Closure to "Revised Soil Classification System for Coarse-Fine Mixtures" by Junghee Park and J. Carlos Santamarina

Junghee Park

Postdoctoral Fellow, Earth Science and Engineering, King Abdullah Univ. of Science and Technology, Thuwal 23955-6900, Saudi Arabia (corresponding author). Email: junghee.park@kaust.edu.sa

Gloria M. Castro

Ph.D. Student, Earth Science and Engineering, King Abdullah Univ. of Science and Technology, Thuwal 23955-6900, Saudi Arabia.

J. Carlos Santamarina, A.M.ASCE

Professor, Earth Science and Engineering, King Abdullah Univ. of Science and Technology, Thuwal 23955-6900, Saudi Arabia.

https://doi.org/10.1061/(ASCE)GT.1943-5606.0001705

We are grateful for the insightful contributions by the discussers. This closure addresses their observations, with emphasis on the transition from coarse-controlled to fines-controlled behavior, the critical fines fraction in view of seepage-induced internal instability, and related observations relevant to the revised soil classification system (RSCS).

Transition from Coarse-Controlled to Fines-Controlled Behavior

We carefully reviewed the work by Gutierrez (2005); however, we failed to confirm results in Dallo's discussion. Nevertheless, we take this opportunity to provide further evidence in support of the transition boundaries adopted in the RSCS.

The volumetric-gravimetric analysis for coarse-fine mixtures leads to the low-threshold fines fraction $F_F|^L$ and the high-threshold fines fraction $F_F|^H$ in terms of densely and loosely packed grains [from Eq. (1) in the original paper]

$$F_F\Big|^L = \frac{e_C^{\min}}{1 + e_C^{\min} + e_F^{\max}} \tag{1}$$

$$F_F\Big|^H = \frac{e_C^{\max}}{1 + e_C^{\max} + e_F^{\min}} \tag{2}$$

In designing the RSCS, we recognized that the packing of smaller grains between the pore space formed by the larger grains is different from packing conditions in bulk. Therefore, a correction factor α is used to compute the data-adjusted high-threshold fines fraction $F_F|^{H*} = \alpha \cdot e_C^{\max}/(1 + \alpha \cdot e_C^{\max} + e_F^{\min})$, where $\alpha = 1.3$ for coarse-fines mixtures (the factor is $\beta = 2.5$ for gravel-sand mixtures, as noted in the original paper).

The low-threshold $F_F|^L$ and data-adjusted high-threshold fractions $F_F|^{H*}$ are expected to bound the transition from fines- to coarse-controlled behavior. Fig. 1 displays trends for maximum and minimum void ratios against the fines fraction F_F. The transition boundaries $F_F|^L$ and $F_F|^{H*}$ are superimposed in each case {data extracted from Gutierrez (2005) (input: $e_C^{\max} = 0.99$, $e_C^{\min} = 0.64$, $e_F^{\max} = 1.60$, $e_F^{\min} = 0.72$, $F_F|^L = 19.8\%$, $F_F|^H = 36.5\%$, $F_F|^{H*} = 42.8\%$) [Fig. 1(a)]; Choo and Burns (2015) (input: $e_C^{\max} = 0.75$, $e_C^{\min} = 0.50$, $e_F^{\max} = 0.87$, $e_F^{\min} = 0.56$, $F_F|^L = 21.1\%$, $F_F|^H = 32.4\%$, $F_F|^{H*} = 38.4\%$) [Fig. 1(b)]; Lade and Yamamuro (1997) (input: $e_C^{\max} = 0.88$, $e_C^{\min} = 0.58$, $e_F^{\max} = 1.17$, $e_F^{\min} = 0.76$, $F_F|^L = 21.1\%$, $F_F|^H = 33.3\%$, $F_F|^{H*} = 39.4\%$) [Fig. 1(c)]; Lade and Yamamuro (1997) (input: $e_C^{\max} = 0.81$, $e_C^{\min} = 0.54$, $e_F^{\max} = 1.17$, $e_F^{\min} = 0.74$, $F_F|^L = 19.9\%$, $F_F|^H = 31.8\%$, $F_F|^{H*} = 37.7\%$) [Fig. 1(d)]; Kang and Lee (2015) (input: $e_C^{\max} = 1.01$, $e_C^{\min} = 0.57$, $e_F^{\max} = 1.18$, $e_F^{\min} = 0.50$, $F_F|^L = 20.7\%$, $F_F|^H = 40.2\%$, $F_F|^{H*} = 46.7\%$) [Fig. 1(e)]; and Fuggle et al. (2014) (input: $e_C^{\max} = 0.77$, $e_C^{\min} = 0.53$, $e_F^{\max} = 0.90$, $e_F^{\min} = 0.64$, $F_F|^L = 21.8\%$, $F_F|^H = 31.9\%$, $F_F|^{H*} = 37.9\%$) [Fig. 1(f)]}. The threshold fractions adequately capture the transitions from coarse- to fines-controlled behavior. Either coarse, fines, or both fractions can be responsible for the mechanical control in transitional mixtures; this has implications on internal instability, which is explored next.

Seepage-Induced Internal Instability

Liu et al.'s discussion identified seepage data gathered for four binary mixtures and three ternary mixtures to test the RSCS, the underlying assumption being that internal instability during seepage implies that the fines are not load carrying. This is an insightful proposition indeed.

Further discussion requires a careful definition of internal instability, and its consistent application to the analysis of results reported by various studies. Previous studies associate internal instability to (1) change in particle size distribution before and after testing, (2) change in the slope of the seepage velocity against the hydraulic gradient, (3) finer particles loss rate, (4) visual observations, and (5) changes in the local hydraulic gradient with time. In the context of this discussion, let's define *internal instability* as the fluid-induced migration of fines out of a stable coarse-grained skeleton [in agreement with Moffat et al. (2011)]. Two corollaries follow from this definition. First, heave prior to internal instability destructures the coarse-grained skeleton and fines migration may follow even if the initial structure was stable prior to heave. Second, compaction and fines migration during fluid flow implies fines were part of the initial granular structure.

We carefully reviewed the seven soils in the three references cited by Liu et al. to identify the criteria used to assess internal instability and to extract experimental details relevant to the analysis: particle size distribution for each soil fraction (F_G, F_S, and F_F), particle shape, extreme void ratios $e^{\max}$ and $e^{\min}$, liquid limit, and experimental boundary conditions (i.e., confining boundary condition, effective stress level, vertical deformation, and flow direction). The main observations and clarifications to the points raised in the discussion follow.

J. Geotech. Geoenviron. Eng., 2018, 144(8): 07018019

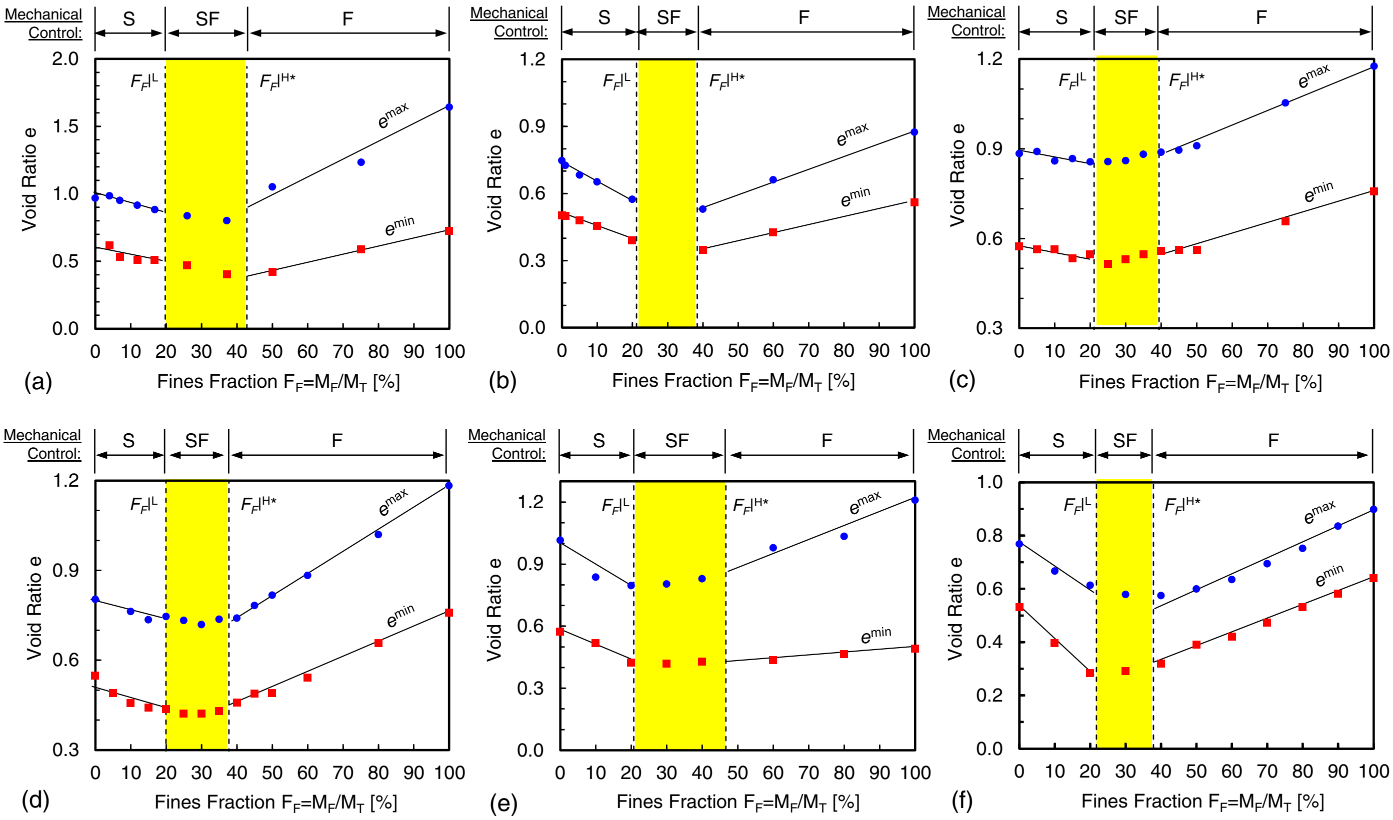

Fig. 1. Maximum and minimum void ratios against fines fraction F_F. Data-adjusted high-threshold fines fraction $F_F|^{H*} = \alpha \cdot e_C^{\max}/(1 + \alpha \cdot e_C^{\max} + e_F^{\min})$, where $\alpha = 1.3$ in all cases. [Data for (a) from Gutierrez 2005; data for (b) from Choo and Burns 2015; data for (c and d) from Lade and Yamamuro 1997; data for (e) from Kang and Lee 2015; data for (f) from Fuggle et al. 2014.]

Binary Mixtures

- Soils A and B from Skempton and Brogan (1994): The discussers use Sieve No. 4 ($d = 4.76$ mm) to separate gravel from sand, and classify both soils as sands S(S). However, the fractions of these gap-graded, subangular gravel-sand specimens are best discriminated by a grain size $d = 0.5$ or 1 mm [Skempton and Brogan (1994) used $d = 2$ mm]; in this case, both Soils A and B are classified as gravels G(G). In addition, heave destructures the granular skeleton and facilitates the migration of the finer fraction.
- Soil HF01 from Li (2008): This GS(S) soil sits near the S(S) boundary ($C_{u,G} = 1.5$, $C_{u,S} = 17.2$, $R_G = 0.3$, and $R_S = 0.3$; particle shape is subangular for both gravel and sand).
- Soil HF03 from Li (2008): The soil experiences downward displacement ($\delta_v = 0.1$–0.4 mm) during the increase in the hydraulic gradient. Therefore, the migrating finer particles were part of the initial load-carrying skeleton, as expected for a soil with only $F_G = 19\%$ gravel fraction. Indeed, this soil is a sand S(S), rather than a gravel G( ).

Ternary Mixtures

- Soil 14A from Wan and Fell (2004): This soil is made of very angular gravel (Picton Sand and Soil, Blue Metal, Sydney, Australia), very angular sand (as part of basalt), silica flour (LL = 23), and kaolinite (LL = 30). Detailed descriptions for each soil fraction found in Wan and Fell (2004) suggest the following index values: roundness $R_G = 0.20$, uniformity $C_{u,G} = 1.82$ for gravel; $R_S = 0.20$, $C_{u,S} = 1.10$ for sand; and liquid limit LL = 30 for fines. The RSCS classifies Soil 14A as a gravel, on the boundary between G(G) and G(F). The discussers suggest it is a gravel G( ).
- Soil 15 from Wan and Fell (2004): This soil experiences ~7% of material loss by suffusion, including both fines and sand grains. The remaining fines fraction $F_F \approx 33\%$ contributes to support loads. Our analysis classifies this soil as GF(F) assuming the following input parameters: roundness $R_G = 0.35$, uniformity $C_{u,G} = 1.82$ for very angular and subrounded gravel mixture; $R_S = 0.55$, $C_{u,S} = 1.10$ for Nepean sand (Payan et al. (2017); and liquid limit LL = 30 for fines ($R_S = 0.55$ for subrounded grains). The discussers suggest it is G( ).
- Soil HF05 from Li (2008): The low gravel fraction $F_G \approx 11\%$ cannot form a primary soil skeleton to support loads, so this soil cannot be classified as a gravel (as suggested by the discussers). This is a SF(F) soil (adopted input parameters are roundness $R_G = 0.30$, uniformity $C_{u,G} = 1.46$ for gravel; $R_S = 0.30$, $C_{u,S} = 4.44$ for sand; and liquid limit LL = 30 for fines). Li (2008) reports fines migration at a gradient $i = 7$; this high gradient reflects the competition between drag forces and skeletal forces carried by particles subjected to effective stress.

Discussion

The detailed analysis of each soil considered by Liu et al. and a careful review of previous studies on seepage-induced internal instability lead to the following observations:

- Internal stability by fines migration should not be determined through unconfined upward seepage because seepage-induced heave and boiling inherently destructure the soil skeleton. Tests should impose effective stress-controlled boundary conditions in order to identify the soil component(s) that controls the mechanical response. Then, the selective migration and loss of fines will confirm their lack of participation in the granular skeleton.

- Gradations that resemble the theoretical Fuller's curve (Fuller and Thompson 1907) can attain self-filtering characteristics as the finer fractions successively fill the pores between coarser grains. Therefore, the deviation of a given grain size distribution from the Fuller's curve hints at the potential for internal instability, as suggested by Kenney and Lau (1985).
- The evaluation of internal stability for gap-graded soils should be determined by the properties of individual fractions rather than by an artificially imposed sieve size, such as Sieves No. 200 or No. 4 in the Unified Soil Classification System (USCS) and RSCS.

Complementary Study

We compiled data for 93 soils from published studies on seepage-induced internal instability (Kenney et al. 1984; Kenney and Lau 1985; Lafleur et al. 1989; Sun 1989; Åberg 1993; Burenkova 1993; Skempton and Brogan 1994; Chapuis et al. 1996; Wan and Fell 2004; Li 2008). The detailed analysis and classification of each soil (not reported here) suggest that soils that cluster into the GF(F), GS(S), and SF(F) classifications have a higher probability of experiencing internal instability. In particular, we can anticipate that fines migration is more likely to occur near the GF(F)–G(F) and SF(F)–S(F) boundaries where the coarser fraction forms the granular skeleton and the finer fraction is free to migrate. Because soil classification boundaries are only indicative of ongoing transitions, special attention is required for soils that fall near classification boundaries.

Closing

We are grateful to the discussers for their insightful comments and feedback. The additional data collection and detailed analyses prompted by their observations show that

- The low- and high-threshold fractions adopted in the proposed RSCS properly predict the coarse-controlled to fines-controlled transition;
- The analysis of gap-graded soils should be based on the grain size that best discriminates the soil fractions, rather than by a preselected sieve size, e.g., No. 200 or No. 4 in the USCS and RSCS; and
- Sediments that fall near the GF(F)–G(F) and SF(F)–S(F) boundaries are more likely to experience fines migration because the coarser fraction forms the granular skeleton and the finer fraction is free to migrate.

An Excel macro for the RSCS is available on the authors' website (EGEL 2017). It simultaneously draws all RSCS-associated charts, identifies classification boundaries, and plots the point that represents the soil under consideration.

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