

ON THE ELECTRICAL SENSITIVITY OF SOFT MARINE SEDIMENTS

Francesca Sollecito

francesca.sollecito@poliba.it

Osvaldo Bottiglieri

osvaldo.bottiglieri@poliba.it

Rossella Petti

rossella.petti@poliba.it

Claudia Vitone

claudia.vitone@poliba.it

DICATECh, Politecnico di Bari, Bari, Italy

Abstract

The geotechnical characterisation of polluted sediments retrieved in natural environments and marine basins appears quite challenging due to their high-water content and soft consistency and the inclusion of several sources of complexities in the soil matrix. Marine sediments may contain, all together, organic matter, shells, microfossils and diatoms, salts, heavy metals and organic pollutants, which may induce some bias in measurement and classification of fine-grained soils. This is the case of sediments coming from Mar Piccolo (Southern Italy), a contaminated marine basin near the coast, exposed to both natural and anthropogenic sources of contamination. Several soil samples have shown peculiar geotechnical properties in terms of plasticity and activity indexes, compressibility and hydraulic permeability. The framework defined for normally consolidated natural clays and the laboratory standards do not focus on soils containing sources of complexity such as those typical of contaminated marine sediments. It follows that some novelties might be introduced in the phase of soil testing and data analysis, to expand the classification of fine-grained soils. This note is aimed to illustrate the results of the application of a new type of classification of fine-grained soils, based on liquid limit determinations, which highlights the electrical sensitivity of clays to pore-fluid chemistry due to chemical-electrical interparticle bounds, soil composition and fabric.

1. Electrical sensitivity classification

Currently every kind of fine-grained sediment can be described through Atterberg Limits that define the phase changes of the material, according to the water content. Besides they are the basis of “Casagrande’s Plasticity Chart”, used by the “Unified Soil Classification System” (USCS).

Pore-fluid chemistry, i.e., pH, ionic concentration, and permittivity, is not addressed in current classification systems although changes in pore-fluid chemistry have been known to alter characteristics of fine-grained sediments (e.g., Santamarina et al., 2002; Mitchell and Soga, 2005; Spagnoli et al., 2011; Goodarzi et al., 2016).

In order to explicitly consider the effect of pore-fluid chemistry on the classification of fine grains, Jang and Santamarina (2016) proposed a new classification of fine soils system based on the liquid limit

determination, as an attempt to address the demands of geotechnical engineers who require a methodology that systematically characterizes fines for diverse geotechnical applications. According to the procedure suggested by the authors, liquid limits are determined by using the fall cone test (BS 1377 1990) on the passing sieve No. 200 soil fraction, mixed with different pore fluids. Specifically, three fluids with different relative permittivity κ_0 and electrical conductivity σ_{el} are identified to explore distinct electrical fluid particle interactions: deionized water ($\kappa_0 = 80$, $\sigma_{el} = 10^{-6}$ S/m), NaCl brine (concentration $c = 2$ M, $\kappa_0 = 55$, $\sigma_{el} = 12$ S/m), and kerosene ($\kappa_0 = 2$, $\sigma_{el} = 10^{-11}$ S/m).

The number of physicochemical interactions in soils was qualitatively expressed by the electrical double layer theory. The Gouy-Chapmann model (Gouy, 1910; Chapman, 1913) suggests that the reduction of the double layer thickness is due to the increase in either electrolyte concentration or cation valence of the fluid as well as the reduction of fluid permittivity. 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. 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 when the liquid limit measured with brine LL_{brine} . 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. Therefore, the liquid limit measured with kerosene LL_{ker} emphasises particle aggregation in the presence of a nonpolar fluid, when the double layer is suppressed.

From these LL measurements, the electrical sensitivity S_E can be computed as reported in Eq. 1. 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.

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

A new classification chart is proposed Jang and Santamarina (2016, 2017) and reported in Fig. 1. 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.

In addition to the areas of no-, low-, intermediate-, or high plasticity of fine soils, the new classification chart of the numerous soils tested allows the authors to identify areas of low, intermediate, or high electrical sensitivity:

- $S_E < 0.4$ zone of low electrical sensitivity: it includes nonplastic silty and sandy soils and diatomaceous soils.
- $0.4 < S_E < 1.0$ zone of intermediate electrical sensitivity: it captures kaolinite and illite.
- $S_E > 1.0$ zone of high electrical sensitivity: it 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 from the authors.

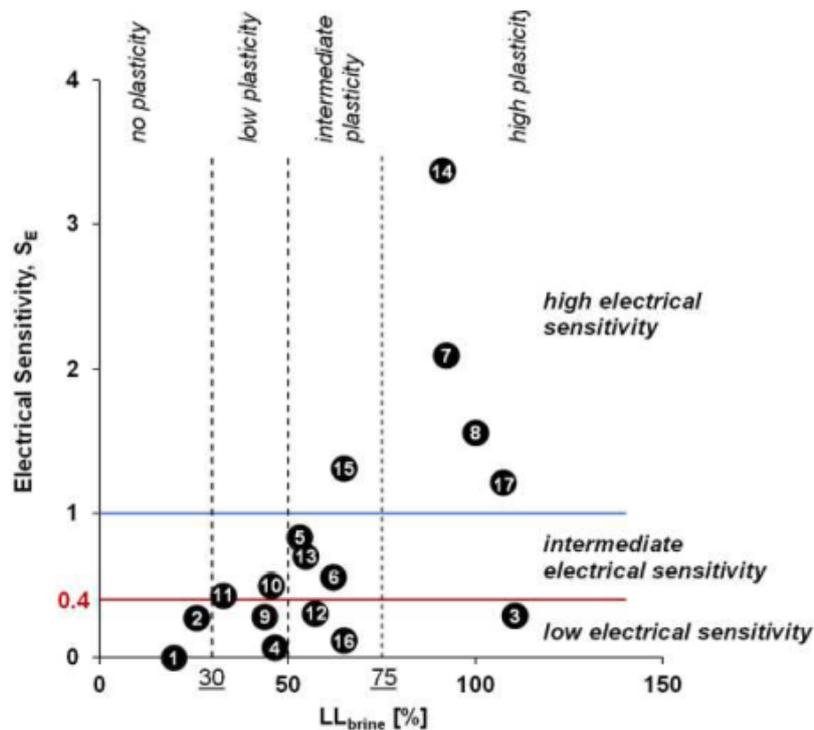


Fig 1. Chart for the classification of fine grains on the basis of electrical sensitivity and liquid limit (Jang and Santamarina 2016); numbers in black circles refer to soils analysed by the authors; the $S_E = 0.4$ and $S_E = 1.0$ lines correspond to the boundaries defined by authors.

2. Electrical sensitivity of sediment samples

1.1 Testing materials

The Mar Piccolo sediments samples were retrieved down 19 boreholes drilled in the basin from 0 to 39 m below seafloor (bsf). It has been shown that the top sediments (by 5 m depth) are contaminated by heavy metals (e.g., arsenic As, lead Pb, cadmium Cd, mercury Hg, copper Cu, zinc Zn), asbestos and organic pollutants (polycyclic aromatic hydrocarbons PAHs, chlorinated solvents, polychlorinated biphenyls PCBs, and dioxins) and contain high concentration of organic matter (LOI = 10-18%). Sediments are mostly fine-grained soils, whose clay fraction (CF) varies between 22.5 and 65.4%, sand fraction (SF) between 0.5 and 29.4%, and silt fraction (MF) from 30.5% to 69.5% (ASTM D 422). The geotechnical characterisation of these clayey sediments has shown that the physical and mechanical properties of the recent MP sediments do not vary solely with the composition of the soil skeleton and the soil deposition-loading history, as expected for uncontaminated recent sediments (Sollecito et al., 2022). Indeed, despite the limited variability in composition with depth, the samples are characterised by a large variability of both the plasticity (PI) and activity index (A), as revealed by the Activity chart in Fig. 2. In particular, the shallow samples (circles in Fig. 2) are characterised by the highest variability of both PI (from 34.0 to 78.8%) and A (from 0.60 to 2.49), and by the highest values of both these indexes.

Two MP samples and a sample collected outside the basin (Mar Grande sample) have been selected as a first attempt to define the electrical sensitivity of the sediment matrix. The shallow sample S9-S represents a peculiar sample which exhibits the lowest activity index among the shallow samples, despite including high CF and high smectite ($S_m = 26.1\%$; Sollecito et al., 2022). S7-ASP was retrieved at depth in the Sub-Apennine clays (ASP, hereafter), which represents the parent formation of most of the sediments deposited in the bays (Cotecchia et al., 2021). Lastly, the Mar Grande (MG) sample represents a remoulded silty sample of intermediate activity (Fig. 3). It was collected from the fill-in basin in the

Port of Taranto into which the sediment dredged from one of the piers was dumped. The composition and the main properties of the tested samples are summarised in Tab. 1. Among the clay minerals of the sediments here of reference, smectite is prevalent (9-27 wt.%), followed by mica (i.e., muscovite 7-12 wt.%), kaolinite (3.2-5.2 wt.%) and chlorite (2.7-3.9 wt.%) (Sollecito et al., 2022).

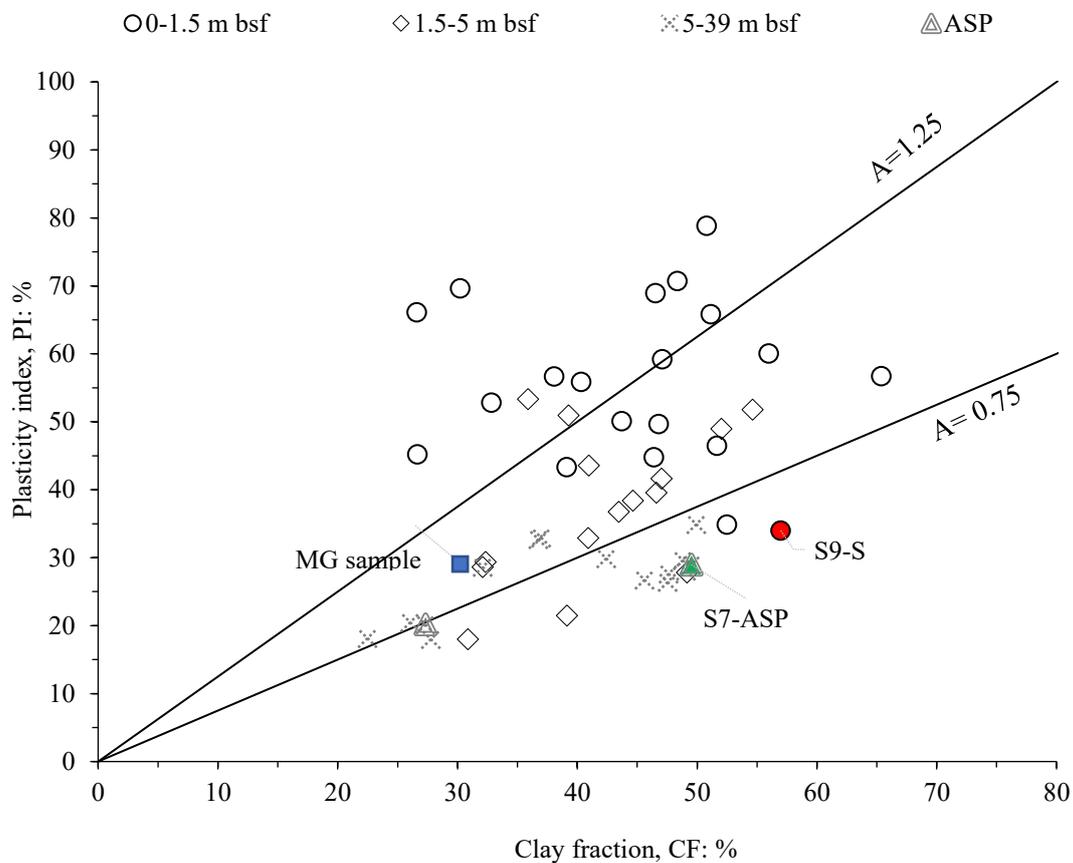


Fig. 2. Activity chart of the MP sediments (after Sollecito et al., 2022).

Sample (site-layer)	Average depth	SF	MF	CF	γ	e_0	LL	PI	A	LI
	m bsf	%	%	%	kN/m ³	-	%	%	-	-
S9-S	0.5	4.0	39.0	57.0	13.97	3.094	61.8	34.0	0.60	2.57
S7-ASP	14.25	3.2	47.3	49.5	19.64	0.741	53.5	29.0	0.59	0.10
MG sample	-	5.8	63.8	30.4	15.95	2.092	53.4	28.2	0.92	1.73

Tab. 1. Composition and plasticity properties of the samples here of reference. Key: SF, sand fraction; MF, silt fraction; CF, clay fraction; γ , total unit weight; e_0 , initial void ratio; LL, liquid limit; PI, plasticity index; A, activity index; LI, liquidity index.

In the experimental phase, consistently with the study by Jang and Santamarina (2016), the sediments were washed with distilled water until negligible salinity values were obtained (Fig. 3). Differently from the procedure recommended by the authors, liquid limit tests were performed on the soil fraction passing the ASTM 40 sieve instead of ASTM 200 sieve, in order to investigate the effectiveness of the method also in compliance with the technical reference standard (ASTM D 4318).

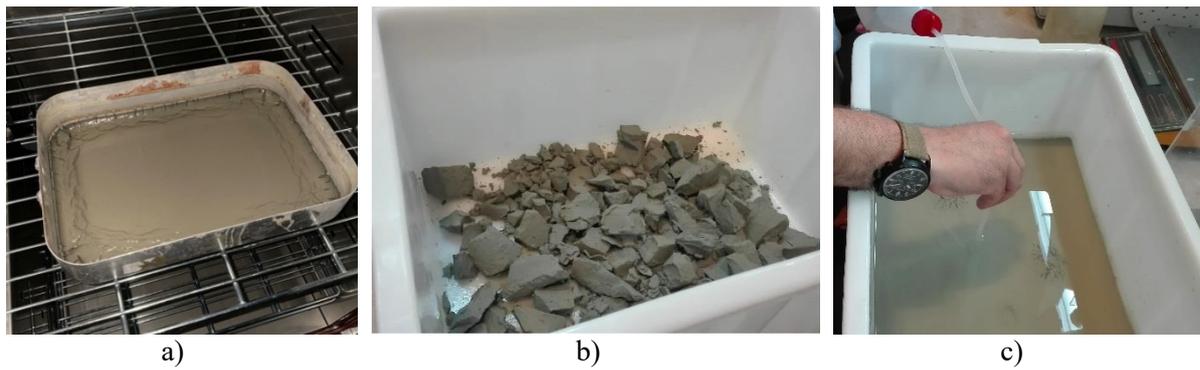


Fig. 3. Pictures of sediment samples after washing a) S9-S; b) S7-ASP; c) MG sample.

1.2 Results and conclusions

The three samples in Tab. 1 have been mixed with the pore fluids suggested by Jang and Santamarina (2016) for the definition of electrical sensitivity features. The results of the liquid limit determinations are listed in Tab. 2.

Sample	LL _{DW}	LL _{brine}	LL _{ker}	S _E	Plasticity classification	Electrical sensitivity classification
S9-S	47.55	51.60	41.80	0.21	intermediate	low
S7-ASP	38.36	48.90	38.09	0.31	low	low
MG sample	43.21	48.39	49.61	0.11	low	low

Tab. 2. Liquid limits of the sediment samples mixed with deionized water, brine and Kerosene and values of electrical sensitivity S_E of marine sediments computed according to Eq. 1.

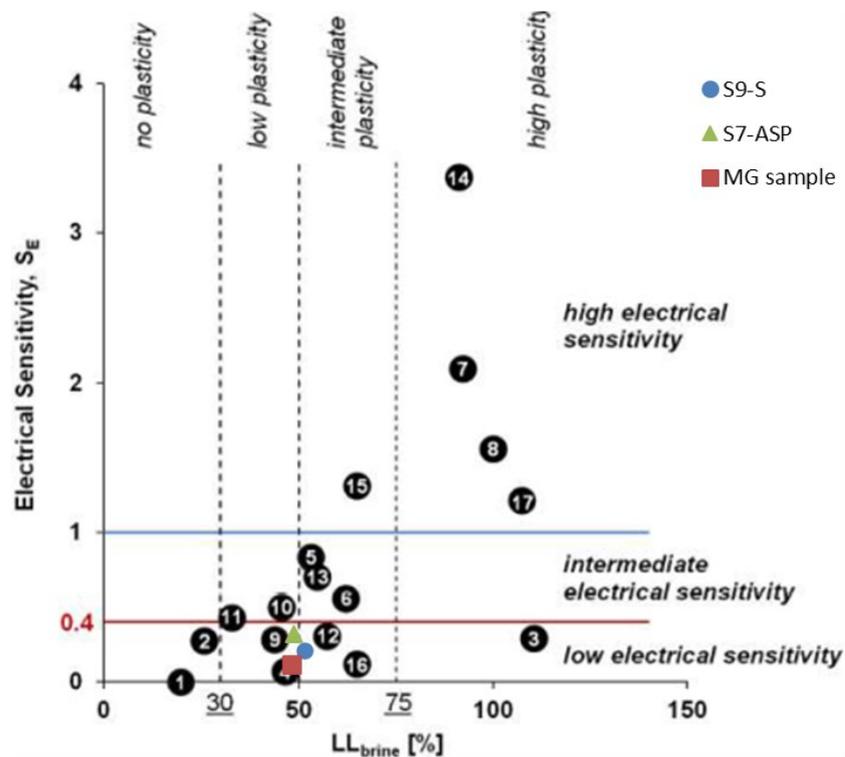


Fig.4. Sediment samples plotted on the electrical sensitivity classification chart (after Jang and Santamarina, 2016).

According to the electrical sensitivity classification suggested by Jang and Santamarina (2016), all the sediments are characterised by low electrical sensitivity and intermediate to low plasticity, as also visible in the electrical sensitivity classification chart (Fig. 4), despite their differences in the plasticity properties (Fig. 2; Tab. 1). For S9-S and S7-ASP $LL_{brine} > LL_{ker}$ and $LL_{brine} > LL_{DW}$, suggesting that the material tends to enhance Van der Waals attraction forces which bring particles together in face-to-face aggregation rather than repulsive forces. MG sample seems to respond to non polar kerosene since exhibits LL_{ker} slightly higher than LL_{brine} , differently from the other samples.

Although preliminary, these results seem to suggest that the sediment matrix sieved at the ASTM 40 sieve has similar sensitivity to external factors despite the differences in index properties exhibited by the three samples (Fig. 2; Tab. 1). It is supposed that the efficacy of the new classification could be limited by the preparation of the samples which includes only their sieving at ASTM 200 sieve. It follows that the effects of some coarser parts which are typical of marine sediments and are represented not only by sandy and gravel fractions but also by ‘electrically active’ elements, such as algae and other organic compounds, are not taken into account in the standard procedure. New tests are ongoing on other sediment samples with different physical properties and test replications are planned to be performed without the sieving phase before the laboratory determinations.

References

- ASTM D 422 (2007): Standard Test Method for Particle-Size Analysis of Soils. ASTM International, West Conshohocken, PA, USA.
- ASTM D 4318 (2017): Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International, West Conshohocken, PA, USA.
- British Standards Institution. British standard (BS) 1377-9. Methods of Test for Soils for Civil Engineering Purpose (1990).
- Chapman, D. L. (1913). “A contribution to the theory of electrocapillarity. *Philosophical Magazine*”. 25, 475–481.
- Cotecchia, F., Vitone, C., Sollecito, F., Mali, M., Miccoli D., Petti, R., Milella, D., Ruggieri, G., Bottiglieri, O., Santaloia, F., De Bellis, P., Cafaro, F., Notarnicola, M., Todaro, F., Adamo, F., Di Nisio, A., Lanzolla, A.M.L., Spadavecchia, M., (...) Corbelli, V. (2021). “A geo-chemo-mechanical study of a highly polluted marine system (Taranto, Italy) for the enhancement of the conceptual site model”, *Nature Scientific Reports*, 11, 4017.
- Goodarzi, A. R., Najafi Fateh, S. & Shekary, H. (2016). “Impact of organic pollutants on the macro and microstructure responses of Na-bentonite”. *Applied Clay Science*, 121–122 (C), 17–28.
- Gouy, G. (1910). “Electric charge on the surface of an electrolyte. *Journal of Physics*”. 4, No. 9, 457–468.
- Jang J., Santamarina C. (2016). “Fines Classification Based on Sensitivity to Pore-Fluid Chemistry”. *J. Geotech. Geoenviron. Eng.*, 142(4): 06015018. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001420](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001420)
- Jang J., Santamarina C. (2017). “Closure to “Fines Classification Based on Sensitivity to Pore-Fluid Chemistry”” DOI: 10.1061/(ASCE)GT.1943-5606.0001420.
- Mitchell, J. K. & Soga, K. (2005). *Fundamentals of soil behavior*. J. Wiley et Sons Ed., 3rd edition.
- Santamarina C., Klein K.A., Palomino A., Guimaraes M.S. (2002). “Micro-scale aspects of chemical-mechanical coupling: Interparticle forces and fabric”. Georgia Institute of Technology, Atlanta, Georgia, USA.
- Sollecito, F., Plötze, M., Puzrin, A.M., Vitone, C., Miccoli, D., Cotecchia, F. (2022). “Effects of bio-chemo-mechanical processes on the properties of contaminated marine sediments”, *Géotechnique*, <https://doi.org/10.1680/jgeot.21.00095>.
- Spagnoli, G., Fernández-Steeger, T., Feinendegen, M., Azzam, R. & Stanjek, H. (2011). “Influence of the dielectric constant, electrolyte concentration and pH of the pore fluids on the shear strength of monomineralic clays”. *Rivista Italiana di Geotecnica* 3/2011.