Discussion of "Fines Classification Based on Sensitivity to Pore-Fluid Chemistry" by Junbong Jang and J. Carlos Santamarina

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Atterberg limits of fine soils are strongly influenced by particle-fluid interaction phenomena, fluid chemistry, particle mineralogy, and testing procedure (Koumoto and Houlsby 2001). The original paper proposed a very interesting approach for soil classification considering particle-fluid interactions. The discussers consider that the additional data required for the evaluation of the impact of the fluid chemistry on liquid limits can be considered of great importance for several actual and new geotechnical and geoenvironmental engineering problems, including soil microstructure, and mineral-contaminant interactions during mass transport. The authors proposed classifying fine soils by determining their liquid limits using three different fluids: distilled water, kerosene and brine (1-M NaCl solution) with the purpose of determining the electrical and dielectric susceptibility of soil particles with regard to the formation of double layers around particles. From the different liquid limits the proposed methodology includes the evaluation of the electrical sensitivity as complementary data to the traditional description of soil plasticity.

The discussers highlight the relevance of fluid chemistry in reactive porous media behavior (e.g., fine-particle soils with high swelling minerals contents). Particle-fluid interactions that take place at a microscale are very often responsible for the macroscopic behavior of soils [e.g., changes in hydraulic conductivity reported by Montoro and Francisca (2010), soil compressibility reported by Tiwari and Ajmera (2014), and liquid sorption capacity reported by Benson et al. (2014)]. Results reported by these authors clearly show that observed behavior of fine soils with similar particle size distribution and similar plasticity but different mineralogy and affinity with water molecules can be attributed to a very different electrical susceptibility, still not captured by current soil classification systems. Also, the hydraulic conductivity of fine particle soils can be related to the free swelling potential of the soil in contact with different liquids (Jo et al. 2001; Kolstad et al. 2004; Lee et al. 2005).

Consistency, or Atterberg, limits determination is a first step of almost every geotechnical investigation. Values of consistency limits and soil classification allow engineers to have rapid and low-cost information that can often be used as indicators of the expected mechanical and hydraulic soil behavior. Terzaghi (1926) stated that consistency limits are important not only for soil classification but also to find out what these tests mean and discover the factors that determine their results. Since Casagrande (1932), typical behavior of fine soils have been grouped in different zones within the plasticity chart. Several decades later it was observed that liquid and plastic limits, traditionally determined by following ASTM D4318 (2014), can be also related to the undrained shear strength (S_u) of the soil at given moisture content. The value of S_u falls between 1.7 and 2.0 $\mathrm{kN/m^2}$ for the liquid limit, while for the plastic limit S_u can be up to 100 times greater than that of liquid limit (Stone and Kyambadde 2007; Nagaraj et al. 2012).

Particle-fluid interaction phenomena and its influence on soil behavior are significant for fine-particle soils. This phenomenon can be attributed to the formation of the diffuse double layer (DDL) around soil particles (Sposito 2008). The DDL's thickness depends on pore-fluid properties such as ion concentration, ion valence, fluid dielectric permittivity, and ionic strength. The influence of DDL formation and interparticle electrical forces on soil properties depends on particle sizes, specific surface, and the particle's mineralogy. However, as indicated by the authors, additional data to the consistency limits determined with deionized water are needed to characterize this complex phenomenon.

There were several efforts to gain advantages of the information that consistency limits and plasticity charts offer. Different zones were identified in the plasticity chart where data gathered from samples with different mineralogy fall in a given region (Seed et al. 1964; Schmitz et al. 2004). Due to the simplicity of these tests, there were several attempts to estimate different soil properties from correlations with consistency limits, including shear resistance, overconsolidation ratio, soil compressibility, and hydraulic conductivity (Sridharan and Nagaraj 2005; Lee et al. 2005; Stone and Kyambadde 2007; Dolinar 2009).

Geoenvironmental engineering problems have been gaining much relevance recently. Most typical problems involve contaminant transport through soils and barrier containment systems design. Bentonite is the most used clay to decrease the hydraulic conductivity of compacted soil liners and to enhance the retention of metal ions within the barrier (Benson 1993; Glatstein and Francisca 2015). Depending on bentonite type, its specific surface ranges from 400 to 900 $\mathrm{m^2/g}$, and therefore, the expected behavior is highly dependent on particle-fluid interaction processes.

The discussers determined the liquid limit of sand, silt, zeolite, kaolinite, and sodium bentonite using the falling cone technique, and employing deionized water, brine, and kerosene. The sand sample was divided in several fractions (Sieves No. 40–60, 60–100, and 100–200). However, in the case of sand it was only possible to determine the liquid limit for the original specimen. The falling cone test failed when testing the different sand fractions given that penetrations could not be measured because the cone penetrated the bottom of the cup for moisture contents as small as 1% for all mixing fluids.

Fig. 1(a) shows the discussers' results plotted considering the relations between liquid limits determined with deionized water, brine, and kerosene proposed by the authors, while Fig. 1(b) presents how the discussers' tested samples are classified according to the original paper's classification system. The sands and silt classifies as no plasticity–low electrical sensitivity, zeolite and kaolinite as low plasticity–low electrical sensitivity, and sodium bentonite as high plasticity–high electrical sensitivity. The proposed classification clearly helps analyze emerging behavior when mixtures of sands with these fine soils were permeated with deionized water, organic fluids, and ionic solutions. The greater the particle's specific surface, the greater the change in liquid limit and electrical sensitivity. These trends are in good agreement with the emergent

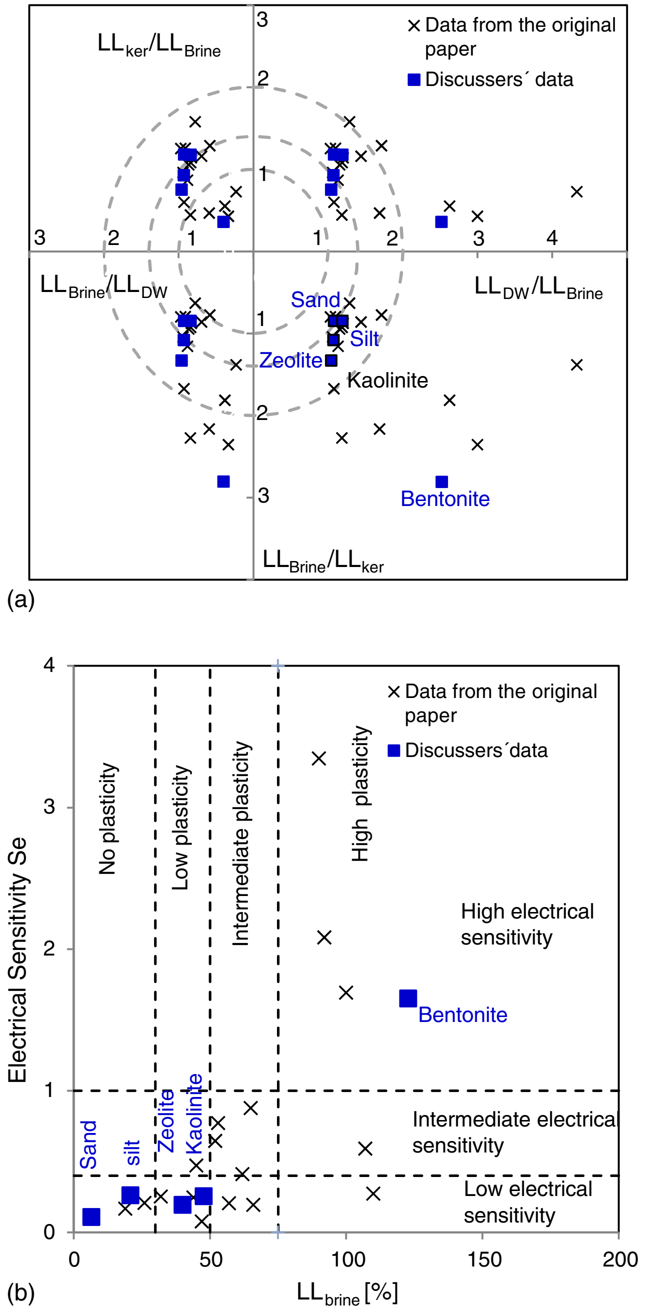

Fig. 1. (a) Soil response to changes in fluid properties; (b) discusser data plotted in the original paper's proposed classification chart

hydraulic conductivities reported by Montoro and Francisca (2010), who analyzed the influence of particle-fluid interaction on hydraulic conductivity by testing soils with deionized water, nonpolar organic fluids, and ionic solutions. They determined that the Kozeny-Carman equation represents reasonably well measured hydraulic conductivities for the same soil shown in Fig. 1 for the coarse-grained soils regarding the permeating fluid, and for fine soils tested with nonpolar organic fluids were particle-fluid interaction are negligible. Fernández and Quigley (1985) and Francisca et al. (2010) showed that hydraulic conductivity increases with the increase in the fluid dielectric permittivity. Also, Francisca et al. (2010) showed that hydraulic conductivity of the soils shown in Fig. 1 were very similar to each other regarding the specific surface of the soil when the permeating liquid has a very low dielectric permittivity (approximately 2).

In every analyzed case, the importance of the change in hydraulic conductivity depends on the electrical sensitivity of the fine particles. From this perspective, considering electrical sensitivity together with consistency limits is of key importance for geoenvironmental engineering problems. The classification system proposed by the authors gives a first description of typical soil behavior when dealing with contaminants. The discussers strongly believe that much research should still be performed in order to establish a unified soil classification system that considers not only plasticity properties but also electrical sensitivity.

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References

ASTM. (2014). "Standard test methods for liquid limit, plastic limit, and plasticity index of soils." *ASTM D4318*, West Conshohocken, PA.

Benson, C. H. (1993). "Probability distribution for hydraulic conductivity of compacted soil liners." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)0733-9410(1993)119:3(471), 471–486.

Benson, C. H., Jo, Y., and Musso, T. (2014). "Hydraulic conductivity of organoclay and organoclay-sand mixtures to fuels and organic liquids." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)GT.1943-5606.0001194, 04014094.

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

Dolinar, B. (2009). "Predicting the hydraulic conductivity of saturated clays using plasticity–value correlations." *Appl. Clay Sci.*, 45(1–2), 90–94.

Fernández, F., and Quigley, R. M. (1985). "Hydraulic conductivity of natural clays permeated with simple liquid hydrocarbon." *Can. Geotech. J.*, 22(2), 205–214.

Francisca, F. M., Montoro, M. A., and Nieva, P. M. (2010). "Macroscopic properties of soils controlled by the diffuse double layer around particles." *Res. Rev. Electrochem.*, 2(1), 1–5.

Glatstein, D. A., and Francisca, F. M. (2015). "Influence of pH and ionic strength on Cd, Cu and Pb removal from water by adsorption in Na-bentonite." *Applied Clay Science*, 118, 61–67.

Jo, H. Y., Katsumi, T., Benson, C. H., and Edil, T. B. (2001). "Hydraulic conductivity and swelling on nonprehydrated GCLs permeated with single-species salt solutions." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(2001)127:7(557), 557–567.

Kolstad, D. C., Benson, C. H., and Edil, T. B. (2004). "Hydraulic conductivity and swell of nonprehydrated geosynthetic clay liners permeated with multispecies inorganic solutions." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(2004)130:12(1236), 1236–1249.

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

Lee, J. M., Shackelford, C. D., Benson, C. H., Jo, H. Y., and Edil, T. B. (2005). "Correlating index properties and hydraulic conductivity of geosynthetic clay liners." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(2005)131:11(1319), 1319–1329.

Montoro, M. A., and Francisca, F. M. (2010). "Soil permeability controlled by particle–fluid interaction." *Geotech. Geol. Eng.*, 28(6), 851–864.

Nagaraj, H. B., Sridharan, A., and Mallikarjuna, H. M. (2012). "Reexamination of undrained strength at Atterberg limits water contents." *Geotech. Geol. Eng.*, 30(4), 727–736.

Schmitz, R. M., Schroeder, C., and Charlier, R. (2004). "Chemo–mechanical interaction in clay: A correlation between clay mineralogy and Atterberg limits." *Appl. Clay Sci.*, 26(1–4), 351–358.

Seed, H. B., Woodward, R. J., and Lundgren, R. (1964). "Clay mineralogical aspects of the Atterberg limits." *J. Soil Mech. Found. Div.*, 4(1), 107–131.

Sposito, G. (2008). *The chemistry of soils*, 2nd Ed., Oxford University Press, London.

Sridharan, A., and Nagaraj, H. B. (2005). "Hydraulic conductivity of remolded fine-grained soils versus index properties." *Geotech. and Geological Eng.*, 23(1), 43–60.

Stone, K. J. L., and Kyambadde, B. S. (2007). "Determination of strength and index properties of fine-grained soils using a soil minipenetrometer." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(2007)133:6(667), 667–673.

Terzaghi, K. (1926). "Simplified soil tests for subgrades and their physical significance." *Public Roads*, 7(8), 153–170.

Tiwari, B., and Ajmera, B. (2014). "Effects of saline fluid on compressibility of clay minerals." *Environ. Geotech.*, 1(2), 108–120.