 4 (or 3) kPa is very important. Hence, point PTFs at suctions of 4 (or 3), 10, 33, 100 and 1500 kPa will be discussed in this paper.

$$\rho_d = \frac{M_s}{V}$$  \hspace{1cm} (1)

Table 1 to Table 5 are non-exhaustive but the number of PTFs at each suction level is indicative that the more common PTFs were developed for suctions at 33 and 1500 kPa which correspond to the field capacity and the permanent wilting point, respectively.

2 ENSEMBLE POINT PTFS

Zou (2018) evaluated point PTFs at suctions of 4 (or 3), 10, 33, 100 and 1500 kPa using a soil database comprising of 250 soils which includes 60 soils from Andersson and Wiklert (1972), 60 soils from Jauhiainen (2004) and 130 soils from UNSODA (Nemes, et al., 2001). The data collated from the literature covers a wide region so that specificity bias of the point PTFs is eliminated in the evaluation. In addition, Zou (2018) conducted the evaluation by separating the soils into coarse and fine-grained soils according to Chin et al. (2010) definition, i.e., coarse-grained soils are soils where percent passing no. 200 Sieve (P200) is less than 30% and fine-grained soils are soils where P200 is equal or greater than 30%. Zou (2018) found that separating the soils into coarse and fine-grained soils gave better performance than not separating the soils into coarse and fine-grained soils.

The best performing point-estimation PTFs for coarse-grained and fine-grained soils for various suction levels are summarized in Table 6. Hence, Table 6 provides the ensemble of PTFs for estimating SWCC of coarse and fine-grained soils.

3 ESTIMATING SWCC USING ENSEMBLE POINT PTFS

Point PTFs are commonly used in soil science and agriculture to estimate the field capacity and permanent wilting point. However, PTFs are not commonly applied in unsaturated soil mechanics (Zou and Leong, 2017). The best performing PTFs at each suction level have been identified as summarized in Table 6. Using an ensemble of PTFs, a quick estimate of SWCC can be obtained for suctions at 4, 10, 33, 100 and 1500 kPa. Five SWCC points are sufficient to determine a continuous unimodal SWCC by fitting the five points with a unimodal SWCC equation, such as Fredlund and Xing (1994) equation.

Six soils from UNSODA database (Nemes, et al., 2001), which include three fine-grained (Soils 1360, 1164, 2361) and three coarse-grained soils (Soils 4650, 1090, 1460), are used to demonstrate the SWCC estimated from the ensemble PTFs. The properties of the six soils are summarized in Table 7. The SWCCs are presented in Figure 2. To avoid unreasonable values of soil suction in the Fredlund and Xing (1994) SWCC parameters during curve fitting, constraints were applied to the parameters given in Chin et al. (2010). For coarse-grained soils, $1.2 < a < 3.5$ kPa, $0.85 < n < 10.3$, $0.59 < m < 1.17$, and $\psi_r = 100$ kPa; for fine-grained soils, $0 < a < 722$ kPa, $0 < n < 0.68$, $0 < m < 0.81$, and $500 < \psi_r < 914$ kPa. The ensemble PTFs provide good estimates of the water contents at 4, 10, 33, 100 and 1500 kPa, and hence, a good estimation of the SWCC can be obtained.
Table 1 Summary of the regression coefficients of point-estimation PTFs suction of 4 (or 3) kPa

| S/N | Reference                        | Sa  (%) | Si  (%) | Cl  (%) | OC (%) | $\rho_d$ (Mg/m$^3$) | $\rho_d^2$ (Mg$^2$/m$^6$) | Intercept |
|-----|----------------------------------|---------|---------|---------|--------|---------------------|---------------------------|-----------|
| 1   | Gupta and Larson (1979)          | 0.71    | 1.024   | 1.01    | 0.633  | -32.12              | -                         |           |
| 2   | Rawls et al. (1982)              | -0.4    | -       | -       | 1.000  | -13.15              | 78.99                    |           |
| 3   | Tomasella and Hodnett (1998)*    | -       | 0.552   | 0.26    | -      | -                   | 18.50                    |           |

*Point-estimation PTF estimated water content at suction of 3 kPa

Table 2 Summary of the regression coefficients of point-estimation PTFs suction of 10 kPa

| S/N | Reference                        | Sa  (%) | Si  (%) | Cl  (%) | OC (%) | $\rho_d$ (Mg/m$^3$) | $\rho_d^2$ (Mg$^2$/m$^6$) | Intercept |
|-----|----------------------------------|---------|---------|---------|--------|---------------------|---------------------------|-----------|
| 1   | Pidgeon (1972)*                  | 0.18    | 0.34    | 1.65    | -      | -                   | 5.32                      |           |
| 2   | Hall et al. (1977)               | -0.30   | -       | -       | -      | -                   | 36.40                     |           |
| 3   | Lal (1979)*                      | 0.05    | 0.85    | 0.89    | 0.50   | -24.23              | -                         |           |
| 4   | Gupta and Larson (1979)          | -0.30   | -       | 0.23    | 3.17   | -                   | 41.18                     |           |
| 5   | Rawls et al. (1982)              | -0.4    | -       | -       | -      | -                   | 10.88                     |           |
| 6   | Battjes (1986)                   | -0.54   | 0.32    | -       | -      | -                   | 9.81                      |           |
| 7   | Dijkerman (1988)                 | -0.38   | -       | -       | 12.4   | -                   | 34.3                      |           |

Note: (1) Sand: 50-2000 μm (* 20-2000 μm); Silt: 2-50 um (* 2-20 μm); Clay: < 2 μm.
(2) *estimated water content is gravimetric water content.

Table 3 Summary of the regression coefficients of point-estimation PTFs at suction of 33 kPa

| S/N | Reference                        | Sa  (%) | Si  (%) | Cl  (%) | OC (%) | $\rho_d$ (Mg/m$^3$) | $\rho_d^2$ (%)*Mg/m$^6$ | Intercept |
|-----|----------------------------------|---------|---------|---------|--------|---------------------|--------------------------|-----------|
| 1   | Rawls et al. (1982)              | -0.20   | -       | 0.36    | 2.99   | -                   | 25.76                    |           |
| 2   | Pidgeon (1972)*                  | -0.17   | 0.32    | 1.58    | -      | -                   | 3.80                     |           |
| 3   | Hall et al. (1977)               | -0.12   | 0.45    | -       | -5.95  | -                   | 20.81                    |           |
| 4   | Lal (1979)*                      | -0.30   | -       | 0.40    | -      | -                   | 33.40                    |           |
| 5   | Gupta and Larson (1979)          | 0.31    | 0.59    | 0.80    | 0.22   | -14.34              | -                       |           |
| 6   | Aina and Perisawamy (1985)       | -0.55   | -       | -       | -0.13  | -                   | 57.88                    |           |
| 7   | Beke and MacCormick (1985)       | -0.50   | -       | -       | -0.23  | -                   | 64.37                    |           |
| 8   | Dijkerman (1988)                 | -0.35   | -       | -       | -      | -                   | 36.97                    |           |
| 9   | Macronique et al. (1991)*        | -0.23   | -       | 0.23    | -28.44 | -                   | 57.84                    |           |
| 10  | Battjes (1996)                   | -0.46   | 0.30    | 2.07    | -      | -                   | -                       |           |
| 11  | Tomasella and Hodnett (1998)     | -0.43   | 0.40    | -       | -      | -                   | 4.05                     |           |
| 12  | Oliveira et al. (2002)*          | -0.33   | 0.39    | -       | -      | -                   | -                       |           |
| 13  | Mohamed and Ali (2006)           | -0.14   | -       | -       | -      | -                   | 37.68                    |           |
| 14  | Reichert et al. (2009)*          | -0.29   | 0.29    | 0.93    | -4.80  | -                   | 10.60                    |           |
| 15  | Dashiaki et al. (2010)           | -0.28   | -       | -       | 17.1   | -                   | 14.1                     |           |

Note: (1) Sand: 50-2000 μm (* 20-2000 μm); Silt: 2-50 um (* 2-20 μm); Clay: < 2 μm.
(2) *estimated water content is gravimetric water content.

4 CONCLUSION

Point pedotransfer functions (PTFs) are commonly used in soil pedotransfer and agriculture to estimate the water content at suction of 4 (or 3) kPa, 10 kPa, 33 kPa, 5 PTFs for 100 kPa and 21 PTFs for 1500 kPa) using 250 soils and found the best performing PTFs at each suction level. In addition, better performance was obtained when the soils are divided into coarse and fine-grained soils according to Chin et al. (2010). Using

Zou (2018) have evaluated a number of point PTFs (3 PTFs for 4 (or 3) kPa, 11 PTFs for 10 kPa, 18 PTFs for 33 kPa, 5 PTFs for 100 kPa and 21 PTFs for 1500 kPa) using 250 soils and found the best performing PTFs at each suction level. In addition, better performance was obtained when the soils are divided into coarse and fine-grained soils according to Chin et al. (2010). Using
the best performing point PTFs to form an ensemble PTF, a quick estimate of SWCC can be obtained at suctions of 4, 10, 33, 100 and 1500 kPa. The proposed method was illustrated for six soils. The estimated SWCCs show a good agreement with the experimental SWCCs. Such ensemble PTF provide an alternative method to estimate unimodal SWCC and should be further explored in unsaturated soil mechanics.

Table 4 Summary of the regression coefficients of point-estimation PTFs at suction of 100 kPa

| S/N | Reference                        | Regression Coefficients | Intercept |
|-----|----------------------------------|-------------------------|-----------|
|     |                                  | Sa (%) | Si (%) | Cl (%) | OC (%) | ρd (Mg/m³) |           |
| 1   | Gupta and Larson (1979)          | 0.16   | 0.36   | 0.72   | 2.39   | -5.76      | -         |
| 2   | Rawls et al. (1982)              | -      | 0.14   | 0.55   | 2.51   | -          | 2.81      |
| 3   | Tomasella and Hodnett (1998)     | -      | 0.37   | 0.35   | -      | -          | 3.20      |
| 4   | Reichert et al. (2009)*^         | -0.08  | 0.15   | 0.23   | 1.08   | -          | 10.20     |
| 5   | Dashtaki et al. (2010)           | -0.31  | -      | -      | 14.30  | -          | 12.20     |

Note: (1) Sand: 50-2000 µm (* 20-2000 µm); Silt: 2-50 um (* 2-20 µm); Clay: < 2 µm.
(2) ^Estimated water content is gravimetric water content.

Table 5 Summary of the regression coefficients of point-estimation PTFs at suction of 1500 kPa

| S/N | Reference                        | Regression Coefficient | Intercept |
|-----|----------------------------------|------------------------|-----------|
|     |                                  | Sa (%) | Si (%) | Cl (%) | OC (%) | ρd (Mg/m³) | Other Term | (-) |
| 1   | Petersen et al. (1968)           | -      | -      | 0.08   | -      | -          | 0.01 Cl²   | 1.74 |
| 2   | Pidgeon (1972)*^                 | -      | 0.19   | 0.39   | 0.90   | -          | -          | -4.19 |
| 3   | Hall et al. (1977)               | -      | -      | 0.84   | -      | -          | -0.01 Cl²  | 1.48 |
| 4   | Lal (1979)*                      | -0.24  | -      | 0.30   | -      | -          | -          | 0.60 |
| 5   | Gupta and Larson (1979)          | -0.01  | 0.11   | 0.58   | 0.22   | 2.67       | -          | -28.40 |
| 6   | Rawls et al. (1982)              | -      | -      | 0.50   | 1.58   | -          | -          | 2.60 |
| 7   | Aina and Perisawamy (1985)       | -      | -      | 0.31   | -      | -          | -          | 0.21 |
| 8   | Beke and MacCormick (1985)       | -      | -      | 0.66   | -      | -          | 1.07 OC³ρb | 4.41 |
| 9   | Dijkerman (1988)*^               | -0.35  | -      | 0.39   | -      | -          | -          | 0.74 |
| 10  | Manrique et al. (1991)*^         | -      | -      | 0.37   | -      | -          | -          | 36.97 |
| 11  | Rajkai and Varallyay (1992)      | -      | -      | 0.36   | 0.22   | -          | -          | 1.39 |
| 12  | Bajise (1996)                    | -0.12  | 0.36   | 0.36   | 0.26   | -          | -          | -      |
| 13  | van den Berg et al. (1997)       | -0.21  | 0.27   | 0.27   | 1.76   | -          | -          | 3.83 |
| 14  | Tomasella and Hodnett (1998)     | -0.15  | 0.40   | 0.40   | -      | -          | -          | 0.91 |
| 15  | Oliveira et al. (2002)*^         | 0.04   | 0.15   | 0.34   | 0.34   | 3.09       | -          | -      |
| 16  | Mohamed and Ali (2006)           | -      | 0.23   | 0.32   | 0.32   | 0.09       | -          | -      |
| 17  | Reichert et al. (2009)*^         | -0.17  | 0.32   | 0.91   | 2.60   | -          | -          | -4.00 |
| 18  | Dashtaki et al. (2010)           | -      | 0.33   | -      | -      | -          | -          | 6.20 |

Note: (1) Sand: 50-2000 µm (* 20-2000 µm); Silt: 2-50 um (* 2-20 µm); Clay: < 2 µm.
(2) ^Estimated water content is gravimetric water content.

Table 7 Properties of six soils from UNSODA (Nemes et al., 2001) used for estimation of SWCC with five SWCC points from PTFs

| Soil | Cl (%) | Si (%) | Sa (%) | ρd (Mg/m³) |
|------|--------|--------|--------|------------|
| 1360 | 44     | 41     | 15     | 1.50       |
| 1164 | 32     | 21     | 47     | 1.64       |
| 2361 | 56     | 36     | 8      | 1.28       |
| 4650 | 1      | 7      | 92     | 1.62       |
| 1090 | 5      | 20     | 75     | 1.59       |
| 1460 | 1      | 1      | 98     | 1.85       |

Table 6 Summary of best performing point-estimation PTFs for coarse-grained and fine-grained soils

| Soils     | Suction | PTF     |
|-----------|---------|---------|
| Coarse-grained | 4 kPa   | Gupta and Larson (1979) |
|            | 10 kPa  | Gupta and Larson (1979) |
|            | 100 kPa | Gupta and Larson (1979) |
|            | 1500 kPa| Rawls et al. (1982)     |
| Fine-grained | 4 kPa   | Gupta and Larson (1979) |
|            | 10 kPa  | Gupta and Larson (1979) |
|            | 100 kPa | Gupta and Larson (1979) |
|            | 1500 kPa| Rawls et al. (1982)     |

REFERENCES

1) Aina, P.O., and Perisawamy, S.P., (1985): Estimating available water-holding capacity of western Nigerian soils from soil texture and bulk density, using core and sieved samples, Soil Science, 140, 55-58.
2) Andersson, S., and Wiklert, P., (1972): Markfysikaliska undersökningar i odlad jord. XXII. Om de vattenhallande egenskaperna hos svenska jordar, Grundförrättring, 25, 53-243. Uppsala, Sweden. (in Swedish)

3) Arya, L.M., and Paris, J.F. (1981): A physic-empirical model to predict the soil moisture characteristics from particle-size distribution and bulk density data, Soil Science Society of America Journal, 45, 1023-1030.

4) Batjes, N.H., (1996): Development of a world data set of soil water retention properties using pedotransfer rules, Geoderma, 71, 31-52.

5) Beke, G.J., and MacCormick, M.J., (1985): Predicting volumetric water retentions for subsoil materials from Colchester County, Nova Scotia, Canadian Journal of Soil Science, 65, 233-236.

6) Catana, M.C., Vanapalli, S.K., and Garga, V.K., (2006): The water retention characteristics of compacted clays. In Proceedings of 4th International Conference of Unsaturated Soils, Carefree, Ariz., 2-6 Apr 2006. 1348-1359.

7) Chin, K.B., Leong E.C., and Rahardjo, H., (2010): A simplified method to estimate the soil-water characteristic curve, Canadian Geotechnical Journal, 47, 1382-1400.

8) Dashtaki, S.G., Homaei, M., and Khodaverdiloo, H., (2010): Derivation and validation of pedotransfer functions for estimating soil water retention curve using a variety of soil data, Soil Use and Management, 26, 68-74.

9) Dijkerman, J.C., (1988): An Ustult-Agult-Tropept cantena in Sirreña Leon, West Africa. II. Land qualities and land evaluation, Geoderma, 42, 29-49.

10) Dodds, J.A., (1980): The porosity and contact points in multicomponent random sphere packings calculation by a simple statistical geometric model, Journal of Colloid and Interface Science, 77, 317-327.

11) Fredlund, D.G., (2006): Unsaturated soil mechanics in engineering practice, Journal of Geotechnical and Geoenvironmental Engineering, 132(3), 286-321.

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

13) Gupta, S.C., and Larson, W.E., (1979): Estimating soil water retention characteristics from particle size distribution, organic matter percent, and bulk density, Water Resources Research, 15, 1633-1635.

14) Hall, D.G.M., Reeve, M.J., Thomasson, A.I., and Wright, V.F., (1977): Water retention, porosity and density of field soils, Soil Surv. Tech. Monogr. 9. Rothamsted Experimental Station, Lawes Agriculture Trust, Harpenden, UK.

15) Houston, W.N., Dye, H.B., Zapata, C.E., Perera, Y.Y., and Harraz, A., (2006): Determination of SWCC using one-point suction measurement and standard curves, In Proceedings of the Unsaturated Soils 2006, 1482-1493.

16) Jauhiainen, M. (2004): Relationship of particle size distribution curve, soil water retention curve and unsaturated hydraulic conductivity and their implications on water balance of forested and agricultural hillslopes. Ph.D. dissertation, Helsinki University of Technology, Helsinki, Finland.

17) Lal, R., (1979): Physical properties and moisture retention characteristics of some Nigerian soils, Geoderma, 21, 209-223.

18) Maier, R.S., Kroll, D.M., Davis, H.T., and Bernard, R.S., (1999): Simulation of flow in bidisperse sphere packings, Journal of Colloid and Interface Science, 217, 341-347.

19) Manrique, L.A., Jones, C.A., and Dyke, P.T., (1991): Predicting soil water retention characteristics from soil physical and chemical properties, Communications in Soil Science and Plant Analysis, 17, 1847-1860.

20) Mayr, T., and Jarvis, N.J., (1999): Pedotransfer functions to estimate soil water retention parameters for a modified Brooks-Corey type model, Geoderma, 91, 1-9.

21) Minasny, B., McBridey, A.B., and Bristow, K.L., (1999): Comparison of different approaches to the development of pedotransfer functions for water-retention curves, Geoderma, 93, 225-253.

22) Mohamed J., and Ali, S., (2006): Development and cooperative analysis of pedotransfer functions for predicting soil water characteristic content for Tunisian soil, In Processing of Tunisian-Japanese Symposium on Society, Science and Technology, El Kantaoui, Sousse, Tunisia, 4-6 Dec. 2006. 170-178.

23) Nemes, A., Schaap, and M.G., Leij, F.J., (2001): Description of the unsaturated soil hydraulic database UNSODA Version 2.0, Journal of Hydrology, 251,151-162.

24) Oliveira, L.B., Ribeiro, M.R., Jacomine, P.K.T., Rodrigues, J.V., and Marques, F.A., (2002): Pedotransfer functions for the estimation of moisture retention and
specific potentials in soils of Pernambuco State (Brazil), Revista Brasileira de Ciencia do Solo, 26, 315-323. (In Portuguese).

25) Petersen, G.W., Cunningham, R.L., and Matelski, R.P., (1968): Moisture characteristics of Pennsylvania soils: I, moisture retention as related to texture, Soil Science Society of American Processing, 32, 271-275.

26) Pidgeon, J.D., (1972): The measurement and prediction of available water capacity of ferritic soils in Uganda, Journal of Soil Science, 23, 431-441.

27) Rajkai, K., and Varallyay, G., (1992): Estimating soil water retention from simpler properties by regression technique, In Processing of International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils, University of California, Riverside, CA, USA, edited by M. Th. van Genuchten. 417-426.

28) Rawls, W.J., Brakensiek, D.L., and Saxton, K.E., (1982): Estimation of soil water properties, Transactions of the American Society of Agriculture Engineers, 25, 1316-1320.

29) Reichert, J.M., Albuquerque, J.A., Kaiser, D.R., Urach, F.L., and Carlesso, R., (2009): Estimation of water retention and availability in soil of Rio Grande Do Sul, Revista Brasileira de Ciência do Solo, 33, 1547-1560.

30) Saxton, K.E., Rawls, W.J., Romberger, J.S., and Papendick, R.I. (1986): Estimating generalized soil water characteristics from texture, Transactions of the American Society of Agricultural Engineers, 50, 1031-1035.

31) Scheinost, A.C., Sinowski, W., and Auerswald, K., (1997): Regionalization of soil-water retention curves in a highly variable soilscape, I. Developing a new pedo-transfer function, Geoderma, 78, 129-143.

32) Tomasel, J., and Hodnett, M.G., (1998): Estimating soil water retention characteristics from limited date in Brazilian Amazonia, Soil Science, 163, 190-202.

33) van den Berg, M., Klamt, E., van Reeuwijk, L.P., and Sombroek, W.G., (1997): Pedotransfer functions for the estimation of moisture retention characteristics of Ferrasols and related soils, Geoderma, 78, 161-180.

34) Vanapalli, S.K., Catana, M.C., (2005): Estimation of the soil-water characteristic curve of coarse-grained soils using one-point measurement and simple properties, In Proceedings of the International Symposium on Advanced Experimental Unsaturated Soil Mechanics, Trento, Italy, 27-29 Jun 2005, 401-407.

35) Zou, L. (2018): Effects of grain-size distribution and hysteresis on soil-water characteristic curve (SWCC). Ph.D. dissertation, Nanyang Technological University, Singapore.

36) Zou, L., and Leong, E.C., (2017): Evaluation of the point pedo-transfer functions for the soil-water characteristic curve, In the proceeding of the Second Pan-American Conference on Unsaturated Soils, Dallas, Texas, November 12–15, 2017. 185-194.