Technical Note

Fines Classification Based on Sensitivity to Pore-Fluid Chemistry

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Abstract: The 75-μm particle size is used to discriminate between fine and coarse grains. Further analysis of fine grains is typically based on the plasticity chart. Whereas pore-fluid-chemistry-dependent soil response is a salient and distinguishing characteristic of fine grains, pore-fluid chemistry is not addressed in current classification systems. Liquid limits obtained with electrically contrasting pore fluids (deionized water, 2-M NaCl brine, and kerosene) are combined to define the soil "electrical sensitivity." Liquid limit and electrical sensitivity can be effectively used to classify fine grains according to their fluid-soil response into no-, low-, intermediate-, or high-plasticity fine grains of low, intermediate, or high electrical sensitivity. The proposed methodology benefits from the accumulated experience with liquid limit in the field and addresses the needs of a broader range of geotechnical engineering problems. **DOI: [10.1061/(ASCE)GT.1943-5606.0001420](#).** *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, http://creativecommons.org/licenses/by/4.0/.*

Author keywords: Fine-grained soils; Soil classification; Electrical forces; Liquid limit; Pore-fluid chemistry.

Introduction

Soil classification is intended to help engineers anticipate soil response and physical properties. Soil classification systems for geotechnical engineering purposes have evolved to properly address prevailing needs. Many geotechnical problems involve changes in pore-fluid chemistry. These range from classical geotechnical systems (e.g., dispersion in dams, rainfall driven hydrochemo coupled erosion of slopes and scouring), geoenvironmental problems [e.g., landfills, nonaqueous phase liquids (NAPL), and salt water intrusion associated to sea level rise], and energy-related geotechnical problems (e.g., shale instability during well drilling, water flooding for oil production, and CO_2 injection for enhanced oil recovery or geological storage).

Classification systems worldwide are based on grain-size distribution and Atterberg limits (Fig. 1). In general, (1) grains are labeled *fine* when they are smaller than 75 μm (sieve No. 200); (2) the transition between fines-dominant and coarse-dominant behavior is at a fines content between 35 and 50; and (3) the liquid limit (LL) of 50 distinguishes between low- and high-plasticity fine-grained sediments.

The 75-μm size discriminator adequately captures differences in formation history, particle shape, and governing interparticle forces between coarse or fine grains (Santamarina et al. 2001). Further differentiation among fine-grained sediments becomes less clear. This ambivalence is in part caused by the extensive use of the term *clay* to refer to pastes that harden and gain strength during firing (e.g., china dishes; Mackenzie 1963), to particles made of phyllosilicate minerals such as kaolinite and smectite (not all phyllosilicates are clay minerals, e.g., mica; van Olphen 1977; Nesse 2000; Mitchell and Soga 2005), to particles smaller than 2-μm diameter or ~ 1-m^2/g specific surface (hence the frequent association with colloids and submicron particles that experience Brownian motion in water; Baver et al. 1972), and to soils that plot above the A-line on the Casagrande chart (Casagrande 1938, 1948; Holtz et al. 2011).

Casagrande's plasticity chart is used in the Unified Soil Classification System (USCS) and in most other geotechnical classification systems. It properly discerns siltlike materials with high LL and plastic limit (PL) yet low plasticity index (PI = LL − PL) (such as diatoms) from sediments with high liquid limit and high plasticity index (such as bentonite). However, the chart has its limitations:
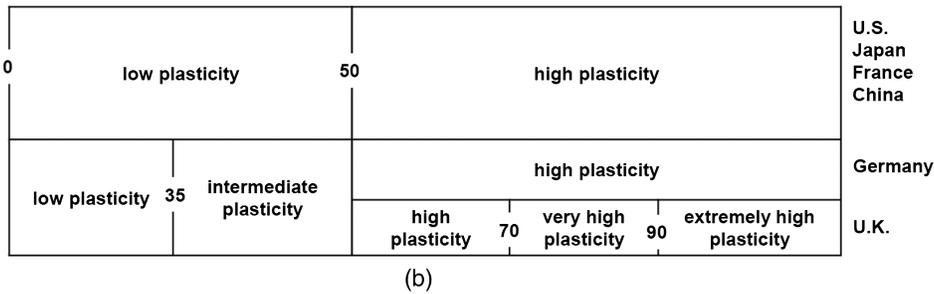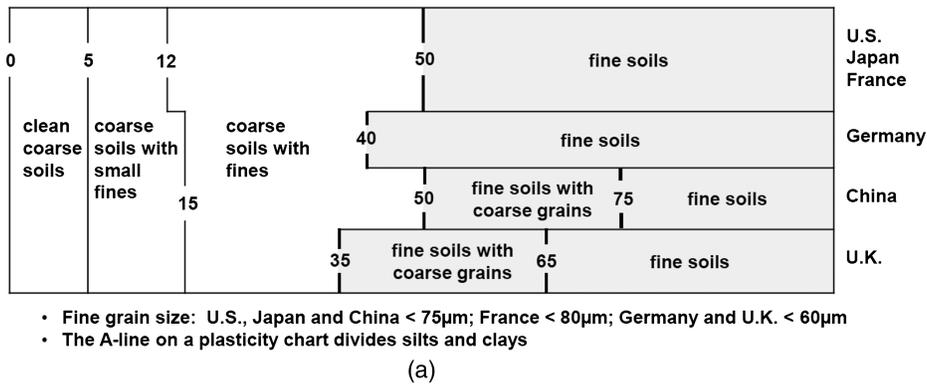
- Clay minerals often plot below the A-line and are classified as "silt" even with liquid limit as high as LL = 250 [see examples in Casagrande's original charts in 1938 and 1948, and multiple cases in the data compilation reported in Fig. 2(a)].
- Organic soils may be found above or below the A-line (Howard 1984).
- The classification of mixtures made of plastic and nonplastic grains may be determined by the weight of the coarse nonplastic fraction, whereas the sediment hydraulic and mechanical properties remain controlled by the high-plasticity fines (further details are discussed subsequently).
- For high-plasticity clays, the plasticity index is dominated by the liquid limit, PI is strongly correlated with LL [Fig. 2(b); see also Seed et al. 1964b], and the plastic limit provides limited additional information for the purposes of clay classification (the plastic limit remains as a convenient field test to assess optimal water content during the compaction of silty and clayey soils; Wesley 2010).

Pore-fluid chemistry, i.e., pH, ionic concentration, and permittivity, is not addressed in current classification systems. Yet, pore-fluid-chemistry-dependent fabric and volumetric strains, because of changes in pore-fluid chemistry, are salient distinguishing characteristics of fine-grained sediments (Lambe 1953; Mitchell 1956; Yong and Warkentin 1966; Santamarina et al. 2002a; Mitchell and Soga 2005). In particular, the aggregation of clay platelets changes when the salt concentration exceeds the threshold of 0.01–0.1 mol/L (Palomino and Santamarina 2005).

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Fig. 1. Soil classification systems: (a) mixture qualifiers based on fines content (percent passing sieve No. 200); (b) plasticity qualifiers based on liquid limit (fraction passing sieve No. 40)
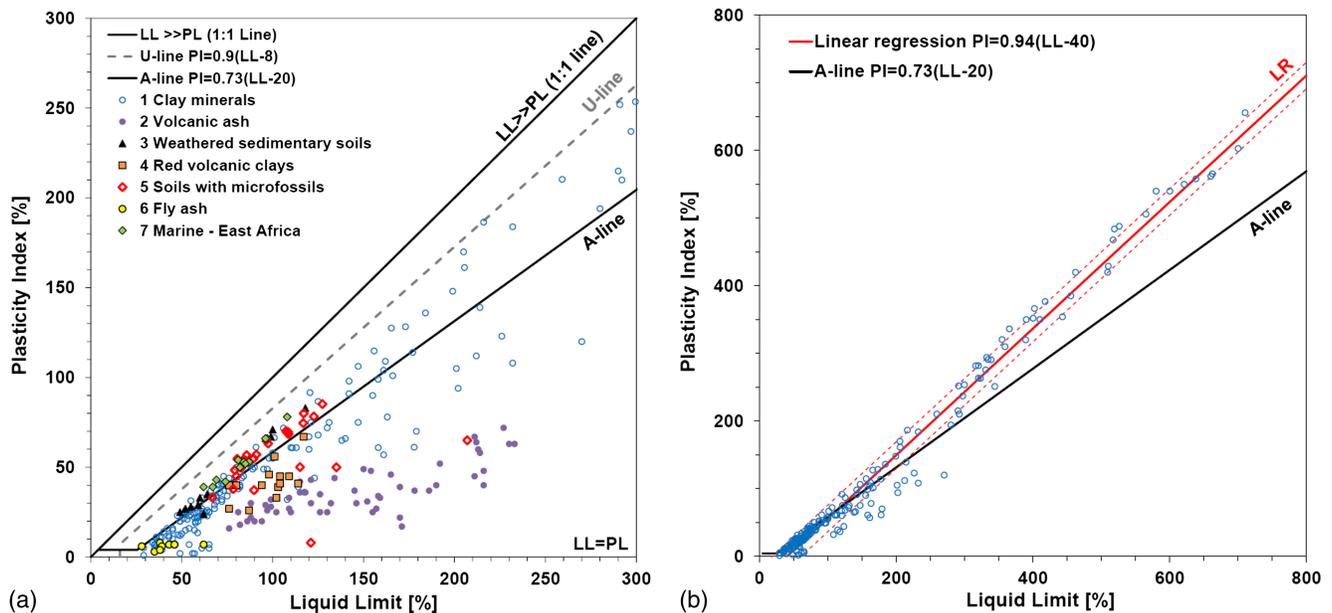
Data sources: [1] White, 1949; Skempton and Northey, 1953; Grim, 1962; Seed et al., 1964-a; Lambe and Whitman, 1969; Bain, 1971; Lupini et al., 1981; Wood, 1982; Fukue et al., 1986; Mesri and Cepeda-Diaz, 1986; Wasti and Bezirci, 1986; Di Maio and Fenelli, 1994; Sridharan and Nagaraj, 1999; Donohew et al., 2000; Feng, 2000; Koumoto and Houlsby, 2001; Cerato and Lutenegger, 2002; Polidori, 2003; Sridharan and Nagaraj, 2004; Dolinar and Trauner, 2005; Spagnoli et al., 2012. [2,3,4] Wesley, 2010. [5] Tanaka and Locat, 1999; Tanaka 2001; Shiwakoti et al., 2002; Lee et al., 2011. [6,7] authors' data.

Fig. 2. Plasticity chart: (a) various soils on the plastic chart; (b) clay minerals only [extracted from the complete data set shown as Fig. 2(a)]; the linear regression (LR) between liquid limit and plasticity and ± 1 standard deviation ($\sigma = 20$) boundaries plot between the A-line and the LL $\gg$ PL line

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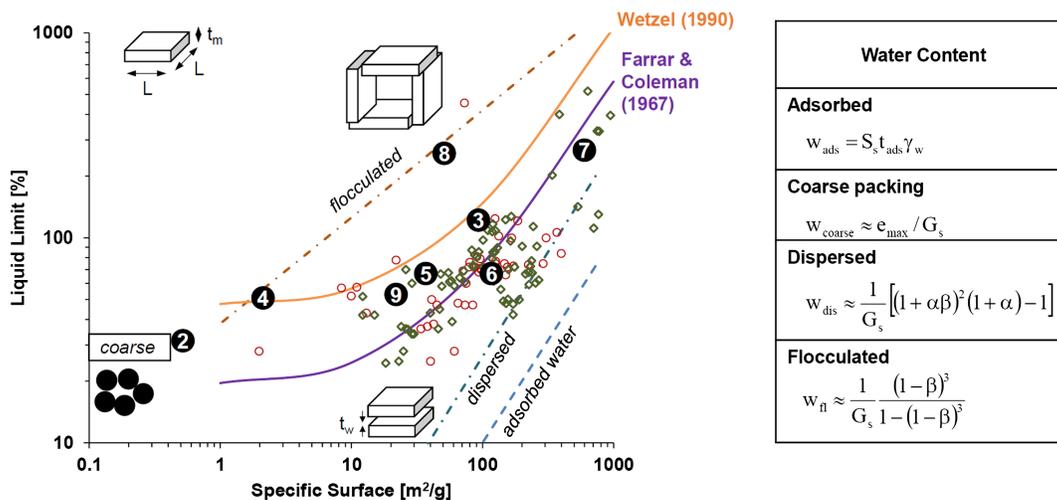
Data sources: Penner (1963); Farrar and Coleman (1967); Locat et al. (1984); Sridharan et al. (1986); Sridharan et al., (1988); Tanaka and Locat, (1999); Donohew et al., (2000); Cerato and Lutenegger (2002); Palomino et al. (2008); Yukselen-Aksoy and Kaya (2013).

Fig. 3. Liquid limit as a function of specific surface; the role of fabric is explored by using regular packings; unfilled circle indicates dry method, whereas unfilled diamond indicates wet method; the trends for flocculated, dispersed, and adsorbed water are calculated by using the following values: dimensionless geometric parameters: $\alpha = t_w/t_m = 0.005\text{--}5$, $\beta = t_m/L = 0.01\text{--}0.2$; assumed adsorbed water thickness $t_{ads} = 10$ Å; and double layer thickness $t_w = 50$ Å; specific surface $S_s = 2(1+2\beta)/(G_s\gamma_w L\beta)$; empirical relations by Wetzel (1990) and by Farrar and Coleman (1967) are included; numbers in black circles refer to soils described in Fig. 4 (data from Penner 1963; Farrar and Coleman 1967; Locat et al. 1984; Sridharan et al. 1986, 1988; Tanaka and Locat 1999; Donhew et al. 2000; Cerato and Lutenegger 2002; Palomino et al. 2008; Yukselen-Aksoy and Kaya 2013)

Liquid limit data are plotted against specific surface in Fig. 3. Superimposed trends show published empirical equations, and three geometric models used to estimate the water content from (1) water adsorbed onto mineral surfaces (lower bound), (2) water held in dispersed fabrics, and (3) water contained in flocculated fabrics (upper bound). Clearly, the liquid limit test measures not only water adsorbed onto particle surfaces (i.e., proportionality with specific surface) but also held in the pore space of the chemistry-dependent fabric (Warkentin 1961; Farrar and Coleman 1967; Warkentin 1972; Wetzel 1990; Muhunthan 1991; Cerato and Lutenegger 2002; Santamarina et al. 2002a, b).

This study aims to explicitly address the effect of pore-fluid chemistry on the classification of fine grains in view of frequent field conditions that involve hydro-chemo-thermo-mechanically coupled process. The study builds on the accumulated experience with index properties in the field and places emphasis on the liquid limit.

Experimental Study

Several index tests were considered as potential candidates for the classification of fine grains in terms of electrical sensitivity, including sedimentation, dilation, and liquid limit tests (the complete study is reported in Jang 2014). The liquid limit did not suffer from segregation or boundary effects, provides consistent and repeatable values, and benefits from the accumulated experience in the field. Therefore, the liquid limit test was selected for the rest of this study.

Materials

Distinct soils are selected for this study, including Ottawa 20-30 sand, silica flour, diatoms, fly ash, kaolinite, illite bentonite, and ground organic matter. The salient properties for all tested fine grains are summarized in Fig. 4.

Three fluids with different relative permittivity κ' and electrical conductivity σ_{el} are identified to explore distinct electrical fluid-particle interactions: deionized water ($\kappa' = 80$, $\sigma_{el} = 10^{-6}$ S/m), NaCl brine (concentration $c = 2$ M, $\kappa' = 55$, $\sigma_{el} = 12$ S/m), and kerosene ($\kappa' = 2$, $\sigma_{el} = 10^{-11}$ S/m). These common fluids are available at geotechnical laboratories worldwide.

Test Procedure: Liquid Limit

Liquid limits were determined by using the fall cone test method to reduce experimental variability with the standard "Casagrande cup" method (Casagrande 1958; Sowers et al. 1960; Sherwood and Ryley 1970; BS 1377 1990; Dueñas and Poblete 2014). The 80-g, 30-degree-apex cone is allowed to penetrate the paste for 5 s [see Evans and Simpson (2015) for a more advanced test methodology]. The liquid limit is the paste water content when the 5-s penetration equals 20 mm, and it corresponds to an undrained shear strength of $1.7 \sim 2.7$ kPa and a suction of ~ 6 kPa (Hansbo 1957; Russell and Mickle 1970; Wroth and Wood 1978; Koumoto and Houlsby 2001; Mitchell and Soga 2005).

The presence of nonplastic coarse grains reduces the measured liquid limit as shown in Fig. 5 (see also Wintermayer 1926; Lambe 1951; Seed et al. 1964b). The trend can be explained by considering a coarse grain embedded in a clay paste with LL_{clay} (see inset in Fig. 5): water is held in the clay matrix and the mixture's LL_{mix} is linearly dependent on the clay fraction $LL_{mix} = LL_{clay} \cdot CF$, where clay fraction CF is defined as $CF = W_{clay}/(W_{sand} + W_{clay})$. The trend is the same for clay-sand mixtures (fraction between sieves No. 40 and No. 200) and for clay-silt mixtures (captured in the concept of "activity"; Skempton 1953). The goal of this study is to assess the pore-fluid chemistry dependency of fines; hence, the reported liquid limit tests are conducted on the passing sieve No. 200 fraction (this does not apply to Ottawa 20-30, which is included in the data set as an extreme case).

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| No. | Soil description | Mean particle size D_{50} [μm] | Specific surface† S_s [m²/g] | Plastic limit [%] | Pass. No.200 sieve [%] | Liquid limit LL [%] | | | USCS | Proposed class | |
						Deionized water	Brine	Kerosene		Plasticity	Sensitivity S_E
1	Ottawa 20-30 sand	720 [6]	0.003	20 [1]	~0	22 [1]	19 [1]	20 [1]	SP	N	L
2	Silica flour	20 [7]	0.5	26	100	31	26	28	ML	N	L
3	Diatom	10 [8]	89	113	100	121	110	138	MH	H	L
4	Fly ash	20	2.1	47	95	50	47	45	ML	L	L
5	Kaolinite	0.36 [9]	34	31	100	67	52	82	CH	I	I
6	Illite	0.5 [10]	110	29	100	67	62	37	CH	I	I
7	Bentonite	0.07 [11]	565	44	100	276	92	39	CH	H	H
8 [2]	Red Sea sediment (microfossils)	120	48	110	36	263	100	55	SW	H	H
9	Piedmont GA-1			34	100	53	44	50	CH	L	L
10 [3]	Clay Adairsville GA-1			37	97	65	45	52	CH	L	I
11	Silt Matanuska Glacier			25 [1]	100	33	32	40	ML	L	I
12	Piedmont GA-2			40 [12]	100	63	57	67	CH	I	L
13 [3]	Clay Adairsville GA-2			34	97	91	53	68	CH	I	I
14 [4]	Ponza bentonite			70 [13]	88	390	90	65	CH	H	H
15 [4]	Bisaccia clay			60 [14]	83	110	65	30	MH	I	H
16	Organic powder - starch			37 [5]	100	75	66	57	OH	I	L
17	Organic powder (intra porous)			120 [5]	100	127	107	47	OH	H	H

[1] LL at fluid saturation

[2] Sediment was sampled below the brine pool in the Red Sea. Therefore, it was washed with deionized water to determine LL_{DW}

[3] PL and passing No.200 sieve from the material data sheet

[4] LL and passing No.200 sieve from Calvello et al., 2005

[5] non-standard plastic transition - low accuracy

[6] Cho et al., 2006; [7] Yun et al., 2007; Salgado et al., 2000; [8] manufacturer; [9] Palomino and Santamarina, 2005; [10] Inoue and Kitagawa 1994; [11] Plaschke et al., 2001; [12] Lutenegger and Harrington; [13] Di Maio, 1996; [14] Picarelli et al., 2003

† Water-based methylene blue test procedure (details in Santamarina et al., 2002-b)

Fig. 4. Experimental results
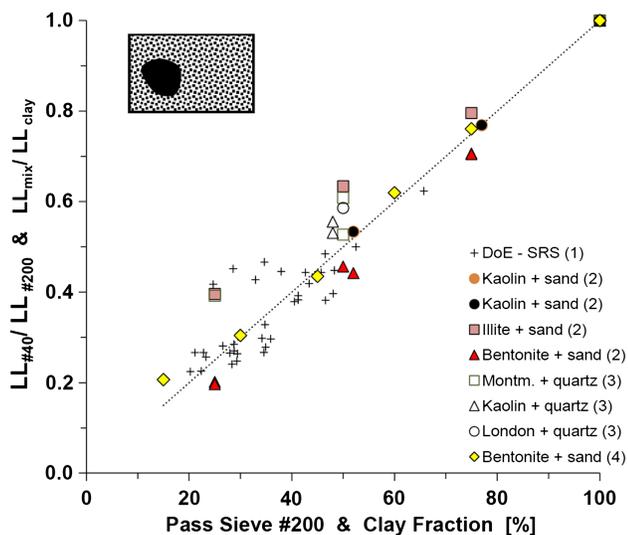
Data sources: (1) LL_{40}/LL_{200} vs. percent passing sieve #200 data for Georgia coastal plain sediments courtesy of B. Gutierrez, (2) Seed et al., 1964-a, (3) Dumbleton and West, 1966, (4) Lupini et al., 1981.

Fig. 5. Effect of nonplastic fines and sand fraction (between sieves No. 40 and No. 200) on the measured liquid limit; the trend $LL_{mix}/LL_{clay} = CF$ does not extended to clay fraction $CF = 0$; the liquid limit of the coarser nonplastic fraction $CF = 0$ can be estimated from the void ratio of a loose packing of nonplastic particles $LL \approx e_{max}/G_s$, as identified in Fig. 3

Soils are dried before preparing mixtures with kerosene. Drying during sample preparation affects test results in diagenetically modified soils such as volcanic ash [Casagrande 1932; ASTM D4318 (ASTM 2005); Herrera et al. 2007; Wesley 2010]. Soils should be dried at 60℃ when such conditions are anticipated [ASTM D2216 (ASTM 2010)].

The liquid limit measured with deionized water LL_{DW} is intended to avoid the face-to-face aggregation of clay platelets when the ionic concentration exceeds the threshold of 0.01–0.1 mol/L, as noted previously. Therefore, sediments saturated with high-ionic-concentration saline water must be washed with deionized water to reduce the ionic concentration before measuring LL_{DW}.

Results and Observations

Liquid limits determined with deionized water LL_{DW}, NaCl brine LL_{brine}, and kerosene LL_{ker} are summarized in Fig. 4. The ratios LL_{DW}/LL_{brine} and LL_{DW}/LL_{ker} are corrected to account for differences in water versus kerosene unit weight γ through specific gravity $G_{ker} = \gamma_{ker}/\gamma_w$, and the precipitation of excess salts during oven drying when the NaCl brine with concentration c_{brine} (g/g) is used to run the test

$$\left.\frac{LL_{DW}}{LL_{ker}}\right|_{corrected} = \frac{LL_{DW}}{LL_{ker}} G_{ker} \tag{1}$$

$$\left.\frac{LL_{DW}}{LL_{brine}}\right|_{corrected} = \frac{LL_{DW}}{LL_{brine}} (1 - c_{brine} LL_{brine}) \tag{2}$$

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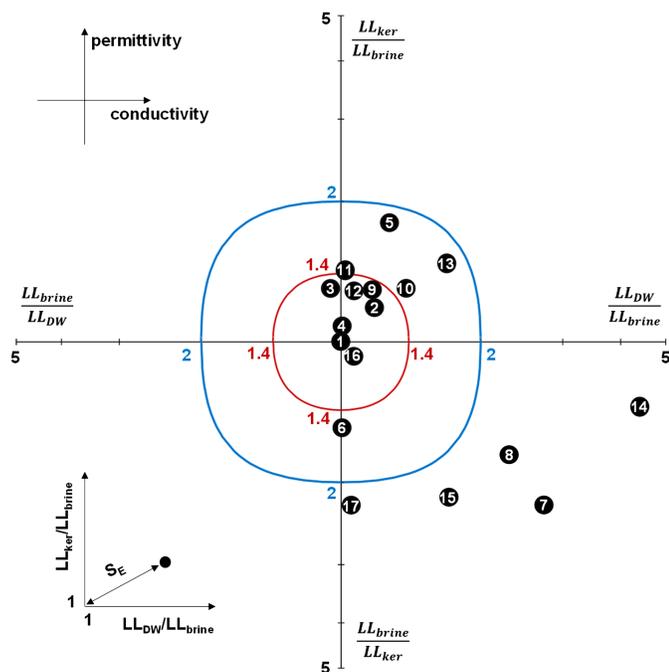J. Geotech. Geoenviron. Eng., 2016, 142(4): 06015018

Fig. 6. Sediment response to changes in fluid conductivity and permittivity; values of liquid limit reported in Fig. 4 are plotted as ratios between LL_{DW} and LL_{brine} (conductivity effect) and LL_{brine} and LL_{ker} (permittivity effect); the scale changes across the origin: LL ratios are larger than 1.0 in all quadrants; the inset shows the definition of electrical sensitivity S_E [Eq. (3)]; numbers in black circles refer to soils described in Fig. 4

The corrected liquid limit ratios are plotted as $LL_{DW}/LL_{\text{brine}}$ versus $LL_{\text{ker}}/LL_{\text{brine}}$ in Fig. 6 for all tested grains including additional data found in the literature. When either LL ratio is less than 1, the reciprocal value is plotted on the opposite quadrant to attain a symmetric assessment of electrical sensitivity to changes in pore fluid:

- Ottawa 20–30 sand, fly ash, silica flour, and diatoms exhibit low or no sensitivity to pore fluids, but kaolinite, illite, and bentonite display clear pore-fluid effects. Organic fines adsorb and swell with water, almost unaffected by salt concentration $LL_{DW} \approx LL_{\text{brine}}$, but do not respond to nonpolar kerosene; therefore, $LL_{\text{brine}} > LL_{\text{ker}}$.
- Fluid conductivity: In general, $LL_{DW} > LL_{\text{brine}}$; hence, most soils plot on quadrants on the right. This result is consistent with changes in double-layer thickness and associated repulsion force (Mitchell and Soga 2005).
- Fluid permittivity: The effect of permittivity is more complex. High-plasticity sediments, probably with prevalent 2:1 clays, display $LL_{\text{brine}} > LL_{\text{ker}}$. Yet, coarser sediments and even 1:1 kaolinite exhibit $LL_{\text{ker}} > LL_{\text{brine}}$. The distinct response of kaolinite to low-permittivity fluids as compared with other clay minerals has been observed by others and attributed to edge charges and van der Waals forces (data compilation and analysis are in Santamarina et al. 2001, 2002a; see forces in Israelachvili 2011).
- Wettability: The affinity of pore fluids to particle surfaces can affect the measured liquid limits in sediments with intragrain porosity, as wetting fluids can invade the small pores more readily and yield higher LL than nonwetting fluids. Although most natural sediments are water-wet, there are exceptions, such as fly ash, which prefer kerosene to water and exhibit $LL_{\text{ker}} > LL_{\text{brine}}$.

The experimental results summarized in Figs. 4 and 6 highlight the complexity of electrical interactions in fine grains whereby particle size and shape, surface and edge charges, and pore-fluid characteristics determine interparticle-electrical forces, define fabric formation, and affect sediment behavior (Yong and Warkentin 1966; Mesri and Olson 1970; Ridley et al. 1984; Chan et al. 1986; Bowders and Daniel 1987; Sivapullaiah and Sridharan 1987; Acar and Olivieri 1989; Meegoda and Ratnaweera 1994; Palomino and Santamarina 2005; Calvello et al. 2005; Mishra et al. 2012).

Discussion: Recommended Classification for Fine Grains

Liquid Limit

Data compilations have led to valuable correlations between the liquid limit and engineering soil properties, such as hydraulic conductivity (Carrier and Beckman 1984), compressibility (Sridharan and Nagaraj 2000), and shear strength (Jamiolkowski et al. 1985; Mayne 2006; Haigh et al. 2013). Given the physical meaning and engineering usefulness of the liquid limit, it is retained in this study for the classification of fine grains.

Electrical Sensitivity

The electrical sensitivity S_E is defined to capture in a single parameter changes in liquid limit with pore-fluid permittivity and electrical conductivity, i.e., van der Waals and double-layer effects. For the first quadrant where $LL_{\text{ker}}/LL_{\text{brine}} > 1.0$ and $LL_{DW}/LL_{\text{brine}} > 1.0$ (the inset in Fig. 6 shows Pythagorean distance)

$$S_E = \sqrt{\left(\frac{LL_{DW}}{LL_{\text{brine}}} - 1\right)^2 + \left(\frac{LL_{\text{ker}}}{LL_{\text{brine}}} - 1\right)^2} \qquad (3)$$

where S_E = distance from the origin at $LL_{\text{ker}}/LL_{\text{brine}} = 1.0$ and $LL_{DW}/LL_{\text{brine}} = 1.0$ to the data point [corrected LL ratios—Eqs. (1) and (2)]. The reciprocal LL ratios are used in Eq. (3) if they are less than 1.0 and data points fall in the second, third, or fourth quadrants.

Recommended Classification

A new classification chart is proposed in Fig. 7. It identifies soils on the basis of their electrical sensitivity S_E and the liquid limit measured with brine LL_{brine}; the value obtained with NaCl brine is selected to minimize any ambiguity associated with existing ions in the soil. Then, the recommended procedure for the classification of fine grains is as follows:
1. Use the soil fraction that passes sieve No. 200.
2. Determine the liquid limit using the fall cone test (BSI 1990) for soil pastes prepared with the following three pore fluids: deionized water, kerosene, and 2-M NaCl brine.
3. Compute LL ratios [Eqs. (1) and (2)], and calculate the electrical sensitivity S_E [Fig. 6 and Eq. (3)].
4. Identify soil types by using the chart in Fig. 7.
5. Report the classification as no-, low-, intermediate-, or high-plasticity fine grains of low, intermediate, or high electrical sensitivity.

Observations

Sediments listed in Fig. 4 are classified by using the standard USCS chart and the proposed chart. Whereas there are basically four

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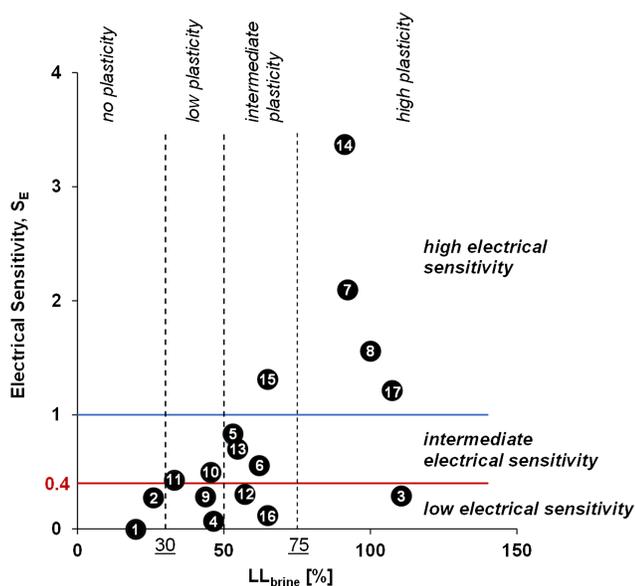J. Geotech. Geoenviron. Eng., 2016, 142(4): 06015018

Fig. 7. Proposed chart for the classification of fine grains on the basis of electrical sensitivity and liquid limit; numbers in black circles refer to soils described in Fig. 4; the $S_E = 0.4$ and $S_E = 1.0$ lines correspond to the boundaries defined in Fig. 6

major categories in the USCS, the proposed classification has 12 sectors to better discern the sediment response; in fact, the USCS CH soils reported in Fig. 4 fall under five different sectors in the LL-S_E chart. Notice how the new chart properly distinguishes plastic clays from intraporous materials such as diatoms that exhibit low electrical sensitivity S_E but high liquid limit LL_{brine}. Most importantly, the new methodology places emphasis on a single and very robust test to assess pore-fluid effects on soil response and avoids test complexities associated with unsaturated soil conditions. Some zones may not become populated in the new chart; in particular, natural materials may not be found on the "nonplastic soil of high electrical sensitivity" category.

Conclusions

Pore-fluid-chemistry-dependent fabric and changes in volumetric strain are salient and distinguishing characteristics of fine-grained sediments and can have critical relevance to frequent field conditions that involve hydro-chemo-mechanical coupled process. Yet, pore-fluid chemistry is not addressed in current classification systems.

The liquid limit measures not only water adsorbed onto particle surfaces but also held in the pore space of the fluid-dependent fabric. Therefore, fluid chemistry–dependent interparticle interactions can be probed by running liquid limit tests on pastes prepared with fluids of contrasting permittivity and electrical conductivity to cause distinct van der Waals and double-layer effects.

Three readily available fluids are selected: deionized water, NaCl brine (high ionic concentration), and kerosene (low permittivity). These fluids can also reflect sediments' affinity to be wetted by either water or organics.

Liquid limits determined with the three fluids are combined to capture soil plasticity and electrical sensitivity S_E. Together, these two measurements can effectively discriminate soils according to their response to pore fluids. They can also identify soils with intraparticle porosity, a noticeable value of the Casagrande chart.

It is recommended that fine grains are classified by using the proposed procedure and chart as no-, low-, intermediate-, or high-plasticity fine grains of low, intermediate, or high electrical sensitivity.

References

Acar, Y. B., and Olivieri, I. (1989). "Pore fluid effects on the fabric and hydraulic conductivity of laboratory-compacted clay." *Transp. Res. Rec.*, 1219, 144–159.

ASTM. (2005). "Standard test methods for liquid limit, plastic limit, and plasticity index of soils." *ASTM D4318*, West Conshohocken, PA.

ASTM. (2010). "Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass." *ASTM D2216*, West Conshohocken, PA.

ASTM. (2011). "Standard practice for classification of soils for engineering purposes (unified soil classification system)." *ASTM D2487*, West Conshohocken, PA.

Bain, J. A. (1971). "A plasticity chart as an aid to the identification and assessment of industrial clays." *Clay Miner.*, 9(1), 1–17.

Baver, L. D., Gardner, W. H., and Gardner, W. R. (1972). *Soil physics*, Wiley, New York.

Bowders, J. J., and Daniel, D. E. (1987). "Hydraulic conductivity of compacted clay to dilute organic chemicals." *J. Geotech. Eng.*, 10.1061/(ASCE)0733-9410(1987)113:12(1432), 1432–1448.

BSI (British Standards Institution). (1990). "Methods of test for soils for soils for civil engineering purposes." *BS 1377*, London.

BSI (British Standards Institution). (1999). "Code of practice for site investigations." *BS 5930*, London.

Calvello, M., Lasco, M., Vassallo, R., and Di Maio, C. (2005). "Compressibility and residual shear strength of smectitic clays: influence of pore aqueous solutions and organic solvents." *Rivista Italiana Di Geotecnica*, 39(1), 34–46.

Carrier, W. D., and Beckman, J. F. (1984). "Correlations between index tests and the properties of remoulded clays." *Geotechnique*, 34(2), 211–228.

Casagrande, A. (1932). "Research on the Atterberg limits of soils." *Public Roads*, 13(8), 121–136.

Casagrande, A. (1938). *Notes on soil mechanics—First semester*, Harvard Univ., Cambridge, MA.

Casagrande, A. (1948). "Classification and identification of soils." *Trans. ASCE*, 113, 901–930.

Casagrande, A. (1958). "Notes on the design of the liquid limit device." *Geotechnique*, 8(2), 84–91.

Cerato, A. B., and Lutenegger, A. J. (2002). "Determination of surface area of fine-grained soils by the ethylene glycol monoethyl ether (EGME) method." *Geotech. Test. J.*, 25(3), GTJ11087J.

Chan, P. C., Selvakumar, G., and Shih, C. Y. (1986). "The effects of liquid organic contaminants on geotechnical properties of clay soils." *Toxic and Hazardous Wastes: Proc., 18th Mid-Atlantic Industrial Waste Conf.*, G. D. Boardman, ed., Technomic, Lancaster, PA, 409–420.

Cho, G. C., Dodds, J., and Santamarina, J. C. (2006). "Particle shape effects on packing density, stiffness, and strength: Natural and crushed sands." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(2006)132:5(591), 591–602.

Deutche Norm DIN18196. (2011). *Erd-und grundbau—bodenklassifikationfürbautechnischezwecke*, BeuthVerlag GmbH, Berlin.

Di Maio, C. (1996). "Exposure of bentonite to salt solution: Osmotic and mechanical effects." *Geotechnique*, 46(4), 695–707.

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Di Maio, C., and Fenelli, G. B. (1994). "Residual strength of kaolin and bentonite: The influence of their constituent pore fluid." *Geotechnique*, 44(2), 217–226.

Dolinar, B., and Trauner, L. (2005). "Impact of soil composition on fall cone test results." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(2005)131:1(126), 126–130.

Donohew, A. T., Horseman, S. T., and Harrington, J. F. (2000). "Gas entry into unconfined clay pastes at water contents between the liquid and plastic limits." *Environmental mineralogy: Microbial interactions, anthropogenic influences, contaminated land and waste management*, J. D. Cotter-Howells, L. S. Campbell, E. Valsami-Jones, and M. Batchelder, eds., Mineralogical Society, London, 369–394.

Dueñas, J. P., and Poblete, M. (2014). "Utilización del penetrómetro de cono en la determinación del límite liquido en suelos de baja plasticidad." *VIII Congreso Chileno De Ingeniería Geotécnica*, Sociedad Chilena de Geotecnia, Chile.

Dumbleton, M., and West, G. (1966). "Some factors affecting the relation between the clay minerals in soils and their plasticity." *Clay Miner.*, 6(3), 179–193.

Evans, T. M., and Simpson, D. C. (2015). "Innovative data acquisition for the fall cone test in teaching and research." *Geotech. Test. J.*, 38(3), 346–354.

Farrar, D. M., and Coleman, J. D. (1967). "The correlation of surface area with other properties of nineteen British clay soils." *J. Soil Sci.*, 18(1), 118–124.

Feng, T.-W. (2000). "Fall-cone penetration and water content relationship of clays." *Geotechnique, 50(2), 181–187.*

Fukue, M., Okusa, S., and Nakamura, T. (1986). "Consolidation of sand-clay mixtures." *ASTM STP 892*, ASTM, West Conshohoken, PA.

GBT50145. (2007). *Standard for engineering classification of soil*, China Planning Press, Beijing.

Grim, R. E. (1962). *Applied clay mineralogy*, McGraw-Hill, New York.

Haigh, S. K., Vardanega, P. J., and Bolton, M. D. (2013). "The plastic limit of clays." *Geotechnique, 63(6), 435–440.*

Hansbo, S. (1957). "A new approach to the determination of the shear strength of clay by the fall-cone test." *Proc. R. Swedish Geotech. Inst.*, 14, 7–48.

Herrera, M. C., Lizcano, A., and Santamarina, J. C. (2007). "Colombian volcanic ash soils." *Characterisation and engineering properties of natural soils*, K. K. Phoon, D. W. Hight, S. Leroueil, and T. S. Tan, eds., Taylor & Francis, London, 2385–2409.

Holtz, R. D., Kovacs, W. D., and Sheahan, T. C. (2011). *An introduction to geotechnical engineering*, Pearson, Upper Saddle River, NJ.

Howard, A. K. (1984). "The revised ASTM standard on the unified classification system." *Geotech. Test. J., 7(4), 216–222.*

Inoue, A., and Kitagawa, R. (1994). "Morphological characteristics of illitic clay minerals from a hydrothermal system." *Am. Mineral.*, 79(7–8), 700–711.

Israelachvili, J. N. (2011). *Intermolecular and surface forces*, Academic Press, San Diego, CA.

Jamiolkowski, M., Ladd, C. C., Germain, J. T., and Lancellotta, R. (1985). "New developments in field and laboratory testing of soils." *Proc., 11th Int. Conf. on Soil Mechanics and Foundation Engineering*, Balkema, Rotterdam, Netherlands, 57–153.

Jang, J. (2014). "Gas-charged sediments: Phenomena and characterization." Ph.D. thesis, Georgia Institute of Technology, Atlanta, GA.

JGS0051. (2009). "Method of classification of geomaterials for engineering purposes." Japanese Geotechnical Society, Tokyo.

Koumoto, T., and Houlsby, G. T. (2001). "Theory and practice of the fall cone test." *Geotechnique, 51(8), 701–712.*

Lambe, T. W. (1951). *Soil testing for engineers*, Wiley, New York.

Lambe, T. W. (1953). "The structure of inorganic soil." *Proc. ASCE*, 79, 1–49.

Lambe, T. W., and Whitman, R. V. (1969). *Soil mechanics*, Wiley, New York.

Lee, C., Yun, T. S., Lee, J.-S., Bahk, J. J., and Santamarina, J. C. (2011). "Geotechnical characterization of marine sediments in the Ulleung basin, East Sea." *Eng. Geol.*, 117(1–2), 151–158.

Locat, J., Lefebvre, G., and Ballivy, G. (1984). "Mineralogy, chemistry, and physical properties interrelationships of some sensitive clays from eastern Canada." *Can. Geotech. J.*, 21(3), 530–540.

Lupini, J. F., Skinner, A. E., and Vaughan, P. R. (1981). "The drained residual strength of cohesive soils." *Geotechnique*, 31(2), 181–213.

Lutenegger, A. J., Cerato, A. B., and Harrington, N. (2003). "Some physical and chemical properties of some Piedmont residual soils." *Proc., 12th Panamerican Conf. on Soil Mechanics and Geotechnical Engineering and the 39th U.S. Rock Mechanics Symp.*, Vol. 1, Verlag Glückauf GMBH, Essen, Germany, 775–782.

Mackenzie, R. C. (1963). "De natura lutorum." *Proc., 11th National Conf. on Clays and Clay Minerals*, Pergamon Press, Oxford, 11–28.

Magnan, J. (1997). "Description, identification et classification des sols." Laboratoire Cetral des Ponts et Chaussées, C208.

Mayne, P. W. (2006). "In-situ test calibrations for evaluating soil parameter." *Characterisation and engineering properties of natural soils*, K. K. Phoon, D. W. Hight, S. Leroueil, and T. S. Tan, eds., Taylor & Francis, London.

Meegoda, N. J., and Ratnaweera, P. (1994). "Compressibility of contaminated fine-grained soils." *Geotech. Test. J.*, 17(1), 101–112.

Mesri, G., and Cepeda-Diaz, A. F. (1986). "Residual shear strength of clays and shales." *Geotechnique*, 36(2), 269–274.

Mesri, G., and Olson, R. E. (1970). "Shear strength of montmorillonite." *Geotechnique*, 20(3), 261–270.

Mishra, A. K., Ohtsubo, M., Li, L. Y., and Higashi, T. (2012). "Influence of various factors on the difference in the liquid limit values determined by Casagrande's and fall cone method." *Environ. Earth Sci.*, 65(1), 21–27.

Mitchell, J. K. (1956). "The fabric of natural clays and its relation to engineering properties." *Proc. Highway Res. Board*, 35, 693–713.

Mitchell, J. K., and Soga, K. (2005). *Fundamentals of soil behavior*, Wiley, Hoboken, NJ.

Muhunthan, B. (1991). "Liquid limit and surface area of clays." *Geotechnique, 41(1), 135–138.*

Nesse, W. D. (2000). *Introduction to mineralogy*, Oxford University Press, New York.

Palomino, A. M., Burns, S. E., and Santamarina, J. C. (2008). "Mixtures of fine-grained minerals—Kaolinite and carbonate grains." *Clays Clay Miner.*, 56(6), 599–611.

Palomino, A. M., and Santamarina, J. C. (2005). "Fabric map for kaolinite: Effects of pH and ionic concentration on behavior." *Clays Clay Miner.*, 53(3), 211–223.

Penner, E. (1963). "Sensitivity in Leda clay." *Nature*, 197(4865), 347–348.

Picarelli, L., Olivares, L., DiMaio, C., Silvestri, F., DiNocera, S., and Urciuoli, G. (2003). "Structure, properties and mechanical behavior of the highly plastic intensely fissured Bisaccia clay shale." *Characterisation and engineering properties of natural soils*, T. S. Tan, K. K. Phoon, D. W. Hight, and S. Leroueil, eds., Balkema, Lisse, Netherlands.

Plaschke, M., et al. (2001). "Size characterization of bentonite colloids by different methods." *Anal. Chem.*, 73(17), 4338–4347.

Polidori, E. (2003). "Proposal for a new plasticity chart." *Geotechnique, 53(4), 397–406.*

Ridley, K. J. D., Bewtra, J. K., and McCorquodale, J. A. (1984). "Behaviour of compacted fine-grained soil in a brine environment." *Can. J. Geotech. Eng.*, 11, 196–203.

Russell, E. R., and Mickle, J. L. (1970). "Liquid limit values by soil moisture tension." *J. Soil Mech. Found. Div.*, 96(SM3), 967–989.

Salgado, R., Bandini, P., and Karim, A. (2000). "Shear strength and stiffness of silty sand." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(2000)126:5(451), 451–462.

Santamarina, J. C., Klein, K. A., and Fam, M. A. (2001). *Soils and waves*, Wiley, New York.

Santamarina, J. C., Klein, K. A., Palomino, A., and Guimaraes, M. S. (2002a). *Micro-scale aspects of chemical-mechanical coupling—Interparticle forces and fabric*, Maratea, Balkema, Rotterdam, Netherlands, 47–64.

Santamarina, J. C., Klein, K. A., Wang, Y. H., and Prencke, E. (2002b). "Specific surface: Determination and relevance." *Can. Geotech. J.*, 39(1), 233–241.

Seed, H. B., Woodward, R. J., and Lundgren, R. (1964a). "Clay mineralogical aspects of the Atterberg limits." *J. Soil Mech. Found. Div.*, 90(SM4), 107–131.

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J. Geotech. Geoenviron. Eng.

J. Geotech. Geoenviron. Eng., 2016, 142(4): 06015018

Seed, H. B., Woodward, R. J., and Lundgren, R. (1964b). "Fundamental aspects of the Atterberg limits." *J. Soil Mech. Found. Div.*, 90(SM6), 75–105.

Sherwood, P. T., and Ryley, M. D. (1970). "An investigation of a cone-penetrometer method for the determination of the liquid limit." *Geotechnique*, 20(2), 203–208.

Shiwakoti, D. R., Tanaka, H., Tanaka, M., and Locat, J. (2002). "Influences of diatom microfossils on engineering properties of soils." *Soils Found.*, 42(3), 1–17.

Sivapullaiah, P. V., and Sridharan, A. (1987). "Effect of polluted water on the physico-chemical properties of clayey soils." *Environmental geo-technics and problematic soils and rocks*, A. S. Balasubramaniam, D. T. Bergado, S. Chandra, and P. Nutalay, eds., Balkema, Rotterdam, Netherlands, 179–190.

Skempton, A. W. (1953). "The colloidal 'activity' of clays." *Proc., 3rd Int. Conf. on Soil Mechanics and Foundation Engineering*, Vol. 1, Organizing Committee ICOSOMEF, Zurich, Switzerland, 57–61.

Skempton, A. W., and Northey, R. D. (1953). "The sensitivity of clays." *Geotechnique*, 3(1), 30–53.

Sowers, G. F., Vesić, A., and Grandolfi, M. (1960). "Penetration tests for liquid limit." *ASTM STP 254*, ASTM, West Conshohoken, PA, 216–226.

Spagnoli, G., Stanjek, H., and Sridharan, A. (2012). "Influence of ethanol/water mixture on the undrained shear strength of pure clays." *Bull. Eng. Geol. Environ.*, 71(2), 389–398.

Sridharan, A., and Nagaraj, H. B. (1999). "Absorption water content and liquid limit of soils." *Geotech. Test. J.*, 22(2), 121–127.

Sridharan, A., and Nagaraj, H. B. (2000). "Compressibility behaviour of remoulded, fine-grained soils and correlation with index properties." *Can. Geotech. J.*, 37(3), 712–722.

Sridharan, A., and Nagaraj, H. B. (2004). "Coefficient of consolidation and its correlation with index properties of remolded soils." *Geotech. Test. J.*, 27(5), 10784.

Sridharan, A., Rao, S. M., and Murthy, N. S. (1986). "Liquid limit of mont-morillonite soils." *Geotech. Test. J.*, 9(3), 156–159.

Sridharan, A., Rao, S. M., and Murthy, N. S. (1988). "Liquid limit of kaolinitic soils." *Geotechnique*, 38(2), 191–198.

Tanaka, H., and Locat, J. (1999). "A microstructural investigation of Osaka Bay clay: The impact of microfossils on its mechanical behaviour." *Can. Geotech. J.*, 36(3), 493–508.

Tanaka, H., Locat, J., Shibuya, S., Soon, T. T., and Shiwakoti, D. R. (2001). "Characterization of Singapore, Bangkok, and Ariake clays." *Can. Geotech. J.*, 38(2), 378–400.

van Olphen, H. (1977). *An introduction to clay colloid chemistry*, Wiley, New York.

Warkentin, B. P. (1961). "Interpretation of the upper plastic limit of clays." *Nature*, 190(4772), 287–288.

Warkentin, B. P. (1972). "Use of liquid limit in characterizing clay soils." *Can. J. Soil Sci.*, 52(3), 457–464.

Wasti, Y., and Bezirci, M. H. (1986). "Determination of the consis-tency limits of soils by the fall cone test." *Can. Geotech. J.*, 23(2), 241–246.

Wesley, L. D. (2010). *Geotechnical engineering in residual soils*, Wiley, Hoboken, NJ.

Wetzel, A. (1990). "Interrelationship between porosity and other geotech-nical properties of slowly deposited, fine-grained marine surface sediments." *Mar. Geol.*, 92(1–2), 105–113.

White, W. A. (1949). "Atterberg plastic limits of clay minerals." *Am. Mineral.*, 34, 508–512.

Wintermayer, A. M. (1926). "Adaptation of Atterberg plasticity tests for subgrade soils." *Public Roads*, 7(6), 119–122.

Wood, D. M. (1982). "Cone penetrometer and liquid limit." *Geotechnique*, 32(2), 152–157.

Wroth, C. P., and Wood, D. M. (1978). "The correlation of index properties with some basic engineering properties of soils." *Can. Geotech. J.*, 15(2), 137–145.

Yong, R. N., and Warkentin, B. P. (1966). *Introduction to soil behavior*, Macmillan, New York.

Yukselen-Aksoy, Y., and Kaya, A. (2013). "Specific surface area effect on compressibility behaviour of clayey soils." *Proc. Inst. Civ. Eng. Geotech. Eng.*, 166(1), 76–87.

Yun, T. S., Santamarina, J. C., and Ruppel, C. (2007). "Mechanical properties of sand, silt, and clay containing tetrahydrofuran hydrate." *J. Geophys. Res.*, 112, B04106.

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