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A comparison of micromechanical assessments with internal stability/instability criteria for soils

Mojtaba Farahnak Langroudi [a], Abbas Soroush [a,*], Piltan Tabatabaie Shourijeh [b]

[a] Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran
[b] Department of Earth Sciences, Shiraz University, Shiraz, Iran

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ABSTRACT

Suffusion is the erosion of small particles through the skeleton of coarse grains. Soils susceptible to suffusion are described as internally unstable. In this study three dimensional discrete element modeling is employed to investigate internal instability in soils. The simulation is achieved by assessing contacts distributions, forces analysis and transmitted stresses between particles. Three types of gradations have been selected for the analyses: linear, concave upward and gap-graded. Observations of mechanical coordination number and contact distributions during isotropic compression show that the number of fine particles with low connectivity is comparatively higher for gap-graded and concave upward gradations. The evolution of contact force networks confirms that internally stable soils have a relatively homogeneous network of contact forces compared to internally unstable soil. Force distribution analyses reflect higher percent of weak contacts and low connectivity for fine particles in internal instability. In addition four commonly used internal instability assessment criteria were contrasted with micromechanical parameters, and findings revealed reasonable compliance between stability indices and micromechanical measures. Finally the stress reduction factor of the soils is calculated, confirming previous experimental and numerical studies that α is higher for internally stable soils.

1. Introduction

Suffusion, is the selective erosion of small particles through the coarse skeleton of internally unstable soils [1,2]. Hithereto, a clear distinction is made between the suffusion potential and suffusion process. The vulnerability to suffusion is controlled by internal geometrical condition (fabric) of soils and is termed internal instability. The commencement of suffusion is governed by hydro-mechanical circumstances of soils; such as, hydraulic gradient, flow direction, effective stress, and vibration [3–6].

Many researchers have investigated the multi-faceted phenomena of internal instability and suffusion. Kenney and Lau [7] assert that a soil is internally unstable when; (1) the soil comprises a skeleton (i.e. primary fabric) of coarse particles bearing imposed effective stresses, (2) loose particles, liable to movement by seepage, exist in pores of the skeleton and (3) some pore constrictions are larger than loose particles affording their movement. Apparently, these conditions depend on a host of soil parameters; for instance, void ratio, grain shape, particle size distribution, etc. Previous studies indicate concave upward soils, with a flat fine tail, and gap-graded (i.e. bi-modal) soils, with a hiatus of particle sizes, which are particularly abundant in alluvial sediments, open-framework gravels, moraines, and glacial tills, may respect conditions of internal instability [8–11].

Thus far various internal instability assessment methods have been proposed, which might provide different declarations regarding internal stability/instability of an identical soil. While such criteria have the merit of being adaptable and simple to implement in engineering problems, they have a major setback and that is, they analyze only gradation shape, and in some cases soil porosity. This is disquieting, since suffusion involves interaction of hydro-mechanical forces and particle migration through the soil fabric, hence governing mechanisms preponderant in suffusion commencement, continuation and termination play role at the scale of individual particles.

The Discrete Element Method (DEM) is a versatile tool in geomechanics for modeling and analysis of soil micromechanics. Originally developed by Cundall and Strack [12], DEM has been widely used to investigate macro/micro-mechanical behaviors of granular soils [13,14].

DEM simulations have previously been incorporated for investigating internal erosion processes. Muir Wood et al. [15] implemented 2D-DEM to evaluate soil critical state behavior as a consequence of gradation changes by erosion. Scholtès et al. [16] described mechanical responses induced by particle removal in granular materials. Summersgill and O'Sullivan [17] utilized 2D-DEM to analyze particle

* Corresponding author at: No.709, Faculty of Civil and Environmental Eng., 424, Hafez Ave., Tehran, Iran, 15914. Tel.: +98 21 6454 3009; fax: +98 21 6641 4213.
E-mail addresses: farahnak@aut.ac.ir (M. Farahnak Langroudi), soroush@aut.ac.ir (A. Soroush), piltan@shirazu.ac.ir (P.T. Shourijeh).

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Notation

α	stress reduction factor
α_D	shape coefficient of grains
β_d	damping coefficient
C_u	uniformity coefficient
C	total number of contacts
C_N	coordination number
D_i, D'_i, d'_i	particle diameter with i% finer by mass respectively in soil gradation, coarse fraction and fine fraction
D_h^c	effective diameter of coarse fraction
D_i^c	average grain size in ith interval of coarse fraction
D_{min}, D_{mean}	minimum and mean particle diameter in gradation, respectively
d_0	average pore size of coarse fraction
e	void ratio
F	percent passing size D in soil gradation
F_f	percent passing delimiting fine and coarse fractions
ΔF_i^c	percent of particles in ith interval of coarse fraction
$<F_n>$	mean normal contact force
$F_n/<F_n>$	normalized normal-contact-forces
G	Hertz shear modulus (g/mm^2)
G_s	Specific gravity of soil particles
H	percent between size D and $4D$ in soil gradation
h', h''	D_{90}/D_{60} and D_{90}/D_{15}, respectively
$(H/F)_{min}$	minimum value of H/F
i_{crit}	critical hydraulic gradient of suffusion instigation
i_{theory}	theoretical critical hydraulic gradient of an internally stable soil
I	dimensionless inertia parameter
n	porosity
n_c	porosity of coarse fraction
ρ_s	scaled density (g/mm^3)
ρ	particles' density
P_c	limiting contact pressure between particles
P	isotropic confining pressure
R_n	normalized radius, that is; $R_n = D_i/D_{mean}$
Δt	time step (s)
μ	friction coefficient
$\dot{\varepsilon}$	strain rate
N_1, N_0	number of particles with one or no contacts, respectively
$\sigma'_{m,f}$	mean effective stress transmitted to the fine fraction
$\sigma'_{m,,c}$	mean effective stress transmitted to the coarse fraction (primary fabric)
X @ F_f	parameter X at location of F_f or for gradation split at F_f
Z_m	mechanical coordination number

size distribution effects on soil microstructure. Ahlinhan and Achmus [18] combined experimental observations with DEM modeling to evaluate stress conditions in internally unstable soils. Farahnak Langroudi et al. [19] investigated the effects of gradation shape (i.e. linear, gap graded, concave upward) on internal stability/instability using 3D-DEM modeling. Shire and O'Sullivan [20] utilized 3D-DEM to micromechanically assess an internal stability criterion. Fonseca et al. [21] studied the microstructure of internally unstable soils by comparing DEM results with high-resolution micro-computed tomography of real sands.

The key intention of this treatment is 3D-DEM modeling of granular soil microstructure, with special attention to gradation shape, and comparing micromechanical measures, viz. contact forces, connectivity of particles and stress transmission between particles, etc., with available internal stability/instability assessment methods. To this end the paper first reviews theoretical considerations of internally unstable soils and a host of assessment criteria. Then details and results of DEM simulation for selected gradations are presented. Finally the micromechanical approach is contrasted against state of the art internal stability assessment criteria commonly used in engineering practice.

2. Theoretical background

2.1. Fabric of internally unstable soils

It is well understood that an internally unstable soil possesses a clast-supported fabric where coarser grains, i.e. coarse fraction, nest in contact, forming a skeleton or primary fabric, with voids, in which finer particles, i.e. fine fraction, reside [6,22–25]. The skeleton of clasts defines the overall soil volume, sustains mechanical loads and is dominant in shear strength mobilization [11,25–28].

Fig. 1 illustrates schematically typical pore spaces in internally unstable clast-supported fabrics. In case of Fig. 1-a, resembling a gap graded soil having a hiatus of grain sizes; finer particles loosely rest in the void space among larger, primary-fabric grains. Owing to lack of intermediate particle sizes, the fine fraction has limited inter-particle contacts, transferring little stress from the primary fabric. Fig. 1-b may be attributed to concave upward (or open frame work) soils, wherein finer particles sparsely fill the pore space. In this condition inter-particle contacts and stress transfer are higher in comparison to Fig. 1-a, yet a minute excitement may afford particles rearrangement. The situation in Fig. 1-c, interprets widely graded (and concave upward) soils within which the pore space is closely packed with finer particles, therefore inter-particle contacts and stress transfer are much higher than Fig. 1-a, b.

It can be perceived from the foregoing, that internal instability intensity stems from the soils' micro-mechanical contacts and stress transfer conditions.

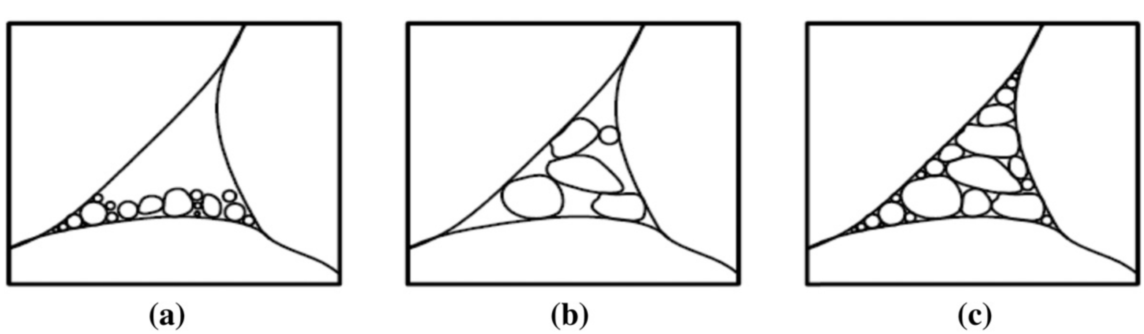

Fig. 1. Conceptual visualization of typical pore spaces in soils with clast-supported fabrics; (a) gap graded, (b) open frame-work, (c) widely graded [25].