A Classification Tree Guide to Soil-water Characteristic Curve Test for Soils with Bimodal Grain-size Distribution

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ABSTRACT: Soil-water characteristic curves (SWCCs) can be unimodal or bimodal. However, insufficient SWCC data points may cause a bimodal SWCC to be erroneously interpreted as a unimodal SWCC. Suggested suction levels to determine SWCC in ASTM 6836-02 (2008) are excessive and can be reduced if the type of SWCC that a soil may have can be identified prior to the SWCC test. Bimodal grain-size distribution is a pre-requisite for soils to have a bimodal SWCC but not all soils with bimodal grain-size distribution have bimodal SWCCs. Models have been proposed to estimate bimodal SWCC of soils with bimodal grain-size distribution. However, the criteria used by these models identify soils with bimodal SWCC are not accurate. In this paper, a classification tree to identify bimodal grain-size distribution (GSD) soils with bimodal SWCC is proposed so that SWCC tests can be better planned to obtain sufficient data for correct interpretation of the SWCC. The classification tree was developed using a database of 226 soils with bimodal GSD. An independent data set consisting of 60 SWCCs from extant literature was used to evaluate the classification tree and the criteria proposed by others. The classification tree was shown to outperform the criteria proposed by others for identifying bimodal GSD soils with bimodal SWCC. Recommendation on suction levels for SWCC tests to obtain unimodal and bimodal SWCCs was made for the test methods in ASTM 6836-16 (2016).

KEYWORDS: Unsaturated soil, Grain-size distribution, Soil-water characteristic curve, Bimodal, Unimodal, SWCC test, Classification tree

1. INTRODUCTION

Soil-water characteristic curve (SWCC) is fundamental to the characterization of unsaturated soils. The SWCC defines the relationship between water content and suction, where suction is expressed on a logarithmic scale. Water content can be expressed in term of volumetric water content, gravimetric water content or degree of saturation (Fredlund et al., 2001). The SWCC is related to the shear strength of unsaturated soils (e.g. Vanapalli et al., 1996; Wulfsohn et al., 1998; Futai and Almeida, 2005; Goh et al., 2010). The unsaturated permeability function of soil is often estimated using the SWCC and the saturated coefficient of permeability (e.g. Mualem, 1976; Fredlund et al., 1994; Tzimopoulos and Sakellariou-Makrantonaki, 1996; Leong and Rahardjo, 1997).

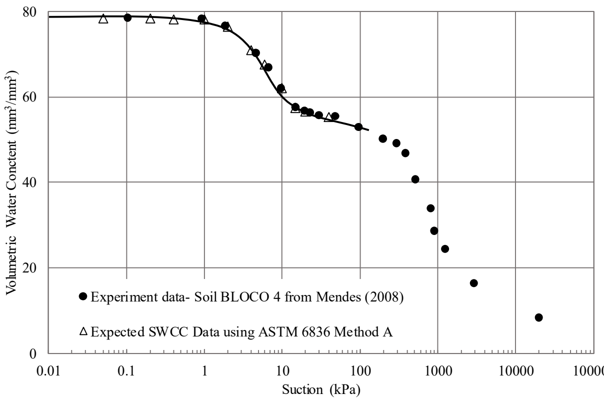
Determination of the SWCC has been standardized in ASTM D6836-16 (2016). According to ASTM D6836-16 (2016), there are five laboratory test methods to determine SWCCs: hanging column (Method A), pressure chamber with volumetric measurements (Method B), pressure chamber with gravimetric measurements (Method C), chilled mirror hygrometer (Method D) and centrifuge (Method E). These five methods determine the water content of the soils at various suction levels. A summary of the five methods together with applicable suction range and suction levels are shown in Table 1. Methods A and E are used for lower suctions (0 to 80 and 0 to 120 kPa, respectively), Methods B and C are used for intermediate suctions (100 to 1500 kPa), and Method D is used for higher suctions (>1000 kPa) of the SWCC. However, the recommended suction levels in ASTM D6836-02 (2008) are too many. Using the SWCC data for BLOCO 4 from Mendes (2008) as shown in Figure 1, the SWCC determined using Methods A, B or C and E gave the points indicated by the triangle, square and circle markers, respectively. Using methods B and C to determine the SWCC for BLOCO 4 will lead to the SWCC being erroneously interpreted as a unimodal SWCC as presented by Figure 1(b) solid line. The SWCC for BLOCO 4 can be obtained correctly if either Method A is used with Method B or C, or Method E is used with Method B or C (given by the dash line in Figure 1b). However, this entails the use of two separate apparatuses and the number of suction levels recommended in Method A is excessive. Due to cost and time constraints, it is important to conduct SWCC tests at only the critical suction levels so that the "correct" SWCC can be obtained in the shortest possible time.

Table 1 Summary of ASTM D6836-02 (2008) methods for determining SWCC

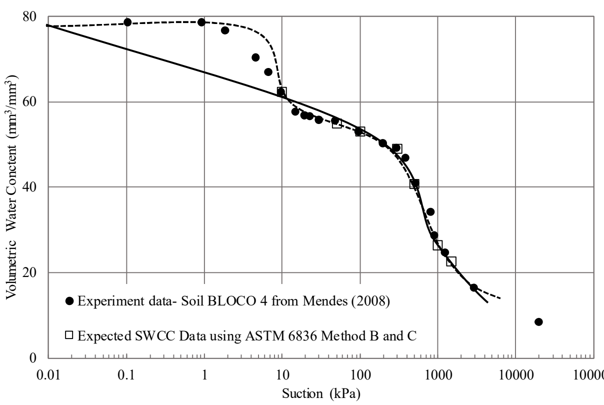
	Method A[1]	Methods B & C	Method D	Method E[2]
Applicable Suction Range	0 to 80 kPa	0 to 1500 kPa	500 kPa to 100 MPa	0 to 120 kPa
Suction Level Applied (kPa)	0.05	10	Not specified	0.5
	0.2	50		2
	0.4	100		8.5
	1	300		34
	2	500		120
	4	1000		
	6	1500		
	10			
	15			
	20			
	40			

[1]Converted from 5, 20, 40, 100, 200, 400, 600, 1000, 1500, 2000, and 4000 mm of water.
[2]Estimated from angular velocities of 100, 200, 400, 800 and 1500 rpm and may vary with centrifuge.

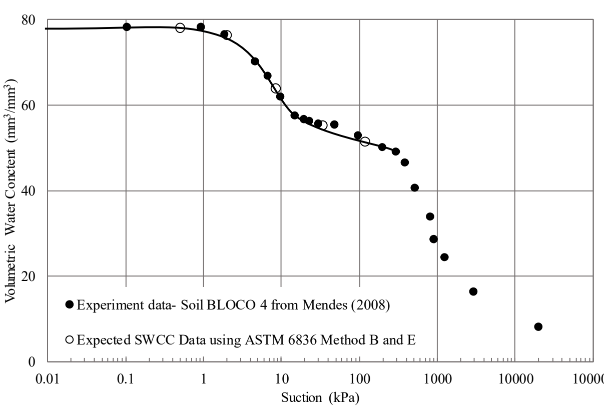
Many researchers have pointed out that the SWCC and grain-size distribution (GSD) are correlated (Arya and Paris, 1981; Haverkamp and Parlange, 1986; Rajkai et al. 1996; Fredlund et al., 1997, 2002; Aung et al., 2001; Hwang and Powers, 2003; Arya et al., 2008; Chin et al., 2010). Bimodal SWCC is a consequence of dual-porosity soils which arises mainly due to bimodal GSD (Zhang and Chen 2005; Satyanaga et al. 2013). In addition, compaction or other features such as cracks in the soil may give rise to dual porosity as well (Li and Zhang, 2009; Satyanaga et al., 2013; Li et al., 2014). Pores in dual-porosity soils are largely governed by the arrangement of coarse grains and fine grains, which cause large pores (macro-pores) and small pores (micro-pores), respectively (Burger and Shackelford, 2001; Zhang and Chen, 2005). Hence, bimodal GSD soil is a pre-requisite for bimodal SWCC. However, bimodal GSD soils may not always give rise to bimodal SWCC. Simple criteria to identify bimodal GSD soils which have bimodal SWCC had been proposed by Satyanaga et al. (2013) and Li et al. (2014). However, these criteria are found to be inadequate. The objective of this paper is to propose an improved method to identify bimodal GSD soils that have bimodal SWCC using parameters of the GSD which can be used as a guide to reduce the number of suction levels needed in a SWCC test.



(a) Using test Method A



(b) Using test method B or C



(c) Using test method E

Figure 1 Expected SWCC using suggested suction levels for test methods A, B or C and E in ASTM D6836-16 (2016) for soil BLOCO 4 from Mendes (2008)

2. EXISTING CRITERIA

Condappa et al. (2008) found that the textural characteristic of soils in tropical and subtropical regions are bimodal containing high sand (Sa) and clay (Cl) size fractions compared to silt (Si) such that

$$\begin{aligned} Sa &\geq Si \\ Cl &\geq Si \end{aligned} \tag{1}$$

The bimodal SWCC zone in the soil textural triangle identified by Equation 1 is given by the shaded zone in Figure 2. Following the shape similarity of cumulative particle-size distribution and SWCC, such bimodal soils are expected to exhibit bimodal hydraulic properties (Condappa et al. 2008). However, this is shown to be not the case for all bimodal GSD soils (Satyanaga et al. 2013; Li et al. 2014).

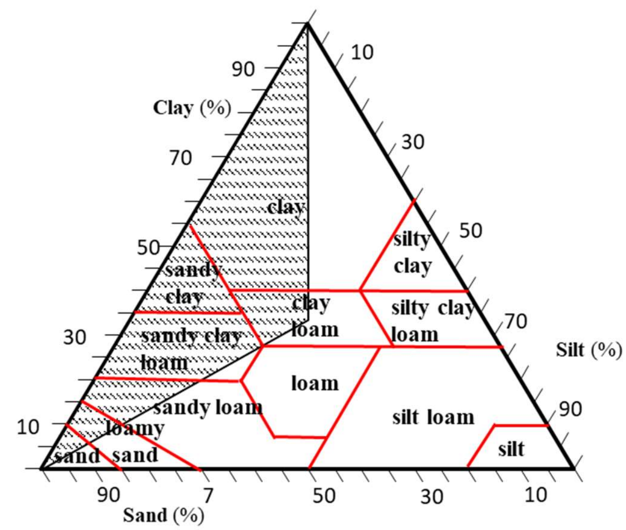


Figure 2 Bimodal soil zone shown as shaded region of the USDA textural triangle (after Condappa et al. 2008)

Satyanaga et al. (2013) suggested that bimodal GSD soils which satisfy the following criteria exhibit bimodal SWCC:

$$\rho_d \leq 1.44\,\mathrm{Mg/m^3}\ \text{, or}$$

$$\rho_d > 1.44\,\mathrm{Mg/m^3}\ \text{and}\ w_{sat} < 18\%\ \text{or}\ w_{sat} > 33\% \tag{2}$$

where ρ = dry density; and w_{sat} = saturated gravimetric water content. The above criteria can be better illustrated using Figure 3.

Li et al. (2014) suggested that bimodal GSD soils have a bimodal SWCC characterized by $\psi_{a2}/\psi_t > 3$ where ψ_{a2} is the air-entry value for water stored in micro pores and ψ_t is the residual suction for water stored in macro pores. Li et al. (2014) found regression equations for ψ_{a2} and ψ_t with D_{10}, D_{30}, D_{60} and e as shown in Equations 3 and 4, respectively, where D_{10}, D_{30}, D_{60} = grain size diameters at 10%, 30% and 60% passing, respectively, and e is void ratio.

$$\psi_{a2} = \frac{0.44 D_{60}^{0.4}}{D_{10}^{0.9} D_{30}^{1.2}} \tag{3}$$

$$\psi_t = \frac{1.4^e D_{60}^{0.14}}{2.118 D_{10}^{0.14} D_{30}} \quad (4)$$

The criteria that Li et al. (2014) proposes for bimodal soils having bimodal SWCC can be simplified to the following expression:

$$\frac{D_{60}^{0.26}}{D_{10}^{0.13} D_{30}^{0.2} 1.4^e} > 3.22 \quad (5)$$

Equations 2 and 5 will be evaluated together with the classification tree proposed later.

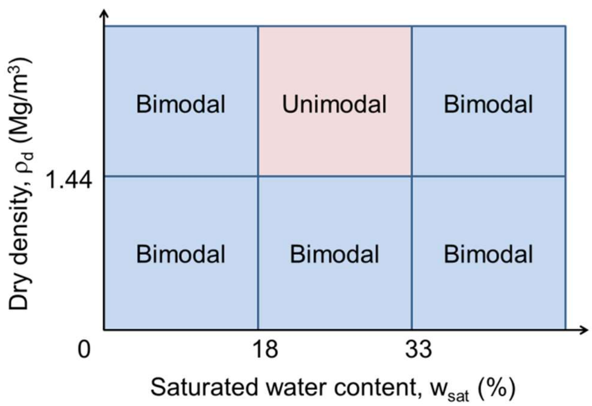


Figure 3 Criteria for unimodal and bimodal SWCCs by Satyanaga et al. (2013)

3. DEVELOPMENT OF CLASSIFICATION TREE

To develop the classification tree, the soil database from Andersson and Wiklert (1972) was used. The database consists of 385 soils from different geographical regions of Sweden. The soils were from 82 soil profiles and were subdivided into top soils from depths of 0 to 200 mm and subsoils from depths of 20 to 100 cm. The soil type ranges from sands to clays with clay content as high as 80%. However, only 226 soils in the database which have bimodal grain-size distribution (bimodal GSD soils) are used to develop the classification tree. The data in the database include bulk density ρ_d, soil particle density ρ_s, grainsize distribution, and SWCC. The SWCCs of the soils were determined using the hanging column method from 0 to 10 kPa suctions, pressure extractor method from 10 to 1500 kPa suction and relative humidity chamber for suctions greater than 1500 kPa. In general, the SWCC tests were conducted on 100 mm long and 70 mm diameter soil cores sampled with the same sampling method as Lewan and Jansson (1996) and Rowell (1996) for 0 to 500 kPa suction and on disturbed samples for suctions greater than 500 kPa. The soil properties are summarized in Table 2.

Table 2 Summary of soil properties for the database

Total Number of Soils		226
Range of Soil Properties (Min~Max/Mean)	e	0.53~1.91/0.92
	ρ_d (Mg/m^3)	0.85~1.77/1.42
	Sand Content (%)	0~100/23.6
	Silt Content (%)	0~87.5/34.5
	Clay Content (%)	0~87/38.3

A soil can exhibit bimodal GSD as long as there is a gap in its cumulative GSD curve. The gap suggested by Condappa et al. (2008) is only for one particular group of soils with bimodal GSD that is dominant in the tropical and subtropical regions. The soil texture of the 226 soils used in this study is shown in Figure 4. Square markers are for bimodal soils with unimodal SWCC, while circle markers are for soils with bimodal SWCC. Figure 4 shows the disagreement of the results suggested by Condappa et al. (2008), which is presented by Figure 2. The 226 soils are uniformly distributed in the USDA soil textural triangle. A better descriptor for the gap in grain size distribution is defined using the frequency plot rather than the cumulative GSD. For the frequency plot, the grain-size bin width is set according to the grain size intervals in Andersson and Wiklert (1972) i.e., 0.0006-0.002-0.006-0.02-0.06-0.2-0.6-2-6-20 mm. The grain sizes corresponding to the two peaks of the grain size frequency plot are defined as major and minor peak grain sizes, respectively, as illustrated in Figure 5. The percentages of grains at the major and minor peak grain sizes are denoted as MaP and MiP, respectively. The span Y between the major and minor peak grain sizes is defined as:

$$Y = \log_{10}\left(\frac{MaP}{MiP}\right) \quad (6)$$

where Y is positive if the major peak grain size is greater than the minor peak particle size, and negative *vice versa*. As Y becomes greater, the possibility of the existence of macro-pores and micro-pores increases. The existence of macro-pores and micro-pores also depends on the relative proportions of grains with major and minor peak grain sizes. Bimodal SWCCs are attributed to the existence of macro-pores and micro-pores. It has been suggested that macro-pores are formed by large grains and micro-pores are formed from small grains (Burger and Shackelford, 2001; Miguel and Bonder, 2012). Bimodal SWCC is the consequence if the major peak grain size is coarser than the minor peak grain size and there are insufficient fine grains to fill the macro-pores created by the coarse grains completely. On the contrary, if the major peak grain size is finer than the minor peak grain size, the finer grains are more likely to fill the macro-pores created by the fewer coarse grains and the soil will most likely exhibit a unimodal SWCC.

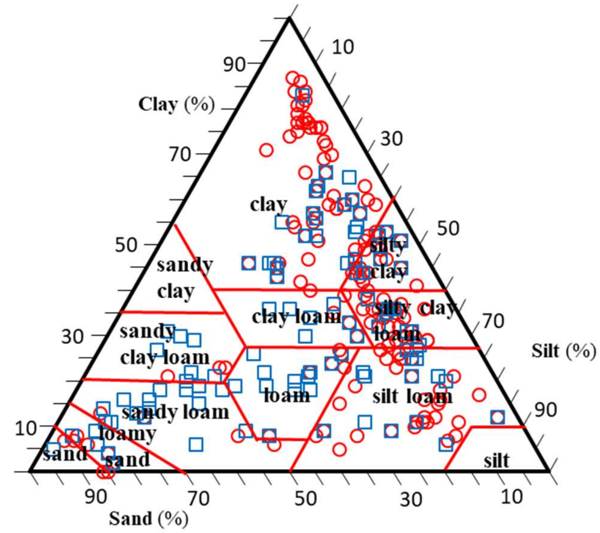


Figure 4 Texture of 226 bimodal soils used to develop classification tree (circle marker: soil having bimodal SWCC; square marker: soil having unimodal SWCC)

Besides Y, MaP and MiP, other grain-size parameters used to develop the classification tree includes clay, silt, and sand (Cl, Si, and Sa) contents, D_{10}, D_{30}, D_{60} and void ratio e as adopted by others. The classification tree was developed using the method of classification and regression trees (CART) (Clark and Pregibon, 1992; Wosten, et al., 2001; Pachepsky et al., 2006). More specifically, the CART

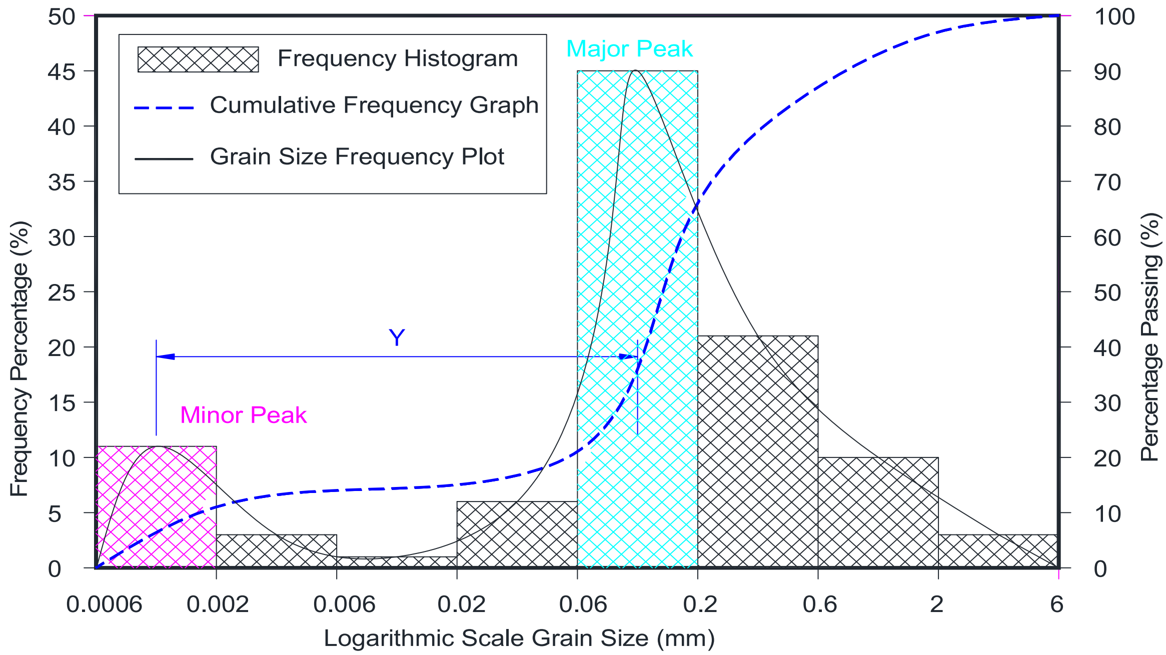


Figure 5 Definition of Y, major and minor peak particle sizes in a frequency particle-size distribution plot

algorithm based on Breiman et al. (1984) was adopted and programmed in software MATLAB Statistics Toolbox (The MathWorks, Inc., 2015) to develop the classification tree. The flowchart for the CART algorithm is shown in Figure 6. The split criterion adopted is the measure of node impurity, Gini's Diversity Index (GDI):

$$GDI = 1 - \sum_{i}[p(i)]^2 \quad (7)$$

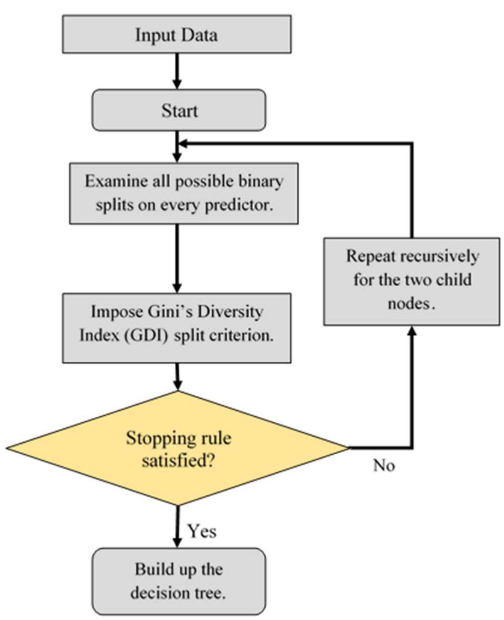


Figure 6 Flowchart for the decision tree implemented in Matlab

where the sum is over the classes i at the node, and p(i) is the observed fraction of classes with class i that reaches the node (The MathWorks, Inc., 2015). A node with just one class has GDI=0; otherwise, GDI>0. For each of the two child nodes, the binary split of the remaining predictors is examined. Splitting stops when one of the following conditions is satisfied:

(i) The node is pure, which means that it only contains observations of one class, i.e., GDI = 0;
(ii) There are less than 10 observations in the data;
(iii) A split imposed on the node produces children with less than 1 observations; or
(iv) The number of nodes exceeds five. Boschi and Rodrigues (2014) recommended that the number of nodes should not exceed five for ease of explanation and implementation.

The quality of the classification tree is determined using the k-fold cross-validation approach (Burman, 1989). In the k-fold cross-validation approach, the data are subdivided into k sample populations of roughly equal sizes and the modelling process is repeated k times, leaving one sample population out each time for validation purposes. The use of k-fold cross-validation approach is to avoid establishing a biased model from the database (Twarakavi et al., 2009). A reliable classification tree can be obtained with k=10 when the data is greater than 100 (Borra and Ciaccio, 2010). Hence, a k=10 cross-validation approach was selected in this study. Briefly, the procedure to establish the classification tree is as follows:

(1) Classify all the SWCCs in the database as either bimodal or unimodal.
(2) Determine the parameters, D_{10}, D_{30}, D_{60}, Cl, Si and Sa from the cumulative grain-size distribution curve. In this paper, only soils with MiP ≥ 5% are considered as bimodal GSD soils.
(3) Re-plot the cumulative grain-size distribution curve as a frequency distribution plot and determine the major peak grain size percentage MaP, minor peak grain size percentage MiP, and Y.
(4) Use variables MaP, MiP, Y, D_{10}, D_{30}, D_{60}, Cl, Si, Sa and void ratio (e) as tentative predictors to develop the classification tree (Model 1).

(5) Evaluate accuracy of the classification tree as ratio of total number of correct classification and total number of data.
(6) Steps 4 and 5 are repeated using |Y| instead of Y to check if using |Y| results in an improved classification tree (Model 2).

For each set of data, three models, which are "Simple Tree", "Medium Tree" and "Complex Tree", can be developed. The maximum split numbers for these three types of tree are 4, 20, and 100, respectively. As recommended by Boschi and Rodrigues (2014), the number of nodes should not exceed five for ease of explanation and implementation. Hence, only the "Simple Tree" is developed in this study.

In developing the classification tree, there is a possibility of class imbalance which is related to the number of observations in one class being more than that of the other class (Batista et al., 2004). As a result, the developed classification tree may nearly always predict the class with the greater number of observations. In this study, of the 226 bimodal GSD soils 30.5% have bimodal SWCC and the remaining 69.5% have unimodal SWCC. Hence, the data is imbalance. To overcome class imbalance, an over-sampling approach called SMOTE (Chawla et al., 2002) was used to create synthetic over-sampling of the minority class which in this study is the soils with unimodal SWCCs.

Models 1 and 2 of the classification tree are shown in Figure 7. The performance of the two models is summarized in Table 3. Model 2 showed better performance and gave good accuracy. Hence, Model 2 was selected as the classification tree to determine the type of SWCC for bimodal GSD soils.

The proposed classification tree (Model 2) uses three parameters (|Y|, e and MaP) compared to two parameters (ρ_d and w_s) in Satyanaga et al. (2013) and four parameters (C_c, C_u, D_{10} and e) in Li et al. (2014). The proposed classification tree has only three nodes which means that the classification tree is simple and easy to use. From Figure 6, it can be observed that when |*Y*| is less than 1.74, the type of SWCC is determined by void ratio (soil structure), otherwise the SWCC is determined by *MaP* (soil texture). A bimodal SWCC may still be possible if the soil has a large void ratio (>1.085). For bimodal GSD soils with |Y| greater than 1.74, a bimodal SWCC is possible if the MaP is less than 68.5%. When MaP is greater than 68.5%, there are insufficient grains with the minor grain size (MiP) to form the micro-pores and hence, the SWCC is unimodal.

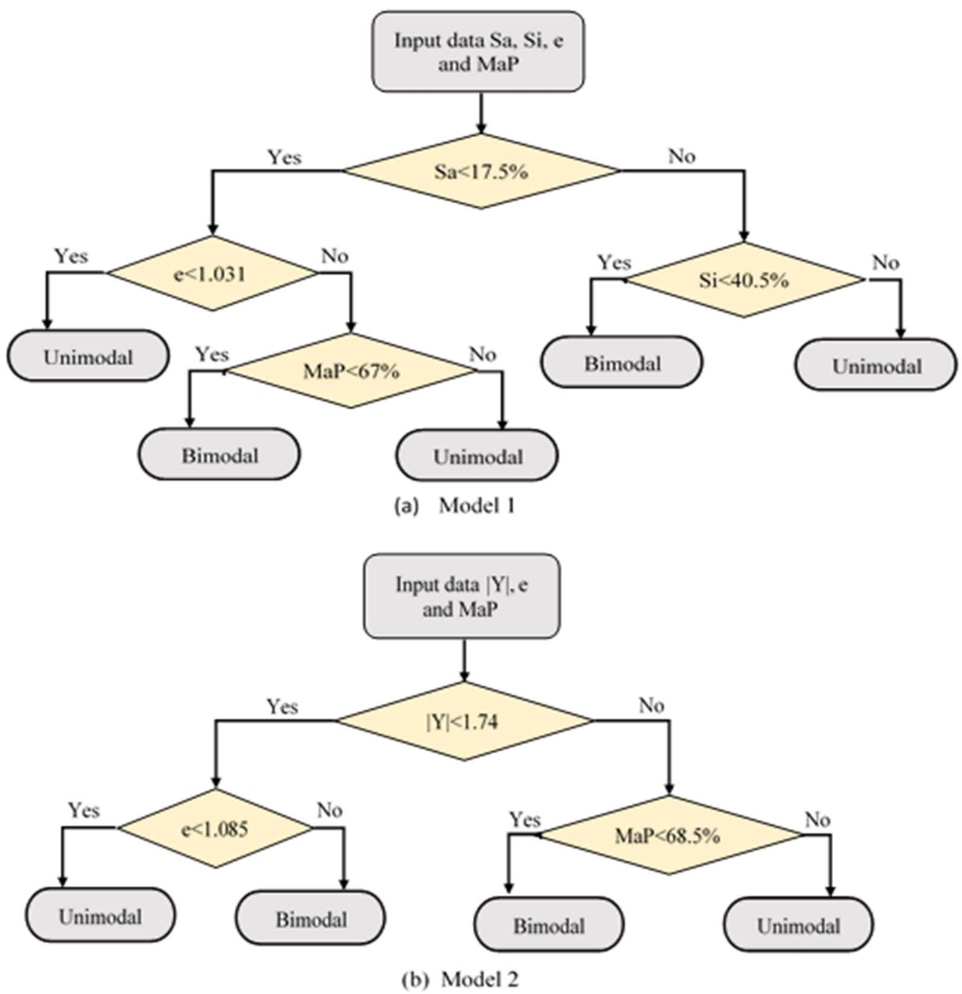


Figure 7 Models 1 and 2 of classification trees for bimodal soils

Table 3 Summary of the performance of the two models

Model	Overall Accuracy	Unimodal Accuracy	Bimodal Accuracy
1	71.70%	78.30%	65.80%
2	83.20%	80.20%	85.80%

4. EVALUATION OF PROPOSED CLASSIFICATION TREE AGAINST CRITERIA PROPOSED BY OTHERS

Sixty soils, which include 30 bimodal GSD soils with unimodal SWCC and 30 bimodal GSD soils with bimodal SWCC from the literature were used to evaluate the proposed classification tree. The textures of the 60 soils in the USDA textural triangle are shown in Figure 8. The 60 soils were also used to evaluate Satyanaga et al. (2013) and Li et al. (2014) criteria for comparison.

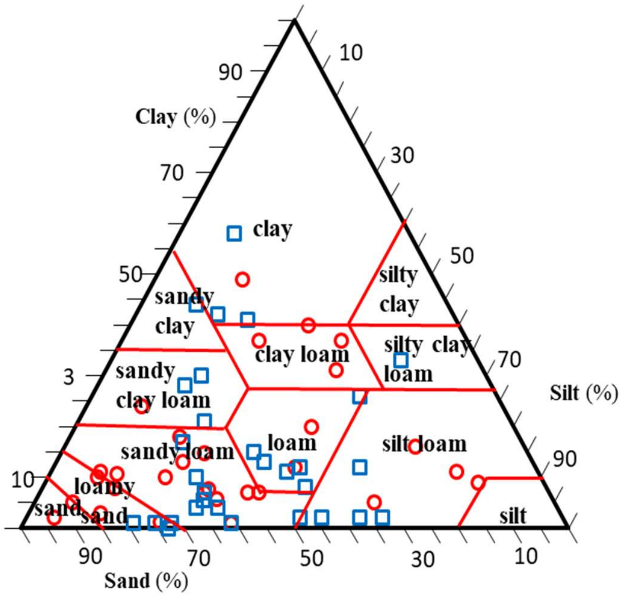


Figure 8 Texture of 60 bimodal GSD soils for evaluation (circle marker: soil having bimodal SWCC; square marker: soil having unimodal SWCC)

The results are summarized in Table 4. The proposed model correctly classified 24 of the 30 bimodal GSD soils with unimodal SWCC (80%) while Satyanaga et al. (2013) only correctly classified 13 of the 30 bimodal GSD soils (43.3%) and Li et al. (2014) correctly classified 22 of the 30 bimodal GSD soils with unimodal SWCC (73.3%). The proposed decision tree correctly classified 25 of the 30 bimodal GSD soils with bimodal SWCC (83.3%) while Satyanaga et al. (2013) correctly classified 23 of the 30 bimodal GSD soils (76.7%) and Li et al. (2014) correctly classified 7 of the 30 bimodal GSD soils (23.3%). Overall, the accuracies of the proposed decision tree, criteria proposed by Satyanaga et al. (2013) and Li et al. (2014) are 81.7%, 60.0% and 48.3%, respectively. Hence, the proposed classification tree showed a better performance than Satyanaga et al. (2013) and Li et al. (2014) criteria to determine the type of SWCC for bimodal GSD soils. The proposed classification tree wrongly predicted six unimodal SWCC as bimodal SWCC, which means that it conservatively suggests more SWCC data points to be obtained in the SWCC test.

5. NUMBER OF SUCTION LEVELS IN A SWCC TEST

Compared to a bimodal SWCC, a unimodal SWCC can be obtained using fewer suction levels. The number of suction levels recommended in ASTM D6836-16 (2016) is excessive for both unimodal SWCC and bimodal SWCC. The number of suction levels required for bimodal SWCC is more than that required for unimodal SWCC. The minimum suction ranges for coarse-grained and fine-grained soils are about two and four log cycles, respectively. The minimum number of data points in a SWCC can be estimated to be at least equal to M, the number of parameters in a SWCC equation. Most unimodal SWCC equations have M between 3 to 5 (Leong and Rahardjo, 1997) while bimodal SWCC equations have M between 8 to 10 (e.g., Gitirana and Fredlund, 2004; Zhang and Chen, 2005; Satyanaga et al. 2013). Considering the minimum number of data points and suction range, it is reasonable that two to three suction levels per log cycle are sufficient to obtain unimodal and bimodal SWCCs, respectively. Therefore, it is recommended that the suggested suction levels in ASTM D6836-16 (2016) be modified and separated into unimodal and bimodal SWCCs as shown in Table 5. Soil BLOCO 4 from Mendes (2008) has |Y| = 2.00, e = 1.414 and MaP = 21%. According to the classification tree in Figure 7(b), it has a bimodal SWCC. Hence, the SWCC data points for soil BLOCO 4 should be obtained using the recommended suction levels for a soil with bimodal SWCC in Table 5 for test method B or C. The resulting SWCC is shown in Figure 9. Thus, the correct type of SWCC can be obtained using only one test method.

Table 5 Recommended suction levels for unimodal and bimodal SWCCs following ASTM D6836-02 (2008) SWCC test methods

Method	A		B & C		D		E*	
Applicable Suction Range	0 to 80 kPa		0 to 1500 kPa		500 kPa to 100 MPa		0 to 120 kPa	
SWCC Type	Unimodal	Bimodal	Unimodal	Bimodal	Unimodal	Bimodal	Unimodal	Bimodal
Suction Level Applied (kPa)	0.2	0.2	1	1	500	500	0.2	0.2
	1	0.5	10	4	1000	1000	1	0.5
	10	1	100	10	10000	2000	10	1
	30	2	500	40	50000	5000	40	2
	80	5	1500	100	100000	10000	120	5
		10		200		20000		10
		30		500		50000		50
		80		1500		100000		120

*Suction levels are suggestions only and depend on centrifuge

Table 4. Evaluation of proposed classification tree, Satyanaga et al. (2013) and Li et al. (2014) criteria

S/N	Soil No.	Reference	SWCC type	Predicted *			S/N	Soil No.	Reference	SWCC type	Predicted *		
				M1	M2	M3					M1	M2	M3
1	Edosaki Sand	Gallage and Uchimura (2010)	U	U	B	U	31	ND-Z=1.5 m	Miguel and Bonder (2011)	B	B	B	U
2	1022	Nemes et al., 2001	U	U	B	U	32	ND-Z=2.5 m	Miguel and Bonder (2011)	B	B	B	U
3	1023	Nemes et al., 2001	U	U	B	U	33	ND-Z=4.3 m	Miguel and Bonder (2011)	B	B	B	U
4	1131	Nemes et al., 2001	U	U	B	U	34	P1C650	Mendes (2008)	B	B	B	U
5	1450	Nemes et al., 2001	U	U	B	U	35	P1C250	Mendes (2008)	B	B	B	U
6	2340	Nemes et al., 2001	U	U	B	B	36	M1C600	Mendes (2008)	B	U	U	U
7	2351	Nemes et al., 2001	U	U	B	U	37	Bloco 4	Mendes (2008)	B	B	B	U
8	3033	Nemes et al., 2001	U	U	B	B	38	Bloco 3	Mendes (2008)	B	B	B	B
9	3260	Nemes et al., 2001	U	U	B	U	39	P1A30	Mendes (2008)	B	B	B	B
10	P1C500b	Mendes (2008)	U	U	U	B	40	M2A30	Mendes (2008)	B	B	B	B
11	2-1-VT-A	Jauhiainen (2004)	U	U	B	U	41	Bloco 1	Mendes (2008)	B	B	B	U
12	2-1-VT-B1	Jauhiainen (2004)	U	B	B	B	42	M2A50	Mendes (2008)	B	B	B	U
13	3-1-OMT-A	Jauhiainen (2004)	U	U	B	U	43	M1C800	Mendes (2008)	B	B	B	U
14	3-3-OMT-C	Jauhiainen (2004)	U	U	U	U	44	Bloco 2	Mendes (2008)	B	B	B	U
15	16-1-MT-C	Jauhiainen (2004)	U	U	U	U	45	M2A30	Mendes (2008)	B	B	U	B
16	25-1-MT-A	Jauhiainen (2004)	U	U	U	U	46	M2B500	Mendes (2008)	B	U	B	U
17	RS	Indrawan et al. (2006)	U	B	U	B	47	P1C350	Mendes (2008)	B	B	B	B
18	RM-75	Indrawan et al. (2006)	U	B	U	B	48	NTU-4-b	Agus et al. (2001)	B	B	U	U
19	RM-50	Indrawan et al. (2006)	U	U	U	U	49	NTU-4-c	Agus et al. (2001)	B	B	U	U
20	BG-8.5m	Aung et al. (2001)	U	B	B	U	50	NTU-1-a	Agus et al. (2001)	B	B	U	U
21	BG-13m	Aung et al. (2001)	U	U	U	U	51	NTU-1-b	Agus et al. (2001)	B	B	U	U
22	NTU-2-b	Agus et al. (2001)	U	U	B	U	52	NTU-3-b	Agus et al. (2001)	B	B	U	B
23	SLR-1-a	Agus et al. (2001)	U	U	B	U	53	SLR-1-a	Agus et al. (2001)	B	B	B	U
24	NTU-3-a	Agus et al. (2001)	U	U	U	U	54	SLR-1-b	Agus et al. (2001)	B	U	B	U
25	SLR-2-b	Agus et al. (2001)	U	B	B	B	55	SLR-2-a	Agus et al. (2001)	B	B	B	B
26	LA-a	Agus et al. (2001)	U	B	U	B	56	SLR-2-c	Agus et al. (2001)	B	U	B	U
27	YS-a	Agus et al. (2001)	U	U	U	U	57	LA-b	Agus et al. (2001)	B	B	B	U
28	SK-5	Goh et al. (2010)	U	U	U	U	58	LA-c	Agus et al. (2001)	B	B	B	U
29	SK-10	Goh et al. (2010)	U	U	U	U	59	LA-d	Agus et al. (2001)	B	U	B	U
30	SK-17	Goh et al. (2010)	U	U	B	U	60	YS-b	Agus et al. (2001)	B	B	B	U
	Accuracy for bimodal soils with unimodal SWCC (%):			80.0	43.3	73.3		Accuracy for bimodal soils with bimodal SWCC (%):			83.3	76.7	23.3

Note: M1: Proposed classification tree; M2: Satyanaga et al. (2013); M3: Li et al. (2014)

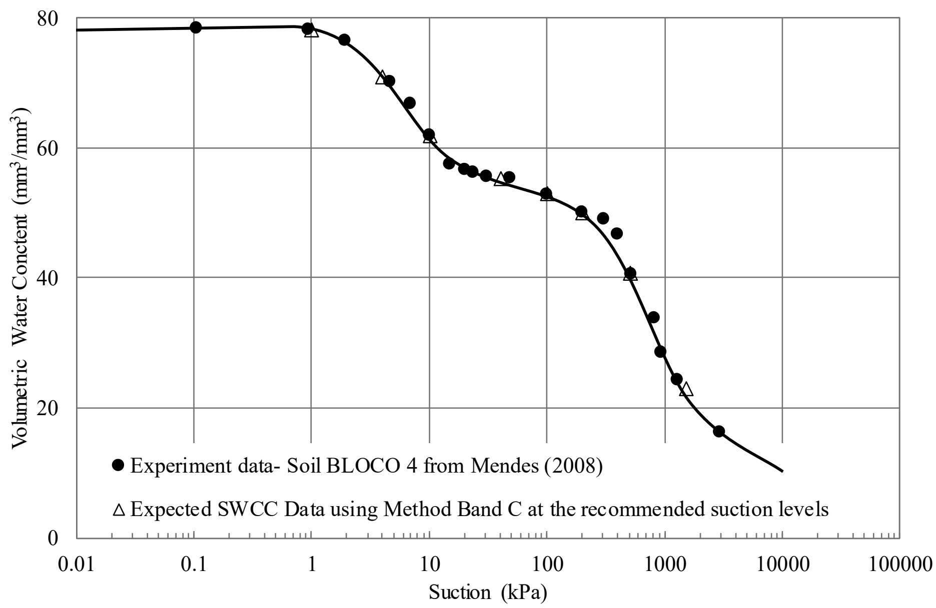


Figure 9 Expected SWCC for soil BLOCO 4 from Mendes (2008) using recommended suction levels in Table 7 for method B&C

6. CONCLUSION

Bimodal GSD soils may not always exhibit bimodal SWCC. In this study, a classification tree to determine the type of SWCC for bimodal GSD soils was developed based on 226 bimodal GSD soils. The proposed classification tree only need three predictors |Y|, MaP and e. The classification tree was evaluated using an independent data set of 60 bimodal GSD soils. The classification tree was shown to outperform existing criteria to distinguish bimodal GSD soils with bimodal SWCC from bimodal GSD soils with unimodal SWCC. More importantly, the decision tree provides a simple guide for planning the SWCC test. The suggested suction levels for determining SWCC in ASTM 6835-16 (2016) are excessive. Hence, it is possible to use a smaller number of suction levels for SWCC tests with the aid of the classification tree, the number of suction levels in the SWCC tests is different for unimodal and bimodal SWCC tests.

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