Revised Soil Classification System for Coarse-Fine Mixtures

Junghie Park1 and J. Carlos Santamarina, A.M.ASCE2

Abstract: Soil classification systems worldwide capture great physical insight and enable geotechnical engineers to anticipate the properties and behavior of soils by grouping them into similar response categories based on their index properties. Yet gravimetric analysis and data trends summarized from published papers reveal critical limitations in soil group boundaries adopted in current systems. In particular, current classification systems fail to capture the dominant role of fines on the mechanical and hydraulic properties of soils. A revised soil classification system (RSCS) for coarse-fine mixtures is proposed herein. Definitions of classification boundaries use low and high void ratios that gravel, sand, and fines may attain. This research adopts \( e_{\text{max}} \) and \( e_{\text{min}} \) for gravels and sands, and three distinctive void ratio values for fines: soft \( e_{\text{F,soft}} \) for mechanical response (at effective stress 10 kPa and 1 MPa, respectively), and viscous \( e_{\text{F,viscous}} \) for fluid flow control, where \( \lambda = 2 \log(\text{LL} - 25) \) and \( e_{\text{F,LL}} \) is the void ratio at the liquid limit. For classification purposes, these void ratios can be estimated from index properties such as particle shape, the coefficient of uniformity, and the liquid limit. Analytically computed and data-adjusted boundaries are soil-specific, in contrast with the Unified Soil Classification System (USCS). Threshold fractions for mechanical control and for flow control are quite distinct in the proposed system. Therefore, the RSCS uses a two-name nomenclature whereby the first letters identify the component(s) that controls mechanical properties, followed by a letter (shown in parenthesis) that identifies the component that controls fluid flow. Sample charts in this paper and a Microsoft Excel facilitate the implementation of this revised classification system.

DOI: 10.1061/(ASCE)GT.1943-5606.0001705. 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: Textural chart; Soil properties; Unified Soil Classification System.

Introduction

Soil classification enables geotechnical engineers to anticipate the properties and behavior of soils by grouping them into similar response categories based on their index properties (Casagrande 1948; Howard 1984; Das 2009; Dundulis et al. 2010; Kovačević and Jurčič-Kačunić 2014).

The Unified Soil Classification System (ASTM 2011) is the foundation for classification systems worldwide, from Japan and China (Japanese Geotechnical Society 2009; Chinese Standard 2007) to Mexico and Switzerland (Association Suisse de Normalisation 1959). The USCS places emphasis on particle size and uses the percentage retained on Sieve No. 200 (75 \( \mu \text{m} \)) to separate coarse-grained soils (more than 50% retained) from fine-grained soils (more than 50% passing). Other classification systems use a lower boundary for fines, either 35% (ASTM 2009; BSI 1999; SETRA and LCPC 2000; and Australia’s guidelines under review) or 40% (Deutche Norm 2011).

Most classification systems, including the USCS, use a 50% split on Sieve No. 4 (4.76 mm) to classify coarse-grained soils as either gravels or sands. The German DIN 18196 classifies soils as gravel when the fraction coarser than 2 mm exceeds 40%.

A detailed analysis of the USCS and other soil classification systems highlighted previously readily discloses great physical insight and understanding of soil behavior and their properties. However, both laboratory and field data gathered during the last century indicate the need for a revised soil classification system (RSCS). There are common limitations to all classification systems. First, they adopt fixed boundaries for coarse-fine mixtures despite the fact that fine-grained soils may exhibit a broad range of plasticity. Second, particle shape and grading affect the packing density of the coarse fraction, and hence the relevance of both the coefficients of uniformity and curvature in the USCS, yet shape does not feature in any classification system. Third, the effect of plastic fines on mechanical and conduction properties is not properly captured by the 50% and the 5–12% fines thresholds adopted in the USCS. Finally, current soil classification systems do not reflect the fact that pore-fluid chemistry plays a significant role in the behavior of fines.

The purpose of this study is to propose a RSCS for engineering purposes by providing a physics-inspired, data-driven approach that benefits from the experience gained since the inception of current soil classification systems. This study starts with gravimetric-volumetric analyses to anticipate fines and sand fraction thresholds, summarizes a data-based analysis focused on the physical properties of soil mixtures, and concludes with a new methodology for soil classification.

Granular Mixtures: Triangular Textural Charts

A soil can be analyzed as a three-component mixture made of gravel, sand, and fines. Triangular textural charts then facilitate the grouping of similar soils [Fig. 1(a) for interpretation guidelines]. Fig. 1(b) depicts the essence of the USCS in such a triangular chart. This soil map does not capture additional classification details.
invoke gravimetric-volumetric relations to compute the mass fraction of fines. By contrast, loosely packed coarse grains filled with densely packed fine grains result in the high threshold fines fraction $F_F^{H}$. The low- and high-threshold fines fractions divide binary mixtures into three groups (Fig. 2): coarse-dominant $F_F < F_F^{L}$, transitional $F_F^{L} < F_F < F_F^{H}$, and fines-dominant $F_F > F_F^{H}$ mixtures. This analysis applies to binary gravel-sand, gravel-fines, and sand-fines mixtures.

### Threshold Ternary Mixtures: Gravel-Sand-Fines Mixtures

Extend the previous gravimetric-volumetric analysis to ternary gravel-sand-fines mixtures. In this case, sand packed at void ratio $e_s$ fills the voids in the gravel $e_G$, and fines $e_F$ fill the remaining pores within the gravel-sand mixture. Then the computed gravel fraction $F_G$, sand fraction $F_S$, and fines fraction $F_F$ are functions of their void ratios (Appendix details the complete mathematical solution)

\[
F_G = \frac{1}{1 + e_G + \frac{e_s}{1 + e_g} + \frac{e_s}{1 + e_F}}
\]

\[
F_S = \frac{1}{1 + e_s + \frac{e_G}{1 + e_s} + \frac{e_F}{1 + e_s}}
\]

\[
F_F = \frac{1}{1 + e_s + \frac{1 + e_g}{1 + e_s} + \frac{1 + e_F}{1 + e_s} + 1}
\]

where $F_G + F_S + F_F = 1.0$. The combination of loose and dense packing conditions for each component leads to various threshold fractions, similar to binary mixtures. These threshold values define a transitional zone in a triangular textural plot for ternary mixtures, rather than the line segment for binary mixtures shown in Fig. 2.

### Low and High Void Ratios: Correlations

The use of gravimetric-volumetric analyses to determine transition thresholds require estimates of feasible low and high void ratios for gravel $G$, sand $S$, and fines $F$. Robust empirical relations between index properties and feasible void ratios can facilitate soil classification.

#### Gravel and Sand

Because packing densities for gravels and sands are insensitive to effective stress, the threshold fractions derived from the packing states of gravels and sands are independent of effective stress as a first approximation. The maximum and minimum void ratios $e_{\text{max}}$ and $e_{\text{min}}$ are adopted to estimate the feasible range of void ratios gravels and sands may attain (Fig. 2).

Maximum and minimum void ratios decrease for rounder and well-graded sands and gravels. Indeed, roundness $R$ and uniformity $C_u$ determine $e_{\text{max}}$ and $e_{\text{min}}$ (Youd 1973)

\[
e_{\text{max}} = 0.032 + 0.154 \frac{R}{C_u} + 0.522 \frac{R}{C_u^2}
\]

\[
e_{\text{min}} = -0.012 + 0.082 \frac{R}{C_u} + 0.371 \frac{R}{C_u^2}
\]

where roundness $R$ is the average radius of curvature of surface features $\sum r_i/N$ divided by the radius of the largest inscribed

---

**Fig. 1.** Soil classification systems: (a) guide for the interpretation of triangular gravel-sand-fines charts; the example corresponds to gravel fraction $F_G = 20\%$, sand fraction $F_S = 50\%$, and fines fraction $F_F = 30\%$; (b) the USCS

related to the coefficients of uniformity and curvature for coarse grains and Atterberg limits for fine grains.

The gravimetric-volumetric analysis of mixtures allows for the systematic definition of threshold boundaries in these triangular charts. The simpler case of binary mixtures is presented first.

### Binary Mixtures

Invoke gravimetric-volumetric relations to compute the mass fraction of fines $F_F$ in coarse-fine mixtures when fine grains completely fill the voids between coarse grains (Fig. 2). In terms of the void ratio of fines $e_F$ and coarse $e_C$ fractions, and assuming the same specific gravities (see Appendix for the detailed mathematical solution)

\[
F_F = \frac{M_F}{M_T} = \frac{M_F}{M_C + M_F} \approx \frac{e_C}{1 + e_C + e_F} \quad \text{and} \quad F_C = 1 - F_F
\]

There are two threshold fines fractions (Fig. 2). Densely packed coarse grains filled with loosely packed fine grains define the low threshold fines fraction $F_F^{L}$. By contrast, loosely packed coarse grains filled with densely packed fine grains result in the high threshold fines fraction $F_F^{H}$.

The low- and high-threshold fines fractions divide binary mixtures into three groups (Fig. 2): coarse-dominant $F_F < F_F^{L}$, transitional $F_F^{L} < F_F < F_F^{H}$, and fines-dominant $F_F > F_F^{H}$ mixtures. This analysis applies to binary gravel-sand, gravel-fines, and sand-fines mixtures.
sphere \( r_{\text{max}} \). Readily available software computes grain roundness \( R \) from grain images; for classification purposes, it is sufficient to visually compare grains against shape charts [chart in Krumein and Sloss (1963), example in Cho et al. (2006)]. Alternatively, the value of \( e_{\text{max}} \) can be quickly determined using a container of known volume and a scale, and \( e_{\text{min}} = 0.74 [e_{\text{max}} - 0.15 (C_u - 1)] \) is an adequate estimate of \( e_{\text{min}} \) (Cho et al. 2006).

**Fines**

**Load Carrying Criterion**

The void ratio of fines (i.e., silts and clays) depends on their plasticity and the applied effective stress. Effective stress is not a soil index property, but is a state variable. One may argue against the use of a state variable in soil classification; however, a sand-clay mixture that behaves as clay-dominant at low effective stress may transform into sand-dominant at high effective stress as clays consolidate and sand grains form the load-carrying skeleton [a similar notion underlies the equivalent liquidity index in Schofield (1980)]. Consequently, the void ratio of fines at preselected effective stress levels are selected as equivalent index parameters that capture the packing condition of fines, analogous to the use of \( e_{\text{max}} \) and \( e_{\text{min}} \) for coarse grains.

The \( K_0 \)-compression line at effective stress \( \sigma' = 10 \text{ kPa} \) and \( \sigma' = 1 \text{ MPa} \) defines two useful reference void ratios \( e_F^{10 \text{ kPa}} \) and \( e_F^{1 \text{ MPa}} \) that represent soft and stiff soil conditions relevant to near-surface engineering applications. Published correlations enable the prediction of reference void ratios in the absence of consolidation data during early soil classification (Burland 1990; Chong and Santamarina 2016)

\[
e_F^{10 \text{ kPa}} = e_F^{1 \text{ kPa}} - C_c = 0.026 \text{LL} + 0.07 
\]

\[
e_F^{1 \text{ MPa}} = e_F^{1 \text{ kPa}} - 3C_c = 0.011 \text{LL} + 0.21 
\]

These lower-bound estimates apply to nonsensitive clays or remolded conditions; they reflect that the void ratio at the liquid limit \( e_F^{1 \text{ LL}} = G_{\text{LL}}/100 \) is a good estimator of the void ratio at \( \sigma' = 1 \text{ kPa} \) because \( e_F^{1 \text{ kPa}} \approx 5/4e_F^{1 \text{ LL}} \approx 0.033 \text{LL} \) (Chong and Santamarina 2016) and of the compressibility of fine-grained sediments \( C_c = 0.007(\text{LL} - 10) \) (Skempton and Jones 1944). For the proposed revised classification system, these estimates must use the liquid limit obtained for fines passing through Sieve No. 200 (75-\( \mu \)m opening).

**Flow Control Criterion**

The presence of fines has a prevalent role on hydraulic conductivity even when fines are packed at a void ratio higher than \( e_F^{1 \text{ LL}} \). In fact, fluid flow can exacerbate the effect of fines by dragging grains until they clog the soil by forming bridges at pore constrictions (Kennedy and Lau 1985; Skempton and Brogan 1994; Valdes and Santamarina 2006, 2008; Shire et al. 2014).

In this context, the threshold fines fraction for fluid flow adopted in this classification is the fines content that causes a 100-fold decrease in the hydraulic conductivity of otherwise clean sands and clean gravels. Fines and water may form a viscous slurry at low fines content. Analyses based on published data (Locat and Demers 1988; Palombo and Santamarina 2005; Pennekamp et al. 2010) and experiments conducted as part of this study indicate that such a slurry will exhibit \( \sim 100 \) times higher viscosity than water when the water content is approximately \( \omega = \lambda \text{LL} \), where \( \lambda = [2 \cdot \log(\text{LL} - 25)] \geq 1 \). Then, the void ratio of fines used to compute the threshold fines fraction for fluid flow \( e_F^{\text{flow}} \) is

\[
e_F^{\text{flow}} = \lambda \cdot e_F^{1 \text{ LL}} = [2 \log(\text{LL} - 25)] \cdot e_F^{1 \text{ LL}} 
\]

\[
\approx 0.05 \text{LL} \cdot \log(\text{LL} - 25) \quad \text{(where } \lambda \geq 1 \text{)}
\]

where \( e_F^{1 \text{ LL}} = \) void ratio of fines at the liquid limit.

**Data Collection: Transitions in Dominant Behavior**

Gravimetric-volumetric analyses in terms of the low and high void ratios identified previously may not properly capture the transition from coarse-controlled to fines-controlled behavior because of multiple grain-scale and pore-scale mechanisms and processes.

This study gathered mixture properties from published studies to examine the transition in hydraulic conductivity, shear wave velocity, compression index, and shear strength. Table 1 presents each data set normalized between the properties for 100% coarse grains and 100% fines to facilitate the comparison across different soil types. In addition, an asymptotically consistent mixture model was selected to fit all trends. The normalization function and mixture models are mathematically analogous for all \( x \)-properties (Table 1).

---

**Fig. 2.** Coarse-fine mixtures: threshold fractions; coarse-dominant, transitional, and fines-dominant mixtures; these conceptual sketches apply to gravel-sand, gravel-fines, and sand-fines mixtures.
Table 1. Property Normalization and Fitting Models

| Trend with fines | Property | Normalization and fitting trend | Threshold fraction \( F_{th} \) |
|------------------|----------|---------------------------------|------------------------|
| Saddles          | Porosity (\( n \)) | \( n = n_c \cdot \left( \exp \left[ \left( \frac{F_i - F_{th}}{\delta F_{th}} \right) \right]^{n_a} - b \right) \) | Coarse-fine (\%) | Gravel-sand (\%) | Notes |
| Increases        | Compression index (\( C_c \)) | \( C_c = \frac{C_{i,c} - C_{f,c}}{C_{i,c} - C_{f,c}} = 1 - \left( \frac{1 - F_{th}^{p}}{1 + \left( \frac{F_i}{F_{th}} \right)^{m}} \right)^{n} \) | 15–40 | 20–40 | \( F_{th} \) decreases with increasing relative size ratio \( R_d \) |
| Decrease         | Hydraulic conductivity (\( k \)) | \( k = k_{c} - k_{f} = \frac{\sqrt{1 - F_{th}^{p}}}{1 + \left( \frac{F_i}{F_{th}} \right)^{m}} \) | 10–65 | No data | \( F_{th} \) increases with decreasing liquid limit of fines |
| Shear wave velocity (\( V_s \)) | \( V_s = \frac{V_{i,c} - V_{s,c}}{V_{i,c} - V_{s,f}} = \frac{\sqrt{1 - F_{th}^{p}}}{1 + \left( \frac{F_i}{F_{th}} \right)^{m}} \) | 7–36 | No data | \( F_{th} \) increases with increasing relative size ratio \( R_d \) and angularity |
| Shear strength (\( \tan \phi \)) | \( \tan \phi_f = \left( \frac{\tan \phi_c - \tan \phi_f}{1 + \left( \frac{F_i}{F_{th}} \right)^{m}} \right) \) | 10–42 | 47–70 | \( F_{th} \) decreases with increasing relative size ratio \( R_d \) and increasing fines plasticity |

Notes: Threshold fraction \( F_{th} \) is near the property arithmetic mean (except for porosity, where it is selected as the fines content at minimum porosity); subscripts \( G = gravel, S = sand, F = fines \); model parameters are \( a, b, m \).

\[
\frac{x_i - x_f}{x_c - x_f} = \frac{\sqrt{1 - F_{th}^{p}}}{1 + \left( \frac{F_i}{F_{th}} \right)^{m}}
\]

Porosity

Fig. 3 illustrates the changes in porosity with fines fraction in coarse-fine mixtures and with sand fraction in gravel-sand mixtures. The minimum porosities are attained at \( F_F = 15–40\% \) in coarse-fine mixtures, and at \( F_S = 20–40\% \) in gravel-sand mixtures. In general, the porosity of mixtures decreases with increases in roundness (Youd 1973; Santamarina and Cho 2004; Cho et al. 2006), coefficient of uniformity \( C_u \) (Istomina 1957; Vukovic and Soro 1992), and relative size ratio \( R_d \) (McGeary 1961; Guyon et al. 1987; Marion et al. 1992; Thevanayagam 2007). Geometric models for idealized packings agree with these data-based observations (e.g., Koltermann and Gorelick 1995; Kamann et al. 2007).

Hydraulic Conductivity

Fig. 4 presents normalized hydraulic conductivity data \( k \) versus fines \( F_F \) and sand \( F_S \) fractions. While hydraulic conductivity varies in orders of magnitude, linear normalization was chosen to reflect the direct proportionality between the flow rate \( q \) and hydraulic conductivity \( k \) in engineering problems, according to Darcy’s law \( q = kIA \) (\( i = \) hydraulic gradient, \( A = \) area). The hydraulic conductivity drops to the arithmetic mean value when the fines fraction is \( F_F = 2–7\% \) in coarse-fine mixtures, and when the sand fraction is \( F_S = 5–17\% \) in gravel-sand mixtures. While these threshold fractions arise from gap-graded mixture data, similar threshold values are expected for well-graded mixtures following the discussion on porosity trends in the previous section.

The data include mixtures with hydraulic conductivity smaller than the hydraulic conductivity of 100% fines in coarse-fine mixtures, or smaller than for 100% sand in gravel-sand mixtures (this is clearly observed in logarithmic scale, but it is faint in the normalized scale used in Fig. 4). Hydraulic conductivity values \( k_{mix} < k_f \) reflect the increased tortuosity of flow paths caused by the presence of coarse grains floating in the porous medium made of the finer grains.

Small-Strain Stiffness in Terms of Shear Wave Velocity

Fig. 5 shows normalized shear wave velocities \( V_s \), as defined in Table 1, for coarse-fine mixtures against fines fraction \( F_F \). The normalized shear wave velocities drop to the arithmetic mean value for threshold fines fractions between \( F_{th} = 5 \) and 36%. The transition from coarse-controlled to fines-controlled shear stiffness is influenced by effective stresses: as the vertical effective stresses increases, the threshold fines fraction \( F_{th} \) increases. Apparently, fines prevent the formation of a coarse-grain skeleton at low stress but consolidate at high stress levels. Fig. 5(b) displays data for sand-mica mixtures in the absence of published data for gravel-sand mixtures. Results indicate that \( \lambda_{sand} / L_{mica} \) affects the transition from coarse-controlled to fines-controlled mixtures, and the threshold fines fraction \( F_{th} \).

Compression Index

Fig. 6 presents the normalized compression index \( C_{sc} \) of coarse-fine mixtures graphed versus fines fraction \( F_F \). The normalized compression index reaches the arithmetic mean compressibility at a fines fraction that varies from \( F_{th} = 10–65\% \) as the liquid limit decreases from high-plasticity clays to silts. The initial void ratio, particle shape, soil fabric, stress conditions, pore fluids, mineralogy, and plasticity of fines all affect the transition from coarse-controlled to fines-controlled compressibility (Kenney 1977; Maio and Feneliff 1994; Sridharan and Nagaraj 2000; Monkul and Ozden 2007; Thevanayagam 2007; Bandini and Sathikumar 2009).

The threshold fines fraction for the sand-silt mixture is \( F_{th} = 65\% \), as illustrated by the open square in Fig. 6. Yet, mixtures...
near the minimum porosity (i.e., at a fines fraction \( F_F \approx 30\% \)) exhibit lower compressibility than the 100% sand specimen (this effect is concealed in the normalized scale used in Fig. 6). Similarly, while coarse grains form a load-bearing skeleton when the fines fraction is lower than threshold values (Monkul and Ozden 2007; Thevanayagam et al. 2001; Lee et al. 2007a), fines improve the stability of the soil matrix by hindering the buckling of the coarse-grain chains (Kenney 1967; Lupini et al. 1981; Maio and Fenelli 1994; Mitchell and Soga 2005; Santamarina and Shin 2009; Skempton 1985). The dominant mechanism depends on whether fines occupy the pores between coarse grains, or separate coarse grains apart (Monkul and Ozden 2007; Thevanayagam et al. 2002; Valleejo and Mawby 2000), and associated changes in the coordination number, rotational frustration, and interlocking (Santamarina et al. 2001; Bareither et al. 2008; Cho et al. 2006).

**Shear Strength in Terms of \( \tan \phi \)**

Fig. 7 presents trends for the normalized \( \tan \phi \) plotted against the fraction of fines and sand. The data in Fig. 7 were obtained by various researchers using different test devices, and include peak, constant volume, and residual friction angles. While diverse in origin, all trends show consistent transitions from coarse-controlled to fines-controlled shear strength. The threshold fraction characterizes the transition from coarse-controlled to fines-controlled shear strength. The fines threshold is \( F_{th} = 10-42\% \) in coarse-fine mixtures while the sand threshold is \( F_{th} = 47-70\% \) in gravel-sand mixtures. The threshold fraction \( F_{th} \) decreases when the relative size ratio \( R_d \) increases, the liquid limit increases, the coarse grains become well graded, and the particle shape becomes rounder. These trends reflect underlying changes in shear mechanisms, e.g., from rolling to sliding shear (Kenney 1967; Lupini et al. 1981; Maio and Fenelli 1994; Mitchell and Soga 2005; Santamarina and Shin 2009; Skempton 1985). The dominant mechanism depends on whether fines occupy the pores between coarse grains, or separate coarse grains apart (Monkul and Ozden 2007; Thevanayagam et al. 2002; Valleejo and Mawby 2000), and associated changes in the coordination number, rotational frustration, and interlocking (Santamarina et al. 2001; Bareither et al. 2008; Cho et al. 2006).

Particle shape rather than size determines the constant volume friction angle (Cho et al. 2006). Therefore, angular fines could exhibit higher friction angle than well-rounded coarser particles.
The packing density and relative fraction of each component support the four observations that follow:

- The maximum and minimum void ratios $e^{\text{max}}$ and $e^{\text{min}}$ for loose and dense sands and gravels depend on the coefficient of uniformity and particle shape.
- The packing of fines depends on the liquid limit and effective stress. Three distinctive values were selected in view of near-surface engineering applications: soft at $\varepsilon_f^{150 \text{kPa}}$ and stiff at $\varepsilon_f^{7 \text{MPa}}$ for mechanical response, and viscous at $\lambda \cdot \varepsilon_f^{15 \text{LL}}$ for fluid flow behavior where $\lambda = 2 \cdot (\text{LL} - 25)$, detailed in Eq. (9).
- Volumetric-gravimetric analyses provide the underlying conceptual framework for soil classification boundaries. However, pore filling does not necessarily occur at either $e^{\text{max}}$ or $e^{\text{min}}$ due to pore- and grain-scale mechanisms and processes such as the effect of boundaries that the large grains impose on the smaller grains, i.e., a function of relative size ratio (Fraser 1935). Hence, physics-inspired analytical boundaries require data-driven corrections.

These analyses and data trends reveal two critical limitations in current soil classification methods as illustrated in Fig. 1. First, the fines begin to control mechanical properties and hydraulic properties at lower fines fractions than the boundaries adopted in current soil classification systems. Second, the fixed boundaries used in existing classification methods do not account for particle shape and underestimate the impact of high-plasticity fines.

Does the gravimetric-volumetric formulation provide adequate thresholds for well-graded soils? Experimental data are scarce, and analyses provide only partial answers even for the ideal packings of spherical particles. Gravimetric-volumetric packing analyses were conducted for well-graded gravely-sandy soils, all with the same coefficient of uniformity and particle shape ($C_u = 10$ and roundness $R = 0.5$), but with different median grain size ($D_{50} = 3.8 \text{–} 204 \text{mm}$). Results show a natural and gradual transition from gravel-dominant soils when the sand fraction $F_S < 10\%$, to sand-dominant behavior when the sand fraction $F_S > 48\%$. Given these results, and in the absence of negative evidence, the gravimetric-volumetric analysis proposed previously is adopted for the analysis of both gap-graded and well-graded soils (the gravimetric-volumetric analyses consider grain size of sand and gravel fractions).
procedure. Mass fractions are computed using Eqs. (1)–(9) in all cases.

Data-based thresholds for indicate that the coarse component in a mixture affects properties even when it is packed at a void ratio $e > e_{\text{min}}^\text{max}$ [similar observations are in Holtz and Gibbs (1956), Vasili'eva et al. (1971), Fragaszy et al. (1992), Vallee and Mawby (2000), Vallee (2001), Simoni and Houlsby (2006), and Kim et al. (2007)]. Correction factors for $e_{\text{min}}^\text{max}$ match the theoretically predicted threshold fractions $F_{\text{th}}$ with the threshold fractions $F_{\text{in}}$ at the arithmetic mean value observed for the various physical properties (Figs. 3–7 and Table 1). Results support the following correction factors (included in Table 2):

- Gravel-sand mixtures (Mixture 5): $\beta = 2.5 \ (e_G = \beta \cdot e_{\text{in}}^\text{max}; e_S = e_{\text{in}}^\text{max})$.
- Gravel-fines mixtures (Mixture 7): $\alpha = 1.3 \ (e_G = \alpha \cdot e_{\text{in}}^\text{max}; e_F = e_{\text{in}}^\text{max})$.
- Sand-fines mixtures (Mixture 8): $\gamma = 1.3 \ (e_S = \gamma \cdot e_{\text{in}}^\text{max}; e_F = e_{\text{in}}^\text{max})$.

Finally, notable ternary mixtures 3, 6, and 9 are calculated as specified in Table 2. Fig. 8(a) displays all notable mixtures on the triangular chart.

These nine mixtures define boundaries for seven soil groups in terms of mechanical properties control [Fig. 8(a)]. A single component is dominant in three of the seven groups: $G = \text{gravel}$, $S = \text{sand}$, and $F = \text{fines}$. The four other soil groups are mixtures in transitional conditions: $GS$, $SF$, $GF$, and $GSF$. Soils that fall within the ternary transitional group $GSF$ may exhibit distinctly different soil properties because boundaries depend on the liquid limit of fines as well as the particle shape and coefficient of uniformity of both sands and gravels.

**Fluid Flow Control**

Notable mixtures that define flow-control thresholds are computed using the low-viscosity criterion $e_{\text{F}}^\text{flow} = \lambda \cdot e_{\text{F}}^\text{in}$ [Eq. (9)] and densely packed gravel or sand. These conditions result in Mixtures 10, 11, 12, and 13, detailed in Table 2 and plotted in Fig. 8(b).

Finally, the mixture of densely packed gravel $e_{\text{F}}^\text{in}$ and loosely packed sand $e_{\text{F}}^\text{max}$ defines the boundary for sand-controlled hydraulic conductivity in gravel-sand mixtures [Mixture 2 in Table 2 and Fig. 8(b)].

Altogether, Mixtures 2, 10, 11, 12, and 13 delimit the three distinct zones for flow control [Fig. 8(b)]: a large region controlled by the fines (F), a smaller region controlled by the sand (S), and the corner reserved for clean gravels (G).

**Classification: Charts**

**Classification Groups and Nomenclature**

Distinct differences between the textural charts for mechanical behavior control [Fig. 8(a)] and for flow control [Fig. 8(b)] suggest the need for a two-name nomenclature whereby the first letters identify the component that controls mechanical properties, followed by a letter that identifies the component that controls flow (shown in parenthesis). For example, consider a S(F) soil: sand controls the mechanical properties but fines control its hydraulic conductivity.

The resulting 10 soil groups are summarized in Fig. 9. The fines fraction in F, GF, SF, and GSF soils controls the hydraulic conductivity in these groups. 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. Clean gravel G(G) and clean sand S(S) classifications can be

---

**Notable Mixtures and Classification Boundaries**

Notable mixtures that mark the transitions between the soil components that control the mechanical response and fluid flow are now identified. These mixtures are specified in Table 2 and displayed in Fig. 8 on the textural triangle. Notable mixtures discussed subsequently assist with the definition of classification boundaries.

**Mechanical Control**

Densely packed soil fractions control the mechanical response of a soil. For example, the gravel carries the load in a gravel-fines mixture when the gravel packing is dense at $e_{\text{G}}^\text{min}$ and fines are at a high void ratio $e > e_{\text{F}}^\text{in}$ [10 kPa]; this is Mixture 1 in Table 2 and Fig. 8(a). Other notable mixtures labeled 2 and 4 follow a similar logic and

---

**Figure 7.** (Color) Normalized shear strength in terms of $\tan \phi$: (a) coarse-fine mixtures; (b) gravel-sand mixtures; Table 1 defines the normalization and the fitting model (plotted here as lines)

---

| Mixture | Notable Mixtures | Classification |
|---------|-----------------|----------------|
| 1       | gravel-sand     | gravel/G(S)    |
| 2       | gravel-fines    | gravel/G(F)    |
| 3       | sand-fines      | sand/S(G)      |
| 4       | fines           | fines/F(S)     |
| 5       | gravel-fines    | gravel/G(F)    |
| 6       | sand-fines      | sand/S(G)      |
| 7       | fines           | fines/F(S)     |
| 8       | gravel-fines    | gravel/G(F)    |
| 9       | sand-fines      | sand/S(G)      |
| 10      | fines           | fines/F(S)     |
| 11      | gravel         | gravel/G(S)    |
| 12      | sand           | sand/S(G)      |
| 13      | fines           | fines/F(S)     |
Table 2. Notable Mixtures Used to Define Soil Classification Boundaries

| Process             | Controlling fraction | Mixture number | Gravel | Sand | Fines | Packing condition | Physical background: interpretation |
|---------------------|----------------------|----------------|--------|------|-------|------------------|--------------------------------------|
| Load carrying       | Gravel               | 1              | $e_G^{\text{min}}$ | $e_S^{\text{max}}$ | $e_F^{10 \text{ kPa}}$ | Gravels carry the load if gravels are densely packed and fines experience $\sigma'_F < 10 \text{ kPa}$ |
|                     |                      | 2              | $e_G^{\text{min}}$ | $e_F^{10 \text{ kPa}}$ | —                 | Gravels carry the load if gravels are densely packed and sands are loosely packed |
|                     |                      | 3              | $e_G^{\text{min}}$ | $e_S^{\text{max}}$ | $e_F^{10 \text{ kPa}}$ | Gravels carry the load if gravels are densely packed, sands are loose, and fines experience $\sigma'_F < 10 \text{ kPa}$ |
| Sand                |                      | 4              | —               | $e_S^{\text{max}}$ | $e_F^{10 \text{ kPa}}$ | Sands carry the load if sands are densely packed and fines experience $\sigma'_F < 10 \text{ kPa}$ |
|                     |                      | 5              | $2.5e_G^{\text{max}}$ | $e_S^{\text{min}}$ | —                 | Sands carry the load if sands are densely packed and contain very loose gravel at $2.5e_G^{\text{max}}$ |
|                     |                      | 6              | $2.5e_G^{\text{max}}$ | $e_S^{\text{min}}$ | $e_F^{10 \text{ kPa}}$ | Sands carry the load if sands are densely packed and contain very loose gravel at $2.5e_G^{\text{max}}$ and soft fines |
| Fines               |                      | 7              | $1.3e_G^{\text{max}}$ | —               | $e_F^{1 \text{ MPa}}$ | Fines carry the load when they are compact and contain loose gravel at $1.3e_G^{\text{max}}$ |
|                     |                      | 8              | —               | $1.3e_S^{\text{max}}$ | $e_F^{1 \text{ MPa}}$ | Fines carry the load when they are compact and contain loosely packed sand at $1.3e_S^{\text{max}}$ |
|                     |                      | 9              | $2.5e_G^{\text{max}}$ | $1.3e_S^{\text{max}}$ | $e_F^{1 \text{ MPa}}$ | Fines carry the load when they are compact and contain very loose gravels and sands |
| Fluid flow          | Fines               | 10             | $e_G^{\text{min}}$ | —               | —                 | The fraction for clean gravels and sands is computed by assuming that the coarse fraction is at $e_G^{\text{min}}$ and that fines form a high-viscosity fluid at a water content equal to $\lambda LL$, i.e., the void ratio of fines is $e_F^{\text{max}} = \lambda e_F^{\text{LL}}$, where $\lambda = [2 \log (LL - 25)]$ |
|                     |                      | 11             | $e_G^{\text{min}}$ | $e_S^{\text{max}}$ | $\lambda e_F^{\text{LL}}$ | |
|                     |                      | 12             | $2.5e_G^{\text{max}}$ | $e_S^{\text{min}}$ | $\lambda e_F^{\text{LL}}$ | |
|                     |                      | 13             | —               | $e_S^{\text{max}}$ | $\lambda e_F^{\text{LL}}$ | |

Note: $F = $ fines; $G = $ gravel; $S = $ sand; estimates: values of $e^{\text{max}}, e^{\text{min}}, e_F^{10 \text{ kPa}}, e_F^{1 \text{ MPa}}$, and $e_F^{\text{LL}}$ can be estimated from index properties [Eqs. (5)–(9)].

Fig. 8. (Color) Notable mixtures and soil classification boundaries; $G = $ gravel, $S = $ sand, and $F = $ fines: (a) mechanical control; $G$, $S$, and $F$ indicate that a single fraction controls the mechanical response zone, GF, SF, GS, and GSF designate transition zones; (b) flow control: fluid flow controlling fraction denoted as a single letter between parentheses; soil properties used for this chart: angular and uniform gravel $e_G^{\text{max}} = 0.81$ and $e_G^{\text{min}} = 0.45$; angular and uniform sand $e_S^{\text{max}} = 0.81$ and $e_S^{\text{min}} = 0.45$; fines resemble kaolinite with liquid limit $LL = 50$, $e_F^{10 \text{ kPa}} = 1.33$, $e_F^{1 \text{ MPa}} = 0.76$, $e_F^{\text{LL}} = 1.32$, and $\lambda = 2.8$; flow-controlling fine fractions are $F_F = 3.3\%$ at Mixture 11 and $F_F = 5.2\%$ at Mixture 12.

Fig. 9. (Color) Charts in Fig. 10 capture mechanical-control and flow-control boundaries superimposed onto a single chart for each case. These charts reflect a wide range of soil conditions and include both angular-uniform and rounded-well-graded sands and gravels, in addition to fines of varying plasticity.

Threshold fractions are markedly different from those used in the USCS. For various combinations of roundness, coefficients of uniformity, and fines plasticity, results indicate
Gravel-sand mixtures: threshold sand fractions range between $FS_j^L \approx 12$–24% and $FS_j^H \approx 45$–65%;
Coarse-fine mixtures, mechanical control: the fines threshold varies between $FF_j^L \approx 3$–27% and $FF_j^H \approx 12$–50%; and
Coarse-fine mixtures, flow control: the fines threshold varies from $FF_j^{\text{flow}} \approx 1$–23%.

The predominant role of fines extends much further into the lower fines content than anticipated by the USCS [compare the RSCS charts in Fig. 10 with the USCS chart in Fig. 1(b)]. In fact, the USCS has the closest resemblance to the triangular textural chart computed for low-plasticity fines (such as kaolinite), and angular sands and gravels. Fines plasticity plays a critical role in the position of boundaries for both mechanical and hydraulic controls. In particular, well-graded rounded sands and gravels can form denser packings than uniform angular coarse grains, therefore a small mass fraction of fines is needed to alter soil behavior in this case [e.g., compare classification charts in Figs. 10(a–d) against Figs. 10(e–h)].

These new classification charts incorporate the main parameters used by the USCS, that is, Sieves No. 200 and No. 4, coefficient of uniformity $C_u$, and liquid limit $LL$ of fines (the values of $e^{\text{max}}$ and $e^{\text{min}}$ implicitly consider the coefficient of curvature). Furthermore,
the development of these charts recognizes the role of particle shape on the behavior of sands and gravels. It also considers the stress regime to which the soil will be subjected in near-surface geotechnical engineering projects.

**Fines Classification**

The classification of fines could be completed using the standard Casagrande chart in the USCS. However, the revised classification RSCS adopts the new fines classification method proposed by Jang and Santamarina (2016) because it takes into consideration both the soil plasticity and its sensitivity to pore fluid chemistry. This classification is based on liquid limits obtained with deionized water, brine (high electrical conductivity), and kerosene (low dielectric constant). Fines fall into 1 of 12 groups: NL, NI, NH, LL, LI, LH, IL, II, IH, HL, HI, and HH, where the first letter indicates the soil plasticity (no, low, intermediate, high) and the second letter indicates the sensitivity of the soil response to changes in pore fluid chemistry (low, intermediate, high).

**Revised Soil Classification System**

The recommended procedure for soil classification follows:

1. **Input parameters:**
   a. Obtain the gravel fraction $F_G$ (where $G >$ Sieve No. 4), sand fraction $F_S$ (Sieve No. 200 < $S <$ Sieve No. 4) and fines fraction $F_f$ (passing Sieve No. 200) by mass;
   b. For gravel and for sand: Determine $e_{\text{max}}$ and $e_{\text{min}}$ for each fraction. For estimates of $e_{\text{max}}$ and $e_{\text{min}}$, use the coefficient of uniformity $C_u$ and roundness $R$ gathered for each fraction [Eqs. (5) and (6)]; and
   c. For fines: Determine $e_f^{10}$ kPa, $e_f^{1}$ MPa, and $e_f^{[\text{LL}]}$ or estimate these values from the liquid limit measured on the passing Sieve No. 200 using the pore fluid that the soil is subjected to in the field [Eqs. (7)–(9)].

2. **Classification chart:** Compute a case specific chart using the notable Mixtures 1–13 specified in Table 2. Computations and graphing schemes are built into Figs. S1 and S2:
   a. Determine the boundaries for the load-carrying component (Mixtures 1–9, Table 2); and
   b. Determine the boundaries for the flow-controlling component (Mixtures 10–13, Table 2).

3. **Soil Classification:** Alternatively, select the textural triangular chart in Fig. 10 that most closely resembles the soil under consideration. Plot the point that corresponds to the soil under consideration and determine its classification using the two-name nomenclature suggested previously: the first letter(s) indicates the load-carrying component, followed by a letter in parenthesis that denotes the component that controls flow. When appropriate, include the RSCS triangular chart as part of the report.

4. **Fines classification:** Follow the classification procedure described in Jang and Santamarina (2016) to consider the fines plasticity and sensitivity to changes in pore fluid chemistry. This method requires additional liquid limit determinations for soil pastes mixed with brine and kerosene.

**Conclusions**

Soil classification is intended to help geotechnical engineers anticipate the properties and behavior of soils by grouping them into
similar response categories based on index properties. Soil classification systems worldwide capture great physical insight. Yet, analyses and data trends reveal critical limitations in the boundaries for various soil groups adopted in classical soil classification systems. In particular, fines begin to play a significant role at threshold fractions that are smaller than boundaries adopted by the existing classification systems.

Classification boundaries can be defined by the void ratio that each fraction may attain. The revised classification adopts \( e^{max} \) and \( e^{min} \) for gravels and sands, and three distinctive values for fines: soft \( e_F \) (e.g., loess and pumice), stiff \( e_F \) (e.g., diatomaceous sand), and viscous \( e_F \) (e.g., clay). There are robust correlations between these void ratios and index properties such as particle shape, coefficient of uniformity, and liquid limit.

Analytically computed and data-adjusted threshold fractions point to very different values to those used as boundaries in the Unified Soil Classification System, both for mechanical control and for flow control. The boundaries in the USCS have some—albeit limited—resemblance to the RSCS boundaries computed for low-plasticity clays (such as kaolinite) and angular sands and gravels.

Threshold fractions for mechanical control and for flow control are quite distinct. The RSCS uses a two-name nomenclature whereby the first letters identify the component that controls mechanical properties, followed by a letter shown in parenthesis that identifies the component that controls flow.

Finally, the detailed classification of fines uses the new fines classification method proposed by Jang and Santamarina (2016) that takes into consideration the plasticity of fines and their sensitivity to pore fluid chemistry.

Appendix. Volumetric-Gravimetric Relations

**Binary Mixtures: Fines Fraction**

Consider a binary mixture made of coarse and fine fractions. The coarse grains are packed at a void ratio \( e_C \). The volume of voids between coarse grains \( V_{vC} \) is related to the volume of solids \( V_{sC} \) through the void ratio \( e_C \):

\[
V_{vC} = e_C V_{sC} \quad (11)
\]

Fine grains packed at void ratio \( e_F \) fill the volume of voids between coarse grains \( V_{sC} \). Then, the volume of solids in the fine grains \( V_{sF} \) is

\[
V_{sF} = \frac{V_{sC}}{1 + e_F} = \frac{e_C}{1 + e_F} V_{sC} \quad (12)
\]

Define the mass fraction of fines as the mass of fines divided by the total mass of fines and coarse fractions \( M_F + M_C \); then

\[
F_F = \frac{M_F}{M_F + M_C} = \frac{1}{1 + \frac{M_F}{M_C}} = \frac{1}{1 + \frac{G_{sC} V_{sC}}{G_{sF} V_{sF}}} \quad (13)
\]

where \( G_{sC} \) and \( G_{sF} \) are the specific gravities of coarse and fine fractions. Replacing Eq. (12) in Eq. 13 gives

\[
F_F = \frac{1}{1 + \frac{G_{sC}}{G_{sF}} e_C e_F} \approx \frac{e_C}{1 + e_C + e_F} \quad (14)
\]

The same equation can be used for gravel-sand, gravel-fines, sand-fines mixtures.

**Ternary Mixture: Gravel, Sand, and Fines Fractions**

Extend the analysis to ternary gravel-sand-fines mixtures, where the gravel is packed at void ratio \( e_G \). The sand packed at void ratio \( e_S \) fills the voids in the gravel \( V_{vG} \). The remaining volume of voids is filled by the fines packed at void ratio \( e_F \). From Eqs. (12) and (13)

\[
M_F = \frac{e_S}{1 + e_F} M_S \left( \frac{G_{sF}}{G_{sS}} \right) \quad (15)
\]

\[
M_S = \frac{e_G}{1 + e_S} M_G \left( \frac{G_{sS}}{G_{sG}} \right) \quad (16)
\]

Finally, the mass fraction of gravel \( F_G \), sand \( F_S \), and fines \( F_F \) relative to the total mass \( M_G + M_S + M_F \) is obtained by successively invoking the previous two equations, Eqs. (15) and (16). For clarity, consider \( G_{sG} \approx G_{sS} \approx G_{sF} \)

\[
F_G = \frac{M_G}{M_G + M_S + M_F} = \frac{1}{1 + \frac{e_G}{1 + e_S} + \frac{e_S}{1 + e_F}} \quad (17)
\]

\[
F_S = \frac{M_S}{M_G + M_S + M_F} = \frac{1}{1 + \frac{e_S}{1 + e_F}} \quad (18)
\]

\[
F_F = \frac{M_F}{M_G + M_S + M_F} = \frac{1}{1 + \frac{e_F}{1 + e_S} + \frac{e_S}{1 + e_C}} \quad (19)
\]

Note that \( F_G + F_S + F_F = 1.0 \).

**Acknowledgments**

Support for this research was provided by the KAUST Endowment at King Abdullah University of Science and Technology. G. Abelskamp edited the manuscript. We are grateful to the anonymous reviewers for their detailed comments and valuable insights.

**Supplemental Data**

Figs. S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

**References**

Association Suisse de Normalization (Swiss Association for Normalization). (1959). “Soil classification.” SNV 70 055, Zurich, Switzerland.

ASTM. (2009). “Standard practice for classification of soils and soil-aggregate mixtures for highway construction purposes.” ASTM D 3282, West Conshohocken, PA.

ASTM. (2011). “Standard practice for classification of soils for engineering purposes (unified soil classification system).” ASTM D 2487, West Conshohocken, PA.

Bandini, P., and Sathiskumar, S. (2009). “Effects of silt content and void ratio on the saturated hydraulic conductivity and compressibility of sand-silt mixtures.” J. Geotech. Geoenviron. Eng., 10.1061/(ASCE)GT.1943-5606.0000177, 1976–1980.

Bareither, C. A., Edll, T. B., Benson, C. H., and Mickelson, D. M. (2008). “Geological and physical factors affecting the friction angle of compacted sands.” J. Geotech. Geoenviron. Eng., 10.1061/(ASCE)1090-0241(2008)134:10(1476), 1476–1489.
