

Closure to “Fines Classification Based on Sensitivity to Pore-Fluid Chemistry” by Junbong Jang and J. Carlos Santamarina

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The proposed new fines classification system is an attempt to address the demands of geotechnical engineers who require a methodology that systematically characterizes fines for diverse geotechnical applications. We received six official discussions, three direct contributions, and several other personal communications regarding procedures and data analysis. Overall, contributors welcomed the proposed methodology for its repeatability, its enhanced discrimination and clustering capabilities, and its ability to identify differences in particle-particle interaction associated with pore-fluid changes. This closure benefits from the input provided by all of these contributions, and is organized in three sections: data, test procedure, and interpretation.

Data

Discussers contributed valuable data that significantly augmented the original paper. Table 1 summarizes the complete database available to date. The database includes information for single-mineral and multiminer natural soils, soil grains with inner porosity (including fly ash and diatoms), and organic materials. Data cluster toward the A-line on the Casagrande chart. The notable exception of diatomaceous soils and organic sediments reflects their ability to capture water in intragrain porosity, hence, they have a high liquid limit yet low plastic limit. Plasticity versus specific surface trends fall within the dispersed and flocculated fabric boundaries (Fig. 3 in the original paper). The data set enables readers to explore other correlations among index properties; some are addressed here.

Test Procedure

Discussers submitted questions related to the test procedure and contributed recommendations. These are summarized next.

- Passing No. 200 sieve: Data in Bandini and Al Shatnawi's discussion confirm the biasing effects of the coarser fraction retained on the No. 200 sieve (Fig. 5 in the original paper). We continue to recommend the use of the fine fraction passing a No. 200 sieve to classify fine-grained soil fractions.
- Initial salt concentration: Soil fabric studies are best performed with monoionic soils without excess salts (van Olphen 1977). However, soil washing with deionized water can dissolve precipitated salts that form part of the soil skeleton, as in saline formations and sabkha soils; clearly, the sensitivity of these soil types to pore fluid requires special consideration and test

procedures (Abduljawad and Al-Amoudi 1995; Frydman et al. 2008). The determination of liquid limit with deionized water in the absence of precipitated salts requires dilution until the salt concentration in the pore fluid is significantly less than 0.1 M because this is the aggregation threshold for common clays (Santamarina et al. 2001). This requirement does not affect soils that interact with freshwater, but it does affect marine sediments because the salt concentration in seawater is ~0.6 M.

- Measurements with kerosene: Bleeding: The packing density of low-plasticity mixtures affects the fall cone test (Thomas 1997), and excess liquid may bleed out as soils densify in the cup during the test. This also applies to kerosene tests and can cause measurement errors, as in Narsilio et al.'s discussion. We obtained repeatable measurements by filling the cup with a dense mix, with negligible kerosene bleeding during the cone insertion.
- Measurements with kerosene: Fumes: The choice of kerosene as a nonpolar fluid reflects its worldwide availability. Discussers raised concerns about fumes and its low flash point in the presence of an ignition source (65–85°C). We dried samples under ventilated fume hoods and completed the drying process either on a hot plate housed within the hood or in an oven (noting that the self-ignition temperature of kerosene exceeds 220°C in the absence of an ignition source).
- Rapid drying: The use of moisture analyzers expedites the determination of fluid mass fractions for repetitive measurements such as liquid limit determinations. Martínez et al. discuss the advantages of using a halogen moisture analyzer. While they report no incidents involving kerosene specimens, halogen lamps operate at temperatures above the self-ignition point of kerosene, and therefore a well-ventilated system is required.
- Cone method: Printed discussions and personal communications welcomed the adoption of the cone method for the determination of the liquid limit. The LVDT-instrumented cone used in Khoubani and Evans's discussion provides informative penetration depth-versus-time signatures that facilitate the determination of the liquid limit and improve the overall test reliability. To avoid corrections for altered weight proposed by the discussers, we suggest the use of a partially hollow cone ensuring that the combined weight of the cone and the LVDT plunger remains at 80 g.

Interpretation

Corrected Ratio

The three liquid limits combine into two ratios to typify the effect of pore fluid. Corrected ratios avoid differences in specific gravity G (kerosene) and residual salt (brine). Expressions for the corrected liquid limit and corrected ratios used for classification purposes that account for the salt concentration c in the brine follow, according to Narsilio et al.'s discussion:

$$LL_{\text{brine}}|_{\text{corrected}} = LL_{\text{brine}} \frac{1}{1 - c_{\text{brine}} \frac{LL_{\text{brine}}}{100}}$$

$$\frac{LL_{DW}}{LL_{\text{brine}}}|_{\text{corrected}} = \frac{LL_{DW}}{LL_{\text{brine}}} \left(1 - c_{\text{brine}} \frac{LL_{\text{brine}}}{100} \right)$$

Table 1. Soils and Index Properties

Contributor	Soil description	Mean particle size D_{50} (μm)	Specific surface S_s (m^2/g)	Plastic limit (PL) (%)	Liquid limit (LL) (%) (uncorrected)		Unified soil classification system (USCS)	New class	
					Deionized water	Brine		Kerosene	Plasticity
Original paper	Ottawa 20-30 sand	720	0.003	20	20	19	SP	N	L
	Silica flour	20	0.5	26	26	28	ML	N	L
	Diatom	10	89	113	110	138	MH	H	L
	Fly ash	20	2.1	47	47	45	ML	L	L
	Kaolinite	0.36	34	31	67	82	CH	I	I
	Illite	0.5	110	29	67	37	CH	I	I
	Bentonite	0.07	565	44	276	39	CH	H	H
	Red Sea sediment (microfossils)	120	48	110	263	100	SW	H	H
	Piedmont GA-1	—	—	34	53	44	CH	L	L
	Clay /Adairsville GA-1	—	—	37	65	45	CH	L	I
	Silt /Matanuska Glacier	—	—	25	33	40	ML	L	I
	Piedmont GA-2	—	—	40	63	57	CH	I	L
	Clay /Adairsville GA-2	—	—	34	91	53	CH	I	I
Ponza bentonite	—	—	70	390	90	CH	H	H	
Bisaccia clay	—	—	60	110	65	MH	I	H	
Organic powder: starch	—	—	37	75	57	OH	I	L	
Organic powder (intraporous)	—	—	120	127	107	OH	H	H	
Calcium carbonate powder	—	—	17	25	23	CL	N	I	
Authors' additional data	Kaolinite	—	24	38	81	55	MH	I	I
	Green clay: illite	—	18	28	48	57	CH	L	I
	Bentonite	—	579	54	288	126	CH	H	H
	Fly ash: TCP-1	—	—	—	50	47	—	L	L
	Fly ash: TCP-2	—	—	—	45	36	—	L	L
	Fly ash: TVA	—	—	—	36	30	—	L	L
	Mesilla soil	60	48	21	41	40	CL-ML	L	L
	Kaolin	0.7	26	31	54	46	ML	L	L
	Diatomite	3.5	112	94	123	101	MH	H	L
	Diatomite:kaolin = 40:60	1.1	60	47	72	63	MH	I	I
	Diatomite:kaolin = 60:40	1.8	73	61	87	74	MH	I	I
	Portland soil	—	—	—	43	40	CL	L	L
	Khoubani and Evans's discussion	Kaolinite	—	—	—	53	56	CH	I
Bentonite		—	—	—	552	148	CH	H	H
Silica flour:kaolinite = 0:100		—	—	—	65	55	—	I	L
Silica flour:kaolinite = 25:75		—	—	—	51	40	—	L	L
Silica flour:kaolinite = 50:50		—	—	—	39	31	—	L	L
Silica flour:kaolinite = 75:25		—	—	—	33	27	—	N	I
Silica flour:kaolinite = 100:0		—	—	—	29	27	—	N	L
Bentonite:kaolinite = 100:0		—	—	—	509	103	—	H	H
Bentonite:kaolinite = 75:25		—	—	—	341	105	—	H	H
Bentonite:kaolinite = 50:50		—	—	—	220	71	—	I	H
Bentonite:kaolinite = 25:75		—	—	—	132	66	—	I	I
Sand		1,000	—	—	7	6.5	—	N	L
Montoro and Francisca's discussion		Bentonite	—	731	192	309	113	MH	H
	Kaolinite	—	58	36	43	40	ML	L	L
	Zeolite	11	61	42.1	50	48	MH	L	L
	Silt	5	1.1	22.5	25	21	MH	N	I

Table 1. (Continued.)

Contributor	Soil description	Mean particle size D_{50} (μm)	Specific surface S_s (m^2/g)	Plastic limit (PL) (%)	Liquid limit (LL) (%) (uncorrected)			Unified soil classification system (USCS)	New class	
					Detonized water	Brine	Kerosene		Plasticity	Electrical sensitivity S_E
Narsilio et al.'s discussion	Weathered mudstone (Silurian)	20	25	21	32	25	41	CL	N	H
	Coo de Island silt	10	61	23	67	41	35	CH	L	I
	Wollert basaltic clay	1	232	27	61	53	32	CH	I	I
	Mount Ridley basaltic clay	1	257	40	69	54	33	MH	I	I
	Braybrook basaltic clay	5	210	30	67	50	30	CH	I	I
	Arumpo bentonite	1	526	44	167	78	54	CH	H	I
	Land cover: Queensland	2	24	15	21	21	32	CL-ML	N	I
	Silty clay (Melbourne Silurian)	2	80	20	48	40	47	CL	L	I
	Silica flour	13	1.5	26	31	30	31	ML	L	L
	Diatomaceous earth	3.7	103	99	130	111	138	MH	H	L
Schneider et al.'s discussion	LPC kaolin	2.4	26	26	53	48	74	CH	I	I
	Edgar plastic kaolin (EPK)	0.34	44	32	69	59	60	CH	I	L
	Montmorillonite			48	450	80	38	CH	H	H
	Santa Barbara Channel 1 (offshore)	13	35	28	45	41	42	ML	L	L
	Santa Barbara Channel 2 (offshore)	14	34	31	39	37	37	ML	L	L
	Santa Barbara Channel 3 (offshore)	13	26	29	37	35	37	ML	L	L
	Santa Barbara Channel 4 (offshore)	11	35	29	51	48	56	ML	I	L
	High-plasticity clay, Galveston, Texas	0.42	132	33	96	63	36	CH	I	I
	Redart clay	6.9	36	21	40	40	43	CL	L	L
	Arduino et al., ^a University of Washington	Volcanic ash	—	—	—	380	83	47	—	H
Kaolin		—	—	—	62	66	88	—	I	L
Tsai silty clay		—	—	—	39	35	43	—	L	L
Oregon red clay		—	—	—	40	45	52	—	L	L
J. Cordero ^a UPC	Barcelona soil	—	44	19	34	36	32	—	L	L
	Raw kaolin (clayey silt), Dresden, Germany	—	—	32	47	43	54	ML	L	I

Note: TCP = Tanner's Creek Plant; TVA = Tennessee Village Authority; UPC = Universitat Politecnica de Catalunya.

^aPersonal communication.

$$\frac{LL_{ker}}{LL_{brine}} \Big|_{corrected} = \frac{LL_{ker}}{LL_{brine}} \frac{1 - c_{brine} \frac{LL_{brine}}{100}}{G_{ker}}$$

where the subscripts *DW* and *ker* = deionized water and kerosene.

Sensitivity to Pore Fluid

Fig. 1 highlights the response of soils to pore-fluid chemistry. This figure corresponds to Fig. 6 in the original paper, but it is presented herein using a linear scale to increase clarity (noting that classification boundaries plot as circles in linear scale).

Soils that are not sensitive to salt concentration in the pore fluid have $LL_{brine} \sim LL_{DW}$; measurement errors related to either tests with brine or deionized water may result in values $LL_{DW}/LL_{brine} \approx 1 \pm 0.05$. Otherwise, the data set in Table 1 indicates that higher liquid limits should be expected in soil-water pastes than in soil-brine pastes: mineral surfaces develop thick double layers, interparticle repulsion increases, and the higher porosity fabric in soil-water pastes than in soil-brine pastes results in $LL_{DW}/LL_{brine} \geq 1.0$. Conversely, surface charges are readily neutralized by thin double layers in soil-brine pastes and the van der Waals attraction brings particles together in face-to-face aggregation.

Kerosene has a low polarity (relative permittivity 1.8) and does not hydrate counterions attracted onto dry mineral surfaces or precipitated salts. van der Waals attraction aggregates dry particles together when mixed with kerosene. The effect is most pronounced when thin platelets are involved; in fact, bentonite-kerosene pastes feel more sandy, require less kerosene to saturate, contract less

during drying, and are weaker after drying than kaolinite-kerosene pastes. Both bentonite-kerosene and kaolinite-kerosene pastes contract during drying; therefore, differences in measured liquid limits are not due to contact angle or surface tension but to particle aggregation in the presence of a nonpolar fluid (surface tensions are 72 mN/m for water, ~80 mN/m for brine, and ~23 mN/m for kerosene).

The horizontal axis in Fig. 1 compares the liquid limit values obtained for soil-kerosene and soil-brine pastes. Approximately 70% of the soils in the database exhibit $LL_{ker} > LL_{brine}$; these soils include 1:1 kaolinite, organic powders with inner pores, diatomaceous sediments, and fly ash. While double layers are thin in brine-saturated soils, the high specific surface of montmorillonitic soils compounds hydration effects to render $LL_{brine} > LL_{ker}$. Experimental evidence collected in our field for decades corroborates the distinct response of montmorillonite and kaolinite to organic fluids (details and references in the original paper).

Classification Boundaries

The complete data set is plotted on the proposed classification chart in Fig. 2 (supersedes Fig. 7 in the original paper). Montoro and Francisca noted meaningful agreement with hydraulic conductivity data for various fluids, Martinez et al. and Bandini and Al Shatnawi contributed mixture data to assist boundary definitions, and Narsilio et al. and Schneider et al. questioned the selection of classification boundaries and their engineering significance. The following observations address the selection of classification boundaries:

- $LL = 30$ boundary: This is the water content when nonplastic silts and sands are approximately at their loosest configuration. Therefore, a higher water content would cause grains to lose contact and liquefy. This threshold resembles the liquid limit $LL = 20$ where the A-line intersects the plastic index (PI) = 0 axis in the Casagrande chart. Martinez et al. suggest lowering the low-plasticity boundary to $LL_{brine} = 25\%$ based on their results with mixtures; the complete database does not show improved clustering or discrimination.

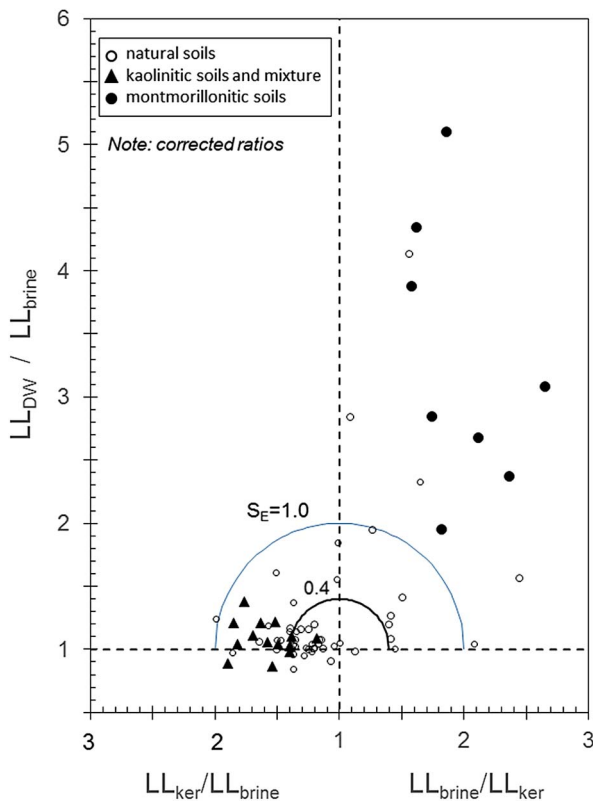


Fig. 1. Sediment response to changes in fluid conductivity and permittivity; circular boundaries correspond to electrical sensitivities $S_E = 0.4$ and $S_E = 1.0$; see Table 1 for more information (data from the original paper and discussions; data courtesy of Arduino et al., University of Washington; J. Cordero, Polytechnic University of Catalonia; and Herle et al., Technische Universität Dresden)

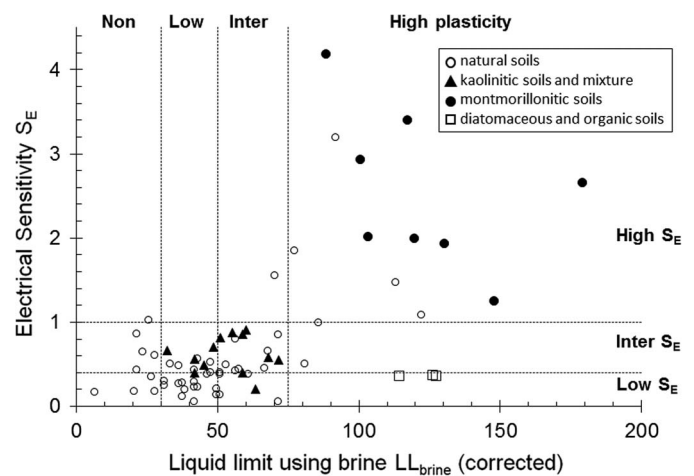


Fig. 2. Soil classification chart; the 12 different zones are labeled using two letters: the first letter indicates plasticity (N, L, I, or H), the second letter electrical sensitivity (L, I, or H); see Table 1 for more information (data from the original paper and discussions; data courtesy of Arduino et al., University of Washington; J. Cordero, Polytechnic University of Catalonia; and Herle et al., Technische Universität Dresden)

- $LL = 50$ boundary: The plot of LL_{ker} versus LL_{brine} shows that a dual trend emerges when $LL_{brine} > 50$. In addition, $LL = 50$ benefits from past experience gained with the Casagrande chart.
- $LL = 75$ boundary: Separates kaolinite and illite from the smectite group.
- $S_E < 0.4$ zone: Includes nonplastic silty and sandy soils and diatomaceous soils.
- $0.4 < S_E < 1.0$ zone: Captures kaolinite and illite.
- $S_E > 1.0$ zone: Involves soils with a high electrical sensitivity to pore-fluid characteristics. The zone is populated by the high specific surface montmorillonitic soils in the database.

Conclusion

We are grateful to all the discussers for their time and generous input. The multiple communications reported here reflect a valuable community effort toward a new fines classification method. Clearly, the three liquid limits provide insightful information

related to the sensitivity of fine soil fractions to pore-fluid characteristics. We encourage researchers to test and report the three liquid limits in future studies so that classification clusters and engineering implications become increasingly apparent.

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