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Revised soil classification system RSCS

Système révisé de classification des sols RSCS

Junghee Park, J. Carlos Santamarina
Earth Science and Engineering Department, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia, junghee.park@kaust.edu.sa

ABSTRACT: Soil classification is intended to help geotechnical engineers anticipate soil properties and behavior. However, the review of soil classification systems used worldwide -within the context of 100 years of experimental data- shows that transition boundaries between various soil denominations are often incompatible with observed behavior. The revised soil classification system RSCS considers attainable packing densities in sands and gravels (a function of their coefficient of uniformity and particle shape), and in the fines component (a function of its plasticity). The overall classification is based on a soil-specific triangular texture chart that is built using gravimetric-volumetric analyses adjusted using extensive soil data. Fines require further analysis when they control either the mechanical or fluid-flow characteristics of the soil; in this case, fines classification recognizes both the plasticity of fines and their electrical sensitivity to changes in pore fluid chemistry.

RÉSUMÉ: La classification des sols est destinée à aider les ingénieurs géotechniciens à anticiper les propriétés et le comportement des sols. Cependant, l'examen des systèmes de classification des sols utilisés dans le monde entier –dans le contexte de données expérimentales de 100 ans - montre que les limites de transition entre les différentes dénominations des sols sont souvent incompatibles avec le comportement observé. Le système révisé de classification des sols RSCS considère une compacité réalisable dans les sables et les graviers (une fonction de leur coefficient d'uniformité et de la forme des particules) et dans le composant des fines (une fonction de sa plasticité). Le classement général est basé sur un diagramme de texture triangulaire spécifique au sol qui est construit à l'aide d'une analyse gravimétrique-volumétrique ajustée en utilisant des données extensives du sol. Les fines nécessitent une analyse plus approfondie lorsqu'elles contrôlent soit les caractéristiques mécaniques, soit les caractéristiques du flux-fluide du sol; dans ce cas, la classification des fines reconnaît leur plasticité ainsi que leur sensibilité électrique aux changements dans la chimie du fluide pore.

KEYWORDS: Textural Chart, Soil Properties, Unified Soil Classification System.

1 SOIL CLASSIFICATON SYSTEMS WORLDWIDE

Soil classification systems have evolved to anticipate the behavior of soils based on simple index properties. The Unified Soil Classification System USCS is used worldwide. The USCS considers the percentage retained on sieve No. 200 (75-µm) to divide coarse-grained soils (more than 50% retained) from fine-grained soils (more than 50% passing). Modifications in the UK and France place the boundary at 35% of fines fractions, while the German classification system uses a 40% fines fraction (DIN 18196). Coarse grains are further grouped into gravels or sands using a 50% split on sieve No. 4 (4.76 mm), except for Germany's DIN which classifies coarse-grained soils as 'gravel' if the gravel fraction exceeds 40%.

In spite of the deep insight and understanding of soil behavior captured in soil classification systems addressed above: (1) particle shape does not enter any classification system yet particle shape plays a dominant role on the packing density of the coarse fraction (Youd 1973; Cho et al. 2006), (2) these systems employ fixed boundaries for coarse-fine mixtures while fine grains may exhibit a broad range of plasticity, (3) soil properties are controlled by fines although the fines fraction F_F is even lower than $F_F = 50\%$, and (4) fluid characteristics are not reflected in current soil classification systems although the pore-fluid chemistry plays a significant role in the behavior of fines.

This manuscript presents a revised soil classification system RSCS that builds on the accumulated lab and field experience since the introduction of the Unified Soil Classification System USCS in the 1930s. This manuscript summarizes detailed reports presented in Jang and Santamarina (2016&2017) and Park and Santamarina (2017).

2 UNDERLYING CONCEPTS

2.1 *Soil mixtures - Thresholds*

Let's define two threshold fines fractions. The low threshold fines fraction $F_F|^L$ is determined when coarse grains are densely packed and fine grains are loosely packed. The high threshold fines fraction $F_F|^H$ is identified when coarse grains are loosely packed and fine grains are densely packed. Fig. 1 shows conceptual sketches for threshold fractions in 2D. These thresholds define three distinct zones: (1) coarse-controlled; (2) transition; and (3) fine-controlled behavior.

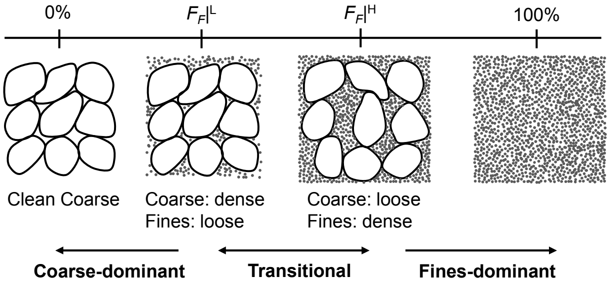

Figure 1. Coarse-fines mixtures: Threshold fractions. Coarse-dominant, transitional, and fines-dominant mixtures.

2.2 *Thresholds based on volumetric-gravimetric analyses*

The gravimetric-volumetric analyses of ternary mixtures (gravel, sand and fines) lead to the definition of analytically computed threshold boundaries in triangular charts. Gravels with void ratio e_G form a skeleton, and then, sands with void ratio e_S fill the pore space formed by the gravels. Finally, fines with void ratio e_F fill the remaining pores. The gravel fraction F_G, sand fraction F_S, and fines fraction F_F by weight computed from the void ratios of each grain e_G, e_S, and e_F are given by:

$$F_G = \frac{1}{\left(1 + \frac{e_G}{1+e_S} + \frac{e_S}{1+e_F}\frac{e_G}{1+e_S}\right)} \tag{1}$$

$$F_S = \frac{1}{\left(\frac{1+e_S}{e_G} + 1 + \frac{e_S}{1+e_F}\right)} \tag{2}$$

$$F_F = 1 - \left(F_G + F_S\right) \tag{3}$$

The various combinations of dense and loose packing states for each component define the individual threshold fractions that form the basis of the analytical soil classification boundaries in a triangular textural chart.

2.3 *Packing densities for sands and gravels*

The void ratios e^{max} and e^{min} capture loose and dense packing conditions of coarse grains (Fig. 1). These extreme void ratios depend on the coefficient of uniformity C_u and particle roundness R as shown in the Appendix.

2.4 *What void ratio should we use for fines?*

Fig. 2 describes the variation of clay fabrics with different pore fluid conditions (i.e. ionic concentration and fluid pH). Clearly, pore-fluid chemistry will play a significant role in the behavior of fines such as hydraulic conductivity and compressibility.

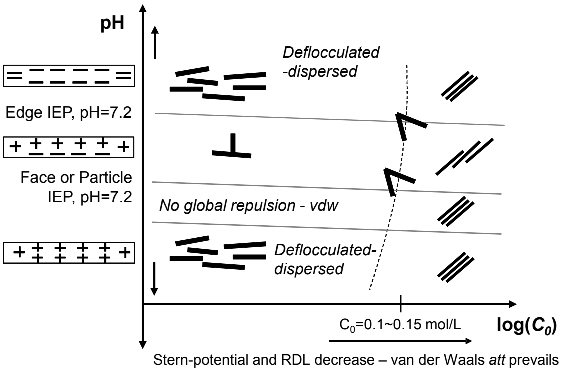

Figure 2. Clay fabrics with different pore fluid conditions (Palomino and Santamarina 2005).

Loading carrying. We select two reference void ratios to represent loose and dense packing condition of fines. The void ratio of fines at σ'=10 kPa ($=e_F|^{10kPa}$) and the void ratio of fines at σ'=1 MPa ($=e_F|^{1MPa}$) – See Appendix for the estimation of these values in terms of liquid limit LL.

Flow control. The seepage force can drag loosely packed fine grains. The fines migration driven by fluid flow through a porous network leads to the formation of bridges at pore throats. Sands and gravels will experience a pronounced decrease in hydraulic conductivity even when the packing condition of fines is very loose with a high void ratio $e_F >> e_F|^{10kPa}$. Hence, we select a void ratio of fines that capture the onset of fines migration and the transition from coarse-controlled to fines-controlled fluid flow by using plasticity dependent factor λ:

$$e_F\big|^{flow} = \lambda e_F\big|^{LL} \quad \text{where} \quad \lambda = 2\log(LL-25) \geq 1 \tag{4}$$

where the void ratio at the liquid limit is $e_F|^{LL} = G_s LL/100$.

2.5 *Data-based corrections*

Soil properties including porosity, hydraulic conductivity, compression index, and friction angle are plotted according to fines fraction in Fig. 3. An extensive compillation of similar data for various soils lead to correction factors for theoretically computed threshold fractions (details in Park and Santamarina 2017).

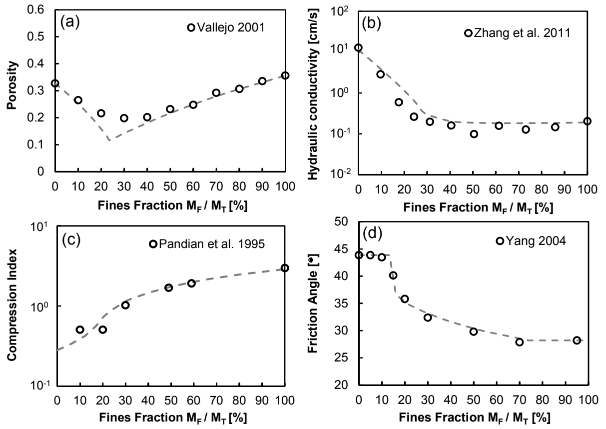

Figure 3. Soil porosity versus fines fraction by weight: (a) Porosity; (b) Hydraulic conductivity; (c) Compression index; (d) Friction angle.

3 REVISED SOIL CLASSIFICATION SYSTEM RSCS

3.1 *Overall Classification: Fluid flow and mechanical control*

Let's accept the general definition of gravel (retained on sieve #4), sand (passing through sieve #4 and retained on sieve #200), and fines (passing through sieve #200). Any one of these soil components can control the mechanical and hydraulic behavior of a soil mixture. For example, a densely packed sand near e_S^{min} will carry the load and control the mechanical behavior of a sand-gravel mixture when the gravel is looser than e_G^{max} and "floats" in the sand. Similar analyses define the void ratios for the 13 notable mixtures listed in Table 1. Specific factors included in the definition of these mixtures reflect data-based corrections discussed above.

We use gravimetric-volumetric equations 1-3 and these notable mixtures to determine classification boundaries in the triangular RSCS classification chart, both for flow-control and for mechanical control. The classification procedure follows:

- Sand and gravel components: input e^{max} & e^{min}. Alternative, determine the coefficient of uniformity C_u and the mean particle roundness R for the gravel and sand components and estimate extreme void ratios with equations in the Appendix.
- Fines: Input the void ratio of fines at σ'=10 kPa, σ'=1 MPa, and at the liquid limit LL. Alternative, input the liquid limit LL and estimate these three values with equations in the Appendix.
- Compute notable mixtures ①-through-⑨ for mechanical-control and ⑩-through-⑬ for flow control; plot the 13 notable mixtures on the triangular chart and draw the classification boundaries as shown in Fig. 4(a).
- Classify the soil under consideration. The double letter nomenclature recognizes: first, the soil fraction that controls the mechanical behavior and second, the soil fraction that controls flow (in parenthesis).

Note: the Excel file available on the authors' websites simultaneously draws the chart, classification boundaries and plots the point that represents the soil under consideration.

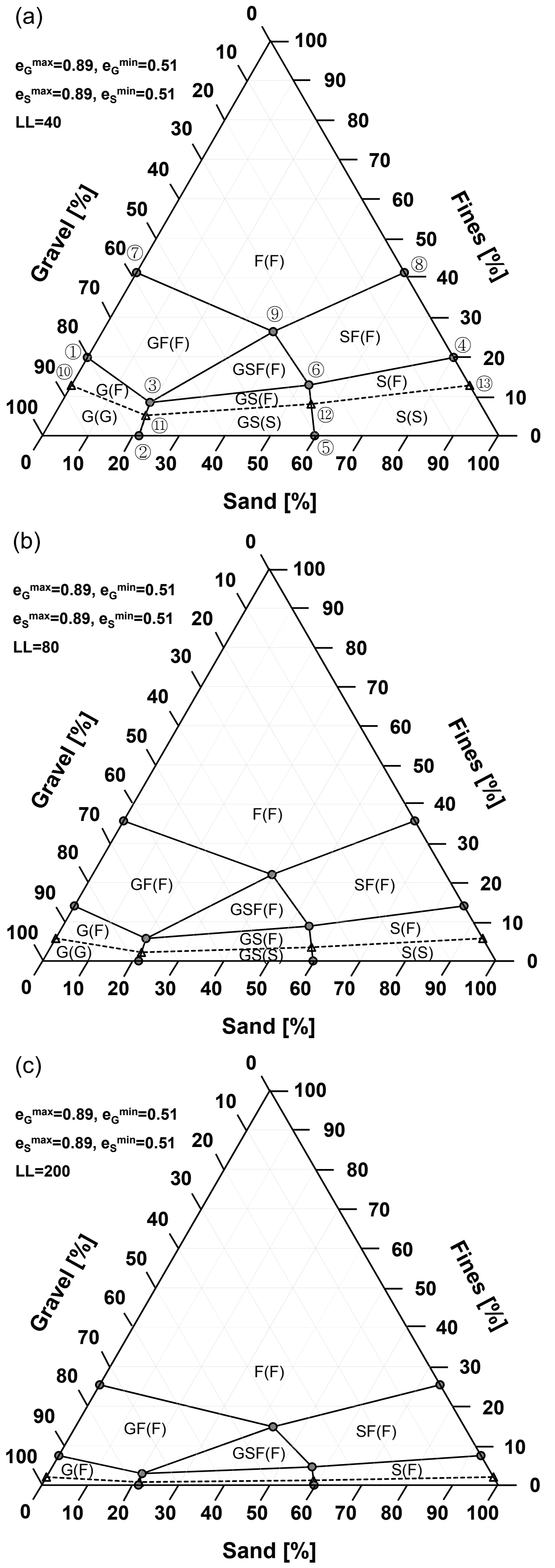

Figure 4. Soil classification boundaries: (a) Low plasticity fines LL=40; (b) Intermediate plasticity fines LL=80; (c) High plasticity fines LL=200. Load-carrying fraction (gray circles) and fluid flow controlling fraction (triangles).

Table 1. Notable mixtures.

		Mixture No.	Packing Condition		
			Gravel	Sand	Fines
(a) Mechanical control	Gravel-controlled	①	e_G^{min}	-	$e_F\vert^{10kPa}$
		②	e_G^{min}	e_S^{max}	-
		③	e_G^{min}	e_S^{max}	$e_F\vert^{10kPa}$
	Sand-controlled	④	-	e_S^{min}	$e_F\vert^{10kPa}$
		⑤	$2.5e_G^{max}$	e_S^{min}	-
		⑥	$2.5e_G^{max}$	e_S^{min}	$e_F\vert^{10kPa}$
	Fines-controlled	⑦	$1.3e_G^{max}$	-	$e_F\vert^{1MPa}$
		⑧	-	$1.3e_S^{max}$	$e_F\vert^{1MPa}$
		⑨	$2.5e_G^{max}$	$1.3e_S^{max}$	$e_F\vert^{1MPa}$
b) Flow control	Fines-controlled	⑩	e_G^{min}	-	$\lambda e_F\vert^{LL}$
		⑪	e_G^{min}	e_S^{max}	$\lambda e_F\vert^{LL}$
		⑫	$2.5e_G^{max}$	e_S^{min}	$\lambda e_F\vert^{LL}$
		⑬	-	e_S^{min}	$\lambda e_F\vert^{LL}$

Note: the physical background and meaning of notable mixtures ①-to-⑬ is detailed in Park and Santamarina (2017).

The two-name nomenclature results in 10 soil groups illustrated in Fig. 4. For example, a S(F) soil has sand-controlled mechanical properties but fines-controled permeability.

The hydraulic conductivity is controlled by the fines fraction in F, GF, SF, and GSF soil groups (Fig. 4). While the two-name nomenclature F(F), GF(F), SF(F) and GSF(F) is redundant in these cases, it clearly states the distinct role of fines on both mechanical and flow properties.

Classification boundaries move down towards lower fines fractions as the plasticity of fines increases (Fig. 4). Indeed, fines plasticity plays a critical role in the position of boundaries for both mechanical and hydraulic controls.

3.2 *Fines classification: Plasticity and electrical sensitivity*

Liquid limit: Electrical sensitivity. Soils that are fines-controlled -either in their mechanical and/or flow response-require further analysis to determine the type of fines. The most salient characteristics of fines are their (1) specific surface and (2) sensitivity to pore fluid chemistry. Both are reflected in liquid limits maeasured with various fluids (details in Jang and Santamarina 2016). Liquid limits should be determined on the soil fraction passing sieve #200 (=75-μm) using the fall cone method for repeatability (BSI 1990).

We select deionized water LL_{DW}, brine LL_{brine} to collapse the double layer (2 M NaCl solution), and kerosene LL_{ker} to explore the effect of van der Waals forces. Then, we correct measured liquid limits for specific gravity and precipitated salts and compute two ratios LL_{ker}/LL_{brine} and LL_{DW}/LL_{brine}:

$$\left.\frac{LL_{\ker}}{LL_{brine}}\right|_{corr} = \frac{LL_{\ker}}{LL_{brine}} \, \frac{1-c_{brine}\dfrac{LL_{brine}}{100}}{G_{\ker}} \tag{5}$$

$$\left.\frac{LL_{DW}}{LL_{brine}}\right|_{corr} = \frac{LL_{DW}}{LL_{brine}}\left(1-c_{brine}\frac{LL_{brine}}{100}\right) \tag{6}$$

where c_{brine} is the concentration of NaCl brine [mol/L] and G_{ker} is the specific gravity of kerosene.

Electrical sensitivity S_E. The electrical sensitivity S_E captures the distance between measured values and the absolute "non-sensitive" soil response at LL_{ker}/LL_{brine}=1 and LL_{DW}/LL_{brine}=1

$$S_E^{(left)} = \sqrt{\left(\frac{LL_{\ker}}{LL_{brine}}-1\right)^2+\left(\frac{LL_{DW}}{LL_{brine}}-1\right)^2} \tag{7}$$

when LL_{ker}/LL_{brine}>1 or

$$S_E^{(right)} = \sqrt{\left(\frac{LL_{brine}}{LL_{\ker}}-1\right)^2 + \left(\frac{LL_{DW}}{LL_{brine}}-1\right)^2} \qquad (8)$$

when $LL_{brine}/LL_{ker}>1$.

Fines classification chart. Fig. 5 presents the classification chart and data contributed by our group and researchers around the world. Fines can fall into 12 classifications as a function of their plasticity (first letter: N, L, I or H) and their electrical sensitivity (second letter: L, I or H).

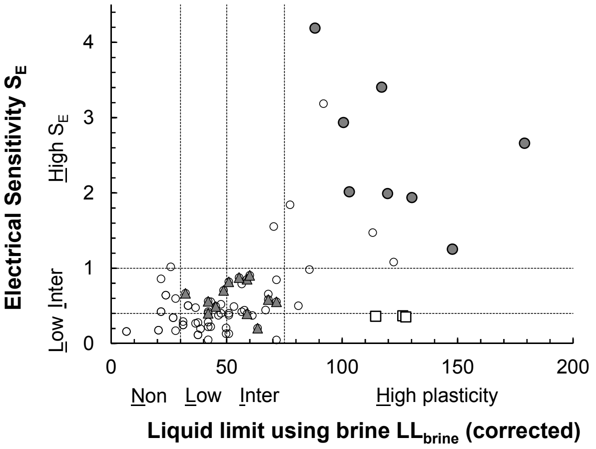

Figure 5. Fines classification chart (Jang and Santamarina 2017 – Contributors acknowledged in the closure). Gray circles: montmorillonitic soils. Gray triangles: kaolinitic soils and mixtures. Squares: diatomaceous and organic soils.

3. 3 *Classification - Reporting*

1. Overall. Use index properties for gravel, sand and fines components to plot the soil-specific triangular textural chart (Excel-sheet available in authors' website egel.kaust.edu.sa). Classify the soil according to the load-carrying fraction(s) and the flow-controlling fraction. Report the overall classification and include the soil-specific triangular chart.
2. Fines. If the soil group includes either "F" or "(F)", then, determine the liquid limit of fines using deionized water, brine and kerosene. Classify fines based on their plasticity and electricial sensitivity. Report the classification and include the fines classification chart.

4 CONCLUSIONS

Soil classification helps geotechnical engineers anticipate soil properties and behavior. The dominant role of fines is much more pronounced than current classification systems imply.

The revised soil classification system RSCS starts with the overall soil classification using a ternary textural chart defined in terms of the packing densities that each soil fraction may attain (estimated from particle shape, coefficient of uniformity and liquid limit). Classification categories use a dual nomenclature to recognize the mechanical-controlling fraction(s) and the flow-controlling fraction.

Fines require further analysis when they control either the mechanical and/or flow properties of the soil. In this case, the RSCS classifies fines in terms of their plasticity and their sensitivity to pore fluid chemistry.

Proper reporting should include the soil-specific triangular textural chart and the plasticity-sensitivity chart.

5 APPENDIX: VOID RATIOS AND INDEX PROPERTIES

Gravel and sand. A correlation based on experimental studies is used to obtain the maximum and minimum void ratios e^{max} and e^{min} of gravels and sands, respectively (Youd 1973; Santamarina and Cho 2006). The void ratios e^{max} and e^{min} represent loose and dense packing conditions of coarse grains as shown in Fig. 1, respectively.

$$e^{\max} = 0.032 + \frac{0.154}{R} + \frac{0.522}{C_u} \qquad (i)$$

$$e^{\min} = -0.012 + \frac{0.082}{R} + \frac{0.371}{C_u} \qquad (ii)$$

where R is roundness and C_u is the coefficient of uniformity.

Fines: Loading carrying. We select two reference void ratios to represent loose and dense packing condition of fines. The void ratio of fines at σ'=10 kPa ($=e_F|^{10kPa}$) and the void ratio of fines at σ'=1 MPa ($=e_F|^{1MPa}$) represent the loose and dense packing conditions of fines, respectively.

$$e_F\Big|^{10kPa} = e_F\Big|^{1kPa} - C_c = 0.026LL + 0.07 \qquad (iii)$$

$$e_F\Big|^{1MPa} = e_F\Big|^{1kPa} - 3C_c = 0.011LL + 0.21 \qquad (iv)$$

where LL is the liquid limit of fines passing through sieve No. 200 (=75-μm).

6 ACKNOWLEDGEMENTS

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